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Federal Railroad Administration

Advanced Power Conditioning For Maglev Systems

National Maglev Initiative
Washington, DC 20590

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16. Abstract

The final report contains parametric scaling data and computer models of power conditioning equipment applicable to the design of an advanced maglev system. The power conditioning topologies were selected based on data from a literature search, on characteristics of present power semiconductor technology devices, and on actual performance characterization of designs using a circuit analysis program. The analyses show that GTOs are the best switches for traction drives, input power conditioning equipment, and the braking chopper. At lower power levels, as required for auxiliary power and superconducting coil power conditioning, the IGBT appeared to be the best switch.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in.) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x - 32) (5/9)] °F = y°C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (kn^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES: 0 1 2 3 4 5 6 7 8 9 10

CENTIMETERS: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 25.40

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

PREFACE

This is a report of work performed on the parametric design analysis of advanced power conditioning for use in maglev systems. This program is sponsored by the U.S. Department of Transportation, Federal Railroad Administration (FRA). The program complements work in related technologies by other BAA contractors.

The authors wish to thank Mr. Richard A. Murphy and Mr. Raymond A. Wlodyka (COTR) for their advice and encouragement. We also appreciate the valuable comments from Mr. K. Campbell, Mr. K. Shaver, and Mr. R. Armstrong of the U.S. Army Engineers.

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LIST OF ABBREVIATIONS

A	amperes
ac	alternating current
BJT	bipolar junction transistor
BV_{CES}	breakdown voltage collector-emitter, base short-circuited to emitter
dc	direct current
°	degrees
°C	degrees Celsius (temperature)
di/dt	derivative of current with respect to time
dV/dt	derivative of voltage with respect to time
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
g_{fe}	forward transconductance
GTO	gate turn-off or gate-turn-off thyristor
Hz	hertz (cycles per second)
I_C	collector current
IGBT	insulated gate bipolar transistor
I_{TGQ}	maximum turn-off current capability of a GTO
J	joule (energy)
kHz	kilohertz (10^3 hertz)
kV	kilovolt (10^3 volts)
kVA	kilovolt-ampere (10^3 VA)
kVdc	kilovolts of direct current
kVac	kilovolts of alternating current
μs	microsecond (10^{-6} seconds)
MOSFET	metal-oxide-semiconductor field effect transistor
MVA	megavolt-ampere (10^6 VA)
MW	megawatts (10^6 Watts)
PCU	power conditioning unit
PWM	pulse width modulation
ROMAG	trademark for Rohr Industries' maglev system
rms	root mean square
s	second
S or (℧)	siemens (conductance, sometime expressed as mhos)
SCR	silicon controlled rectifier
V	volts
Vac	volts alternating current
V_{CE}	collector-emitter voltage
V_{CE}(sat)	collector-emitter saturation voltage
Vdc	volts direct current
V_{CEX}	breakdown voltage collector-emitter, base connected to emitter terminal through a specified circuit
VVVF	variable voltage, variable frequency

1. INTRODUCTION

1.1 OVERVIEW

This report provides scaling data for power conditioning equipment which may be useful to the maglev systems engineer who is trying to synthesize an optimum maglev transportation system. The data cover power conditioning for processing the main power to the rails, for traction, levitation, and hotel loads, and for superconducting coils. Performance characteristics such as mass, volume, cost, and efficiency are presented for several power conditioning topologies in which GTOs, BJTs, or IGBTs are the primary switching components.

The data provided may be used to design power conditioning for both active and passive maglev vehicle systems. Power transmission and power collection methods were beyond the scope of this study and must be considered separately.

Results and conclusions from the design and analysis are presented in Section 2 of this report. The data are presented in four subsections as shown in Figure 2.2. The report is organized to provide the user with sufficiently detailed information to select individual power conditioning subsystems according to the desired maglev system architecture. A maglev system engineer may combine power conditioning data from each relevant subsection, and add the selected subsystem results to obtain the resulting overall mass, volume, and cost data.

While the data are provided for several power circuit topologies, the maglev engineer may sometimes need to consider power conditioning topologies operating outside the parameter space used in the designs performed under this contract. For this reason, the report contains detailed explanation of the methodology used in the analysis, and an explanation of each circuit topology used. The circuits were analyzed using PSpice (by Microsim). The spreadsheet program used was LOTUS 1.2.3 for Windows release 1.0. Circuit models and spreadsheets were delivered to the FRA on magnetic media.

1.2 BACKGROUND

Key factors in making any transit system successful are convenience, low cost, high efficiency, and low environmental impact. Maglev offers high potential in all of these areas. Maglev systems developed in Germany and Japan have appealing features, but use technology available at the time their designs were frozen.

The emphasis on maglev technology in the US has changed markedly since serious work began in the mid-1960s. The peak of the effort occurred in the 1970s, with a decline thereafter reflecting a lack of government sponsorship. Development of maglev systems in Japan started several years earlier than the US program, and has been a continuously funded effort. Germany started their maglev development effort in 1970, and has continued without interruption. Both Japan and Germany have an operational demonstration system, which gives these countries apparent advantages in pursuing today's market needs. Neither the Japanese nor the Germans have revenue systems in operation. While it is tempting to adopt one of the developed technologies, one must keep in mind that these systems use outdated power system technology.

Power semiconductor and capacitor technologies progressed significantly during the 70s and 80s, enabling substantial reductions in mass, volume, and cost, as well as improvements in the efficiency of power conditioning. Figure 1-1 shows the evolution of competing technologies of power semiconductors during the last 20 years, with projections for the next five years. From this graph, it is seen that the two competing power semiconductor technologies during most of this period have been the bipolar transistor (BJT) and the gate turn-off thyristor (GTO). In conducting design trades for new systems, one must consider not only the improvements in power rating of these devices, but also the emergence of the insulated-gate bipolar transistor (IGBT). IGBTs, introduced around 1980, offer major advantages in some power converter topologies.

The impressive advance in power rating of semiconductor devices illustrated by Figure 1-1 also implies an obsolescence rate in power conditioning systems based on earlier device technologies. An advanced maglev system therefore must build on the most recent technology advances if it is to have the most compact, efficient, and economical power conditioning equipment available.

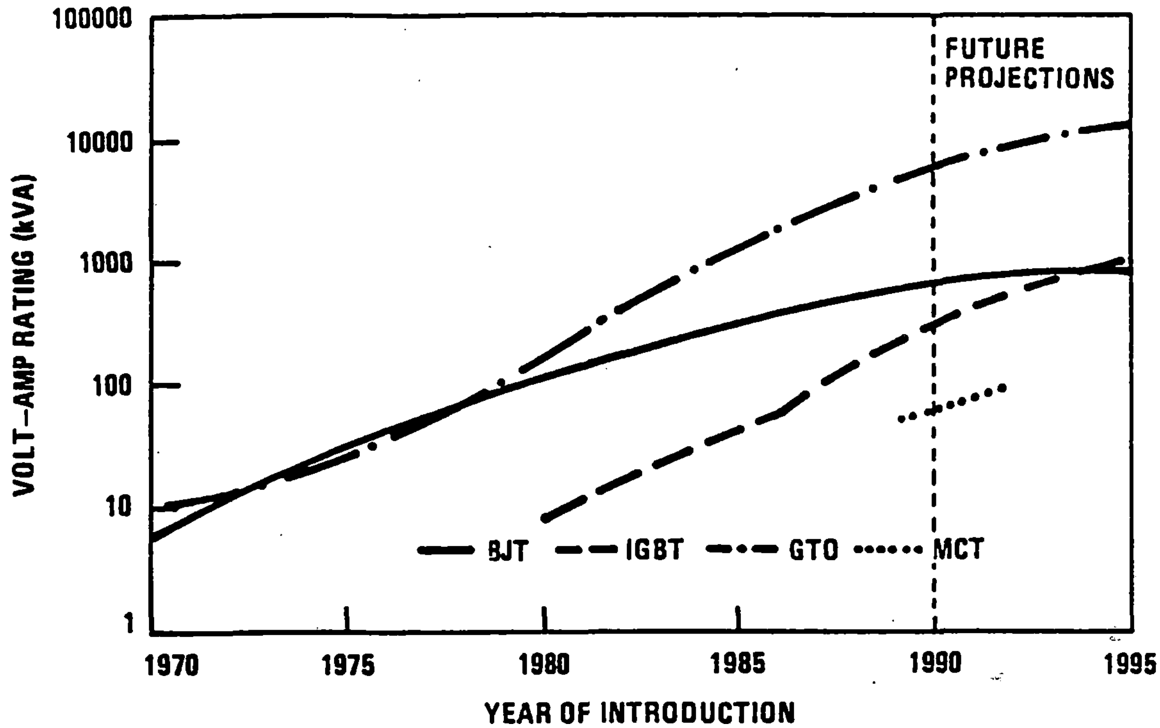

Figure 1-1. Advances in power semiconductors.

1.3 TECHNICAL APPROACH

Figure 1-2 shows a program roadmap of the study. In Task 1, critical requirements were defined based on a literature search, on computer modelling of 40 metric ton and 100 metric ton vehicles in assumed maglev operating scenarios, and on guidance from FRA. The requirements list is shown in Table 1-1 for immediate overview. Applicable sections of this list will be restated in the discussion of results and analysis presented in Sections 2 and 3.

In Task 2, power converter circuits were designed with BJTs, GTOs, or IGBTs used as switching devices. Task 3 consisted of PSpice analyses to characterize the performance of each circuit and verify that it would meet the requirements. In task 4, selected power circuits were optimized and schematics were prepared. Spreadsheets for parametric analysis of the selected power converter circuits were prepared in Task 5, with the parametric design and scaling calculations completed in Task 6.

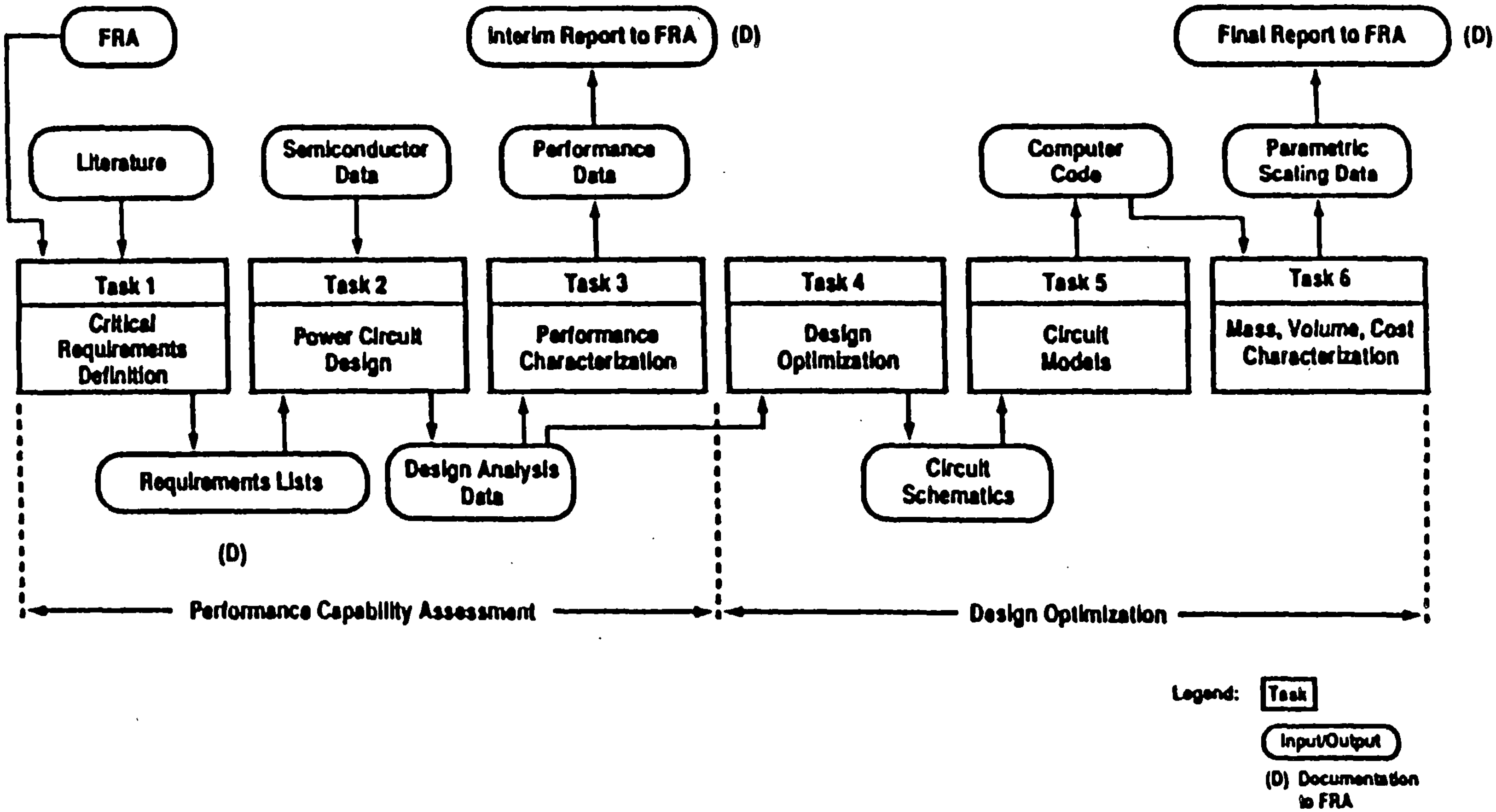

Figure 1-2. Program roadmap.

TABLE 1-1

REQUIREMENTS LIST

Traction Power:	
Input voltage	7 kVdc - 35 kVdc, or 5 kVac - 25 kVac, 60 Hz (three phase line-line)
Output voltage	0 - 5 kVac (three phase line-line) variable frequency
Output power	5 MVA - 25 MVA per vehicle for an active vehicle system, or 25 MVA - 50 MVA per guideway section for a passive vehicle system
Cooling	Liquid cooling with liquid-to-air heat exchanger Auxiliary fan cooling as required
Hotel power	Provision for auxiliary loads on vehicle (power will be backed up with battery energy storage)
Auxiliary loads	(a) 100 kVA - 250 kVA 120/208 Vac three phase, four wire, 60 Hz (b) 100 kVA 0 - 100 Vdc, 0 - 3000 A variable voltage computer controlled

The data and results in Tasks 1 through 3 were reported in a Final Interim Report to FRA dated March 1992. This material is also included in this Final Report as indicated in Table 1-2, with the exception that semiconductor data sheets were only included for the devices which were used in the final analysis. A binder containing the publications obtained as a result of the literature search will be made available to the FRA upon request.

TABLE 1-2

SUPPORTING DATA

1. Statement of Work (Appendix A)
2. Literature Search (Appendix B)
3. Typical Transit Vehicle Parameters (Section 5.1)
4. Establishing the Parameter Space for Maglev Power Conditioning (Section 5.2)
5. Circuit Topologies (Section 2)
6. Power Semiconductors for Advanced Power Conditioning (Section 2)
7. Device Performance Characterization (Section 2)
8. Semiconductor Computer Models (Section 4)
9. Computer Circuit Models (Section 4)
10. Design Analysis (spreadsheet) (Section 3)
11. Design Analysis Data (graphs) (Section 2)

1.4 BASIS FOR PARAMETRIC DATA AND ASSUMPTIONS

The data for parametric trades was obtained by analyzing the detail design of each circuit topology. The manufacturer and part number of each component of the detailed design was specified and data on pricing, mass, volume, and performance was obtained. In the case of the gate drive and control circuit, which are not discrete components, the data were scaled from existing semiconductor gate drive and control circuits.

Only components presently available were considered and the list price per thousand was used for the cost basis. One can speculate on price reductions due to technology improvements and very large production volumes, but in this study commercially available components were assumed with the price based on a production run of 1000 power conditioning units beginning in 1992.

Forced air cooling was not considered practical in these high power converter systems because of the additional mass and volume of the heat sinks required to maintain the silicon junctions of the power switching semiconductors within safe operating limits. Liquid cooling with liquid/air cooling systems was therefore assumed in the analysis. The cooling systems included refrigeration units to control the coolant temperature.

Labor costs were scaled from General Atomics' manufacturing experience. In this analysis total labor costs exceed material costs by 39%. Labor costs will decrease with the design maturity and manufacturing volume. The amortized cost of the initial development along with possible profit margins have been excluded from this analysis.

Realism was ensured by comparing cost predictions with costs of existing converters manufactured by General Atomics and General Electric Drive Systems.

2. RESULTS

The objective of this study was to quantify the performance and economic advantages of power systems and power system technology currently available for use in maglev systems. Initially, a review was made of available solid state switching devices and their performance characteristics. This information is summarized quantitatively and qualitatively in Section 2.1. The study then proceeded with the formulation of power circuit topologies and development of computer models for analysis of their performance in order to determine the detailed design parameters. Section 4 presents detailed computer models and simulation results. The final analysis was then performed as described in Section 2.2. This section also presents a list of assumptions used in each system design. Section 2.3 presents the results of the analyses of the selected candidate power system configurations. Estimates of mass, volume, efficiency and cost were made for each candidate design as described in the following sections.

2.1 POWER SEMICONDUCTORS FOR ADVANCED POWER CONDITIONING

As a prelude to the analysis effort, quantitative and qualitative characteristics of solid state switching devices were tabulated. These indicate the general nature and performance of the semiconductor types presently available for power conversion. Desirable characteristics are high volt-ampere ratings, high blocking voltage, and fast self-commutation.

Table 2-1 includes quantitative information on discrete solid state devices which were appropriate for study. This table shows that the devices with the highest volt-amp product include the silicon-controlled rectifier (SCR), the gate turn-off (GTO) thyristor, the bipolar junction transistor (BJT) and the insulated gate bipolar transistor (IGBT). Since the SCR is not capable of self-commutation, it was not considered further. The BJT, IGBT and GTO thyristor components are described briefly below:

BJTs - These devices were used in the Federal Transit Administration (FTA) funded studies of ROMAG[1]-like systems during the years roughly 1960-1980. Since then, the volt-amp product ratings of BJTs have increased by approximately a factor of three. The breakdown voltage ratings have increased by a factor of two permitting power converter designs with dc voltage input of 600 V.

IGBTs - These devices combine the high input impedance and switching characteristics of power metal-oxide semiconductor field-effect transistors (MOSFET) with the high conductivity characteristics of power BJTs. Circuits designed with the IGBT typically have fewer auxiliary components and lighter filters than designs with BJTs owing to the reduced gate drive power required during operation. Present day IGBTs have BV_{CES}[2] ratings of 1400 V which is as high as the 1400 V V_{CEX}[3] rating for BJTs. It is projected that in the near future, the IGBT BV_{CES} ratings will range up to 1700 V.

GTO Thyristors - With their high off-state voltage ratings and high on-state current ratings, GTOs are ideally suited for present day traction variable voltage, variable frequency (VVVF) inverters operating from poorly regulated third rail voltages. With off-state voltage ratings up to 6000 volts, the GTO can be designed into an inverter circuit with a comfortable margin of safety for line disturbances, regulation and transients. The switching frequency attainable with GTOs is considerably lower than what is achievable with IGBTs, however, and GTOs require large snubber elements.

Table 2-2 includes information on emerging custom devices which may offer some advantages over presently commercialized devices. Table 2-3 shows qualitative characteristics of candidate solid state devices.

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[1]Trademark for Rohr Industries' maglev system

[2]breakdown collector-emitter with base shorted to emitter.

[3]Breakdown collector-emitter voltage rating with specified base-emitter circuit

TABLE 2-1
QUANTITATIVE CHARACTERISTICS OF POWER SEMICONDUCTOR DEVICES

DEVICE	SYMBOL	MAX BLOCKING VOLTAGE AVAILABLE (V)	MAX SINGLE DEVICE CW CURRENT AVAILABLE (A)	MAX VOLT-AMP PRODUCT AVAILABLE $V_{max} \times I_{cw}$[1] (kVA)	PART NUMBER FOR MAX VOLT-AMP DEVICE	ON-STATE VOLTAGE DROP AT CW RATING[2] (V)	TURN-ON TIME[2] (μs)	TURN-OFF TIME[2] (μs)	PEAK OPERATING FREQUENCY[2,3] (kHz)	MAXIMUM OPERATING TEMP (°C)	COMMU-TATION TYPE	MAJOR MANU-FACTURERS	SUBJECT OF REPORT ANALYSIS
Field Effect Transistor (FET)		1000	100	39 78 A at 500 V	Advanced Power Technology APT10021-DFN	4.7	0.05 (user-controlled via gate)	0.05 (user-controlled via gate)	50-100	150	Self Commutation	APT, Harris, IR, IXYS, Motorola, Siemens, Toshiba	No, power level too low. IGBT preferred
Bipolar Transistor (BJT)		1400	1200	412 750 A at 550 V	Marconi DT600	3.4	1.0 (user-controlled via gate)	2.0 (user-controlled via gate)	4-5	150 (175)	Self Commutation	AEG, Fiji, Marconi, Motorola, Powerex, Siemens, Westcode	Yes
Insulated Gate Bipolar Transistor (IGBT)		1400	200	200 200 A at 1000 V	Advanced Power Technology APT200G-100	3.3	0.2 (user-controlled via gate)	0.8 (user-controlled via gate)	8-10	150	Self Commutation	APT, Fuji, Harris, IR, IXYS, Motorola, Siemens, Toshiba	Yes
Gate Turn-Off Thyristor (GTO)		8000	1900	7200 1200 A at 6000 V	Toshiba SG3000JX24	3.1	5	2	0.5-0.7	125	Self Commutation (via gate current counter- pulse)	AEG, ABB, Fuji, Marconi, Powerex, Toshiba, Westcode	Yes
Silicon Controlled Rectifier (SCR)		6500	7900	26,000 5000 A at 5200 V	Asea Brown Boveri CS2104	1.8	2	Cannot turn off, forced by external circuit	0.7-1.0	125 (140)	Force Commutated	AEG, ABB, General Electric, Marconi, Powerex (Westinghouse), Westcode	Device model only
MOS-controlled thyristor (MCT)		1000	100	100 100 A at 1000 V	Harris MCTA60P60	1.3	0.2	2	5-7	150	Self Commutation	Harris	No, not commercially available

1) I_{cw} is the continuous dc current rating at 25 °C case temperature.
2) Data for the maximum volt-ampere device.
3) These frequency ranges represent design compromises between switching and conduction loss in high power pulse width modulation use. Higher frequencies are possible with the penalty of reduced current capability.

TABLE 2-2
QUANTITATIVE CHARACTERISTICS OF POWER HYBRID POWER CIRCUITS AND CUSTOM MODULES

DEVICE	SYMBOL	MAX BLOCKING VOLTAGE AVAILABLE (V)	MAX SINGLE DEVICE CW CURRENT AVAILABLE (A)	MAX VOLT-AMP PRODUCT AVAILABLE $V_{max} \times I_{cw}$[1] (kVA)	PART NUMBER FOR MAX VOLT-AMP DEVICE	ON-STATE VOLTAGE DROP AT CW RATING[2] (V)	TURN-ON TIME[2] (μs)	TURN-OFF TIME[2] (μs)	PEAK OPERATING FREQUENCY[2,3] (kHz)	MAXIMUM OPERATING TEMP (°C)	COMMUTATION TYPE	MAJOR MANUFACTURERS
GTO/FET CASCODE		8000	1900	7200 1200 A at 6000 V	NONE	3.5	5	2	1-2	250	Self Commutation	Research by International Rectifier, et. al.
SCR/FET/ IGBT HYBRID		6500	7900	412 5000 A at 5200 V	NONE	2.2	2	0.8 (user-controlled via gate)	1-2	125	Self Commutation	Custom by General Atomics
IGBT CUSTOM MODULE		1200	2000	200 2000 A at 1000 V	KWT8000	3.3	0.2 (user-controlled via gate)	0.8 (user-controlled via gate)	8-10	150	Self Commutation	Custom by Gentron Corp.

1) I_{cw} is the continuous dc current rating at 25 °C case temperature.
2) Data for the maximum volt-ampere device.
3) These frequency ranges represent design compromises between switching and conduction loss in high power pulse width modulation use. Higher frequencies are possible with the penalty of reduced current capability.

TABLE 2-3
QUALITATIVE CHARACTERISTICS OF SOLID STATE SWITCHES

FIELD EFFECT TRANSISTOR (FET)	BIPOLAR TRANSISTOR	INSULATED GATE BIPOLAR TRANSISTOR (IGBT)
○ Optimally applied 50 to 200 V. + Fast turn-on and turn-off. ○ Reverse conducting (equal to forward current rating). + Wide safe operating area, no second breakdown; rugged. ○ Positive temperature coefficient of resistance (parallel sharing). + Active device, conductivity modulated via gate. + Little temperature effect on switching parameters. □ High on-state resistance at high voltage ratings.	○ Optimally applied 500 to 1400 V. + Medium turn-on and turn-off speed. Reverse blocking but only at low voltage. □ Safe operating area has second breakdown. □ Negative temperature coefficient of resistance makes sharing difficult. ○ Active device, conductivity modulated via base. □ Temperature affects switching parameters. □ High on-state voltage drop at high current. □ Conduction requires base drive of 10 % of forward current.	+ Optimally applied 400 to 1200 V. + Fast turn-on, medium turn-off speed. ○ Reverse blocking, but to a low voltage. + Wide safe operating area, no second breakdown. + Positive temperature coefficient of resistance (parallel sharing). + Active device, conductivity modulated via gate. ○ One volt threshold and then less than a linear voltage rise with current. + Little temperature effect on switching parameters. □ High on-state voltage drop at high voltage.

SILICON CONTROLLED RECTIFIER	GATE TURN-OFF THYRISTOR (GTO)	MOS CONTROLLED THYRISTOR (MCT)
○ Optimally applied 50 to 6500 V. + Highest power device; lowest cost per watt switched. □ Only turns off at zero current. □ Negative temperature coefficient of resistance makes sharing difficult. □ Requires recovery time for voltage hold-off after zero current. + Reverse blocking to full forward voltage. + Moderate turn-on time and dI/dt. + Low on-state voltage drop. □ Device destruction if dI/dt rating is exceeded, but otherwise very rugged.	+ Optimally applied 800 to 8000 V. + Turns off with a gate counter-pulse ~15% of forward current. + Reverse blocking types available. □ Negative temperature coefficient of resistance makes sharing difficult. ○ Moderate turn-on time, but low dI/dt. + Highest power self-commutated turn-off switch available. + Moderate on-state voltage drop. □ Device destruction if turn-off attempted above rating, if dI/dt rating is exceeded, if gate pulse is inadequate, or if retriggered too soon.	+ Excellent promise for high voltage, low-loss turn-off switch. □ Not commercially available. □ Negative temperature coefficient of resistance makes sharing difficult. ○ Loses turn-off capability above rating, but device will survive if turn-off is attempted.

+ Advantage
○ Typical Characteristic
□ Disadvantage

Taken together, these tables offer some insight into the comparison process. However, because there are many caveats in the application of these semiconductors, a true comparison can only be made in a given circuit topology for a given application. Therefore, this study proceeded to identify and analyze several topologies appropriate for comparison using the above described power semiconductor devices.

2.2 INTRODUCTION TO ANALYSIS RESULTS

A block diagram representation of power conditioning subsystems as envisioned in a typical maglev application is shown in Figure 2-1. The bidirectional arrows which connect the blocks in the diagram represent bidirectional power flow which applies to both ac and dc systems. This means that while the vehicle is accelerating, cruising, or climbing grades, the net power flow is from the power source into the system, and that the power grid or rail is also capable of accepting regenerated power from deceleration, downgrade cruising, and braking (two quadrant converter operation).

In Section 2.2, we present data plots of the performance characteristics (output power, switching frequency, efficiency) vs. mass, volume and cost for each power conditioning subsystem. These plots originate from several spreadsheets which are described in detail in Section 3. These spreadsheets calculate parameters according to the following sequence:

1. Determine the number of series and parallel switch modules required based on output voltage, output power, ac line frequency, switch element electrical characteristics and thermal requirements.

2. Determine power dissipation in all of the major heat-generating components based upon the series-parallel configuration.

3. Determine mass, volume, and cost of the entire series-parallel configuration including buswork and frame estimates.

The detailed assumptions for each calculation are provided in Section 3. Some of the general assumptions used in designing all the spreadsheets are:

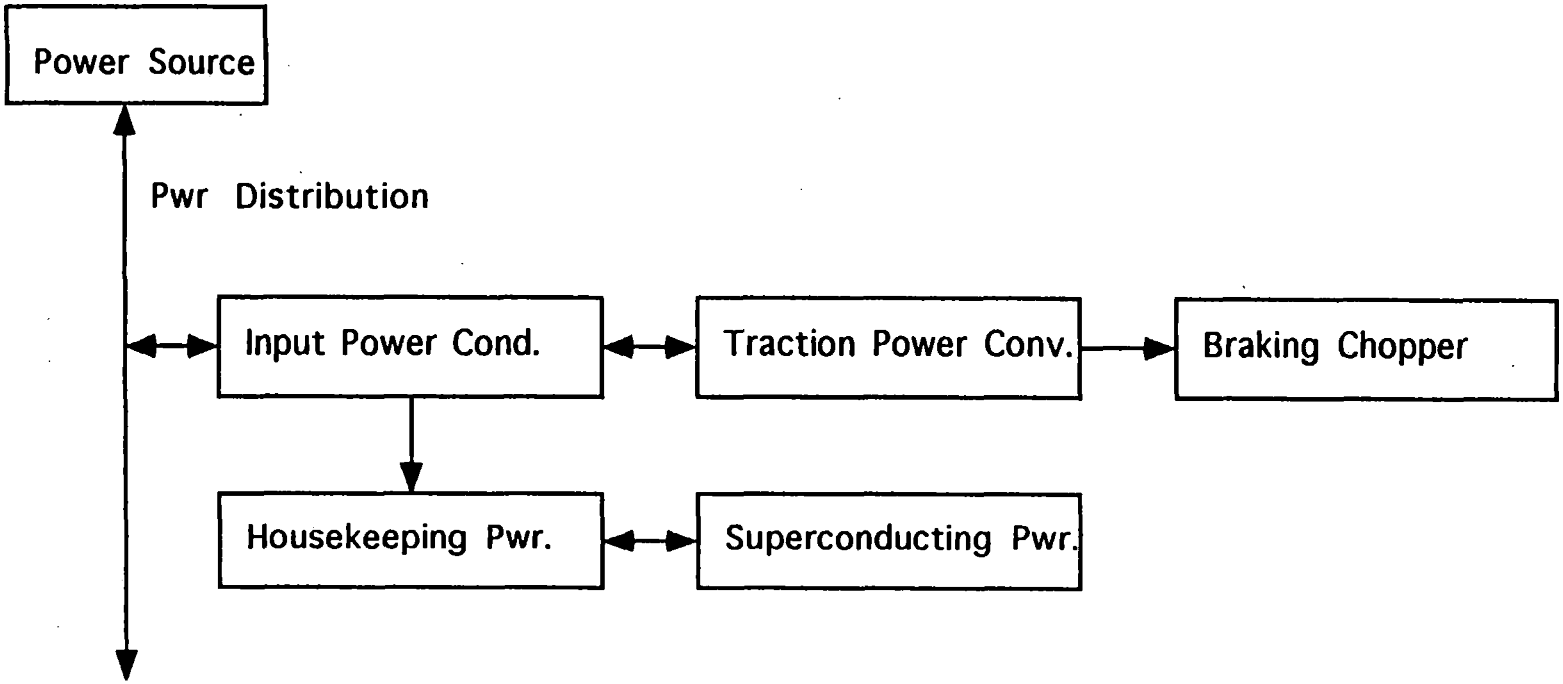


Figure 2-1. Block diagram of maglev power conditioning system.

1. In all cases, liquid cooling is assumed for all of the semiconductor devices and other high heat flux components. The cooling system includes refrigeration capability to assure a maximum converter/inverter inlet temperature of 25 °C under all anticipated ambient conditions. The power consumed by the heat exchanger is included in the total efficiency estimates in each spreadsheet.

2. The voltage derating factor for all switches is 2.5. Therefore, the spreadsheet will calculate that for a 2 kV dc rail, a device rated at 5 kV (2.5 x 2 kV) is required, or that several devices in series with a 5 kV total rating will be used.

3. The operating temperature of the devices is not allowed to exceed the manufacturer's maximum rating minus 25 °C.

4. Buswork and frame estimates are scaled from actual hardware.

5. All inverters synthesize the output sine waves by a unipolar, pulse width modulation (PWM) technique. The rms values are calculated in the spreadsheets based on this modulation technique. It is recognized that other PWM methods may have more optimal results in some maglev systems.

6) The ac line frequency is fixed at 60 Hz for all ac configurations.

2.3 CIRCUIT TOPOLOGY FINAL ANALYSIS

The final analysis of the candidate power system configurations are presented in this section. Figure 2-2 gives an overview of the analyses that were performed, each indicated by an X, the location of the data plots by paragraph number, and the switch type that was the basis for the analysis.

The data presented in the following sections cover selected parameter values and ranges. Additional data maybe obtained by selecting other values as input parameters to the appropriate spreadsheet calculation programs as discussed in detail in Section 3.

All input power conditioning circuits require capacitor filters. Recent advances in capacitor technology has indicated advantages in using polypropylene film capacitors for this purpose.

Function	CONFIGURATION	SWITCH BASIS: BJT	SWITCH BASIS: GTO	SWITCH BASIS: IGBT
2.3.1 Input Power Conditioning	2.3.1.1 Passive dc filter	NA	NA	NA
2.3.1 Input Power Conditioning	2.3.1.2 Single phase ac-dc converter	X	X	X
2.3.1 Input Power Conditioning	2.3.1.3 Three phase ac-dc converter	X	X	X
2.3.2 Traction/Levitation	2.3.2.1 dc-ac, three phase inverter	X	X	X
2.3.2 Traction/Levitation	2.3.2.2 dc-ac, three phase with staggered switch firing	-	X	-
2.3.3 Braking Chopper	2.3.3.1 Shunt braking, dc-dc	-	X	-
2.3.4 Auxiliary/Housekeeping/ Hotel Power	2.3.4.1 dc-ac, three phase inverter	X	X	X
2.3.4 Auxiliary/Housekeeping/ Hotel Power	2.3.4.2 Three phase ac, current fed converter	-	-	X

Figure 2-2. Organization of analysis and data.

A comparison of electrolytic and polypropylene capacitors was made to determine what type would offer the best performance for this application. Table 2-4 compares polypropylene and electrolytic capacitors.

TABLE 2-4

CAPACITOR COMPARISON

Capacitor Type	Relative Weight	Relative Volume (including mounts)	Relative Number of Capacitors
Polypropylene	1.0	1.0	1
Electrolytic	1.6	2.2	50

Polypropylene capacitors were chosen in this study because of their significant advantages over the electrolytic types. Each capacitor is equipped with a bleeder resistor. A vacuum discharge safety relay and a dump resistor are provided to discharge the capacitor bank rapidly when the prime power is removed. Line circuit breakers, disconnects and soft-start apparatus are assumed to be located on the ac side of the system and are not considered in this design because no suitable dc components are available at voltage levels above 3 kVdc.

2.3.1 Input Power Conditioning Subsystem

The input power conditioning subsystem connects directly to the main power source. Its outputs are used to supply the traction power subsystem and the general vehicle "housekeeping" or "hotel loads." Typical input power source characteristics are as follows:

Input voltage: 7 kV - 35 kVdc or
5 kVac - 25 kVac 60 Hz, single or three phase.

Power throughput: 5 - 50 MW

2.3.1.1 Input Power Conditioning Without Conversion

This approach is shown in Figure 2-3 and may be used if the input power source voltage is directly useable as the dc input voltage to the traction/levitation power conditioning.

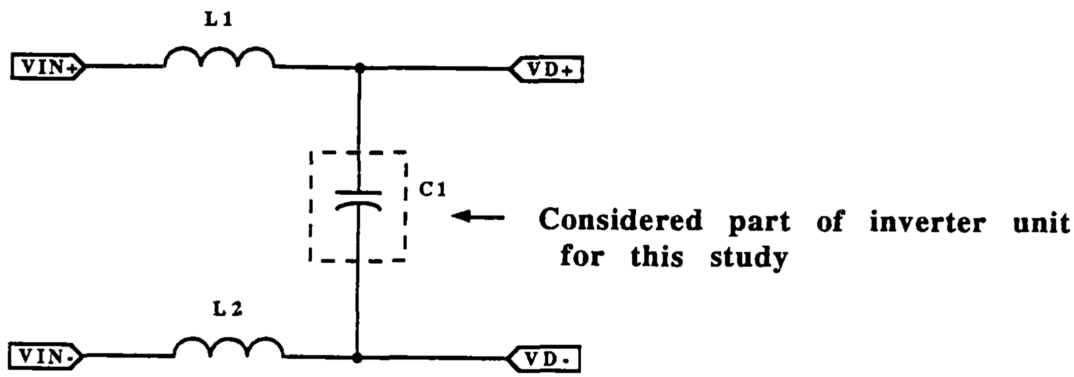


Figure 2-3. Input power conditioning without conversion.

2.3.1.2 Single Phase AC to DC Converter

This converter is intended to condition a single phase 60 Hz feed into a dc output voltage to feed the traction/levitation motor drive and the auxiliary power system. A schematic of the approach is shown in Figure 2-4. A single phase high voltage ac feed is tied to the primary of a step down transformer with several secondaries, each of which feed a single phase, full wave bridge converter. The outputs of the converters are tied in parallel to achieve the required output current for the traction drive. Although not shown, separate lower voltage secondaries and converters will be provided for the auxiliary power inverter.

The graphical results of the spreadsheet analysis for the single phase input converter for the BJT case are shown in Figure 2-5.1 and 2-5.2, the GTO results are shown in Figure 2-6.1 and 2-6.2 and the IGBT results are shown in Figure 2-7.1 and 2-7.2. The discontinuities in the curves reflect points where an additional set of switch modules is added to meet the output power requirement.

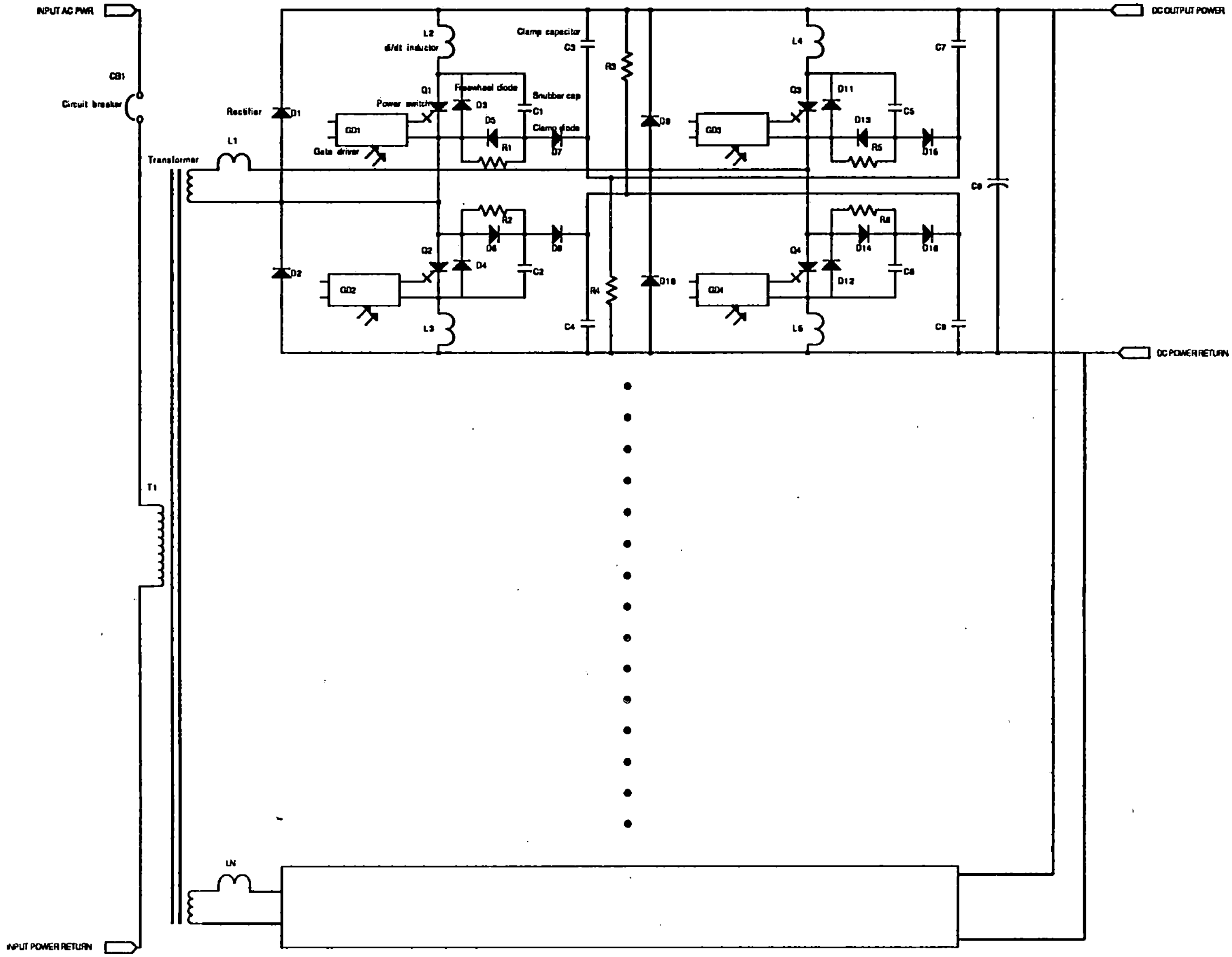


Figure 2-4. Input power conditioning from single phase power distribution system.

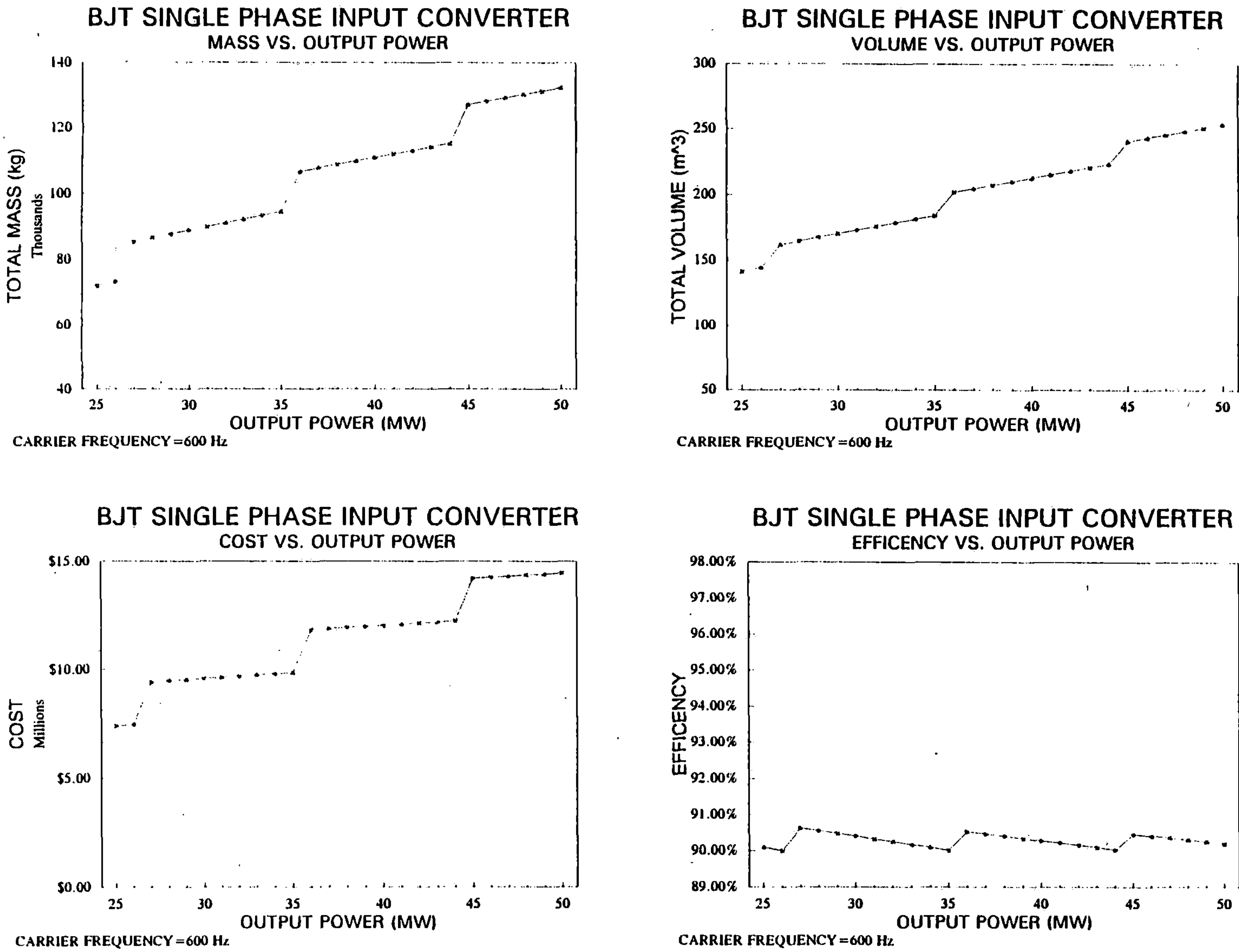


Figure 2-5.1 BJT single phase input converter characteristics vs. output power.

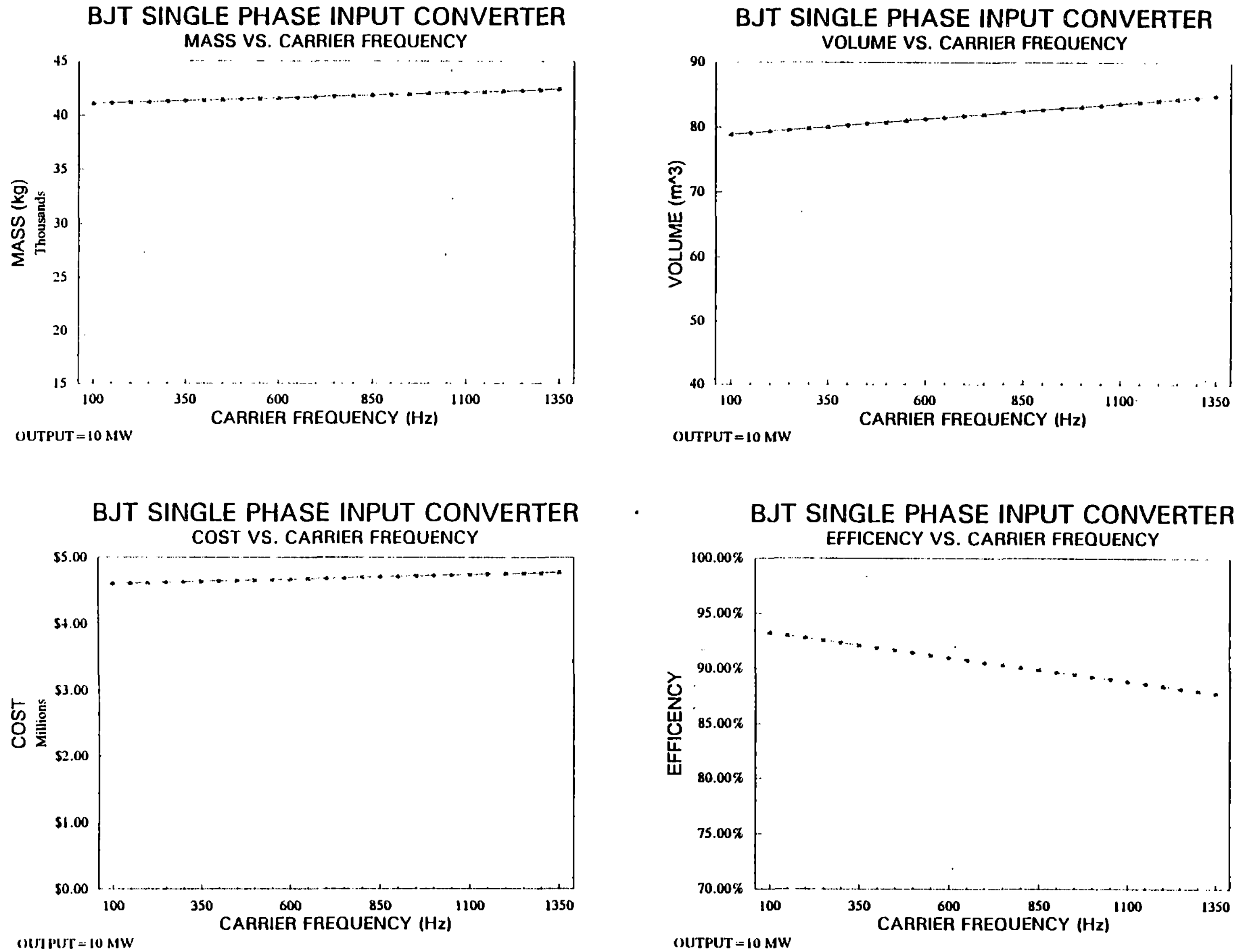


Figure 2-5.2 BJT single phase input converter characteristics vs. carrier frequency.

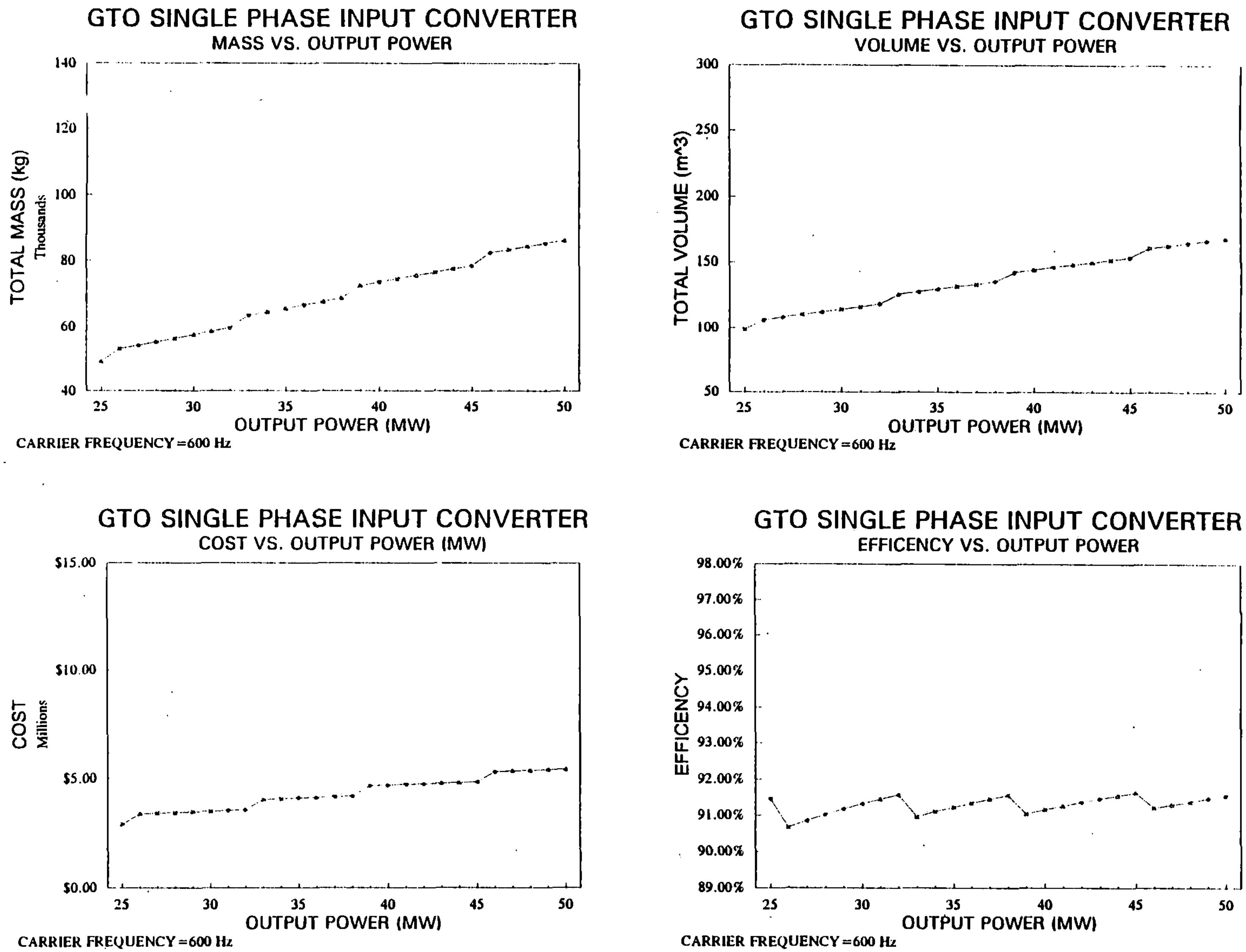


Figure 2-6.1 GTO single phase input converter characteristics vs. output power.

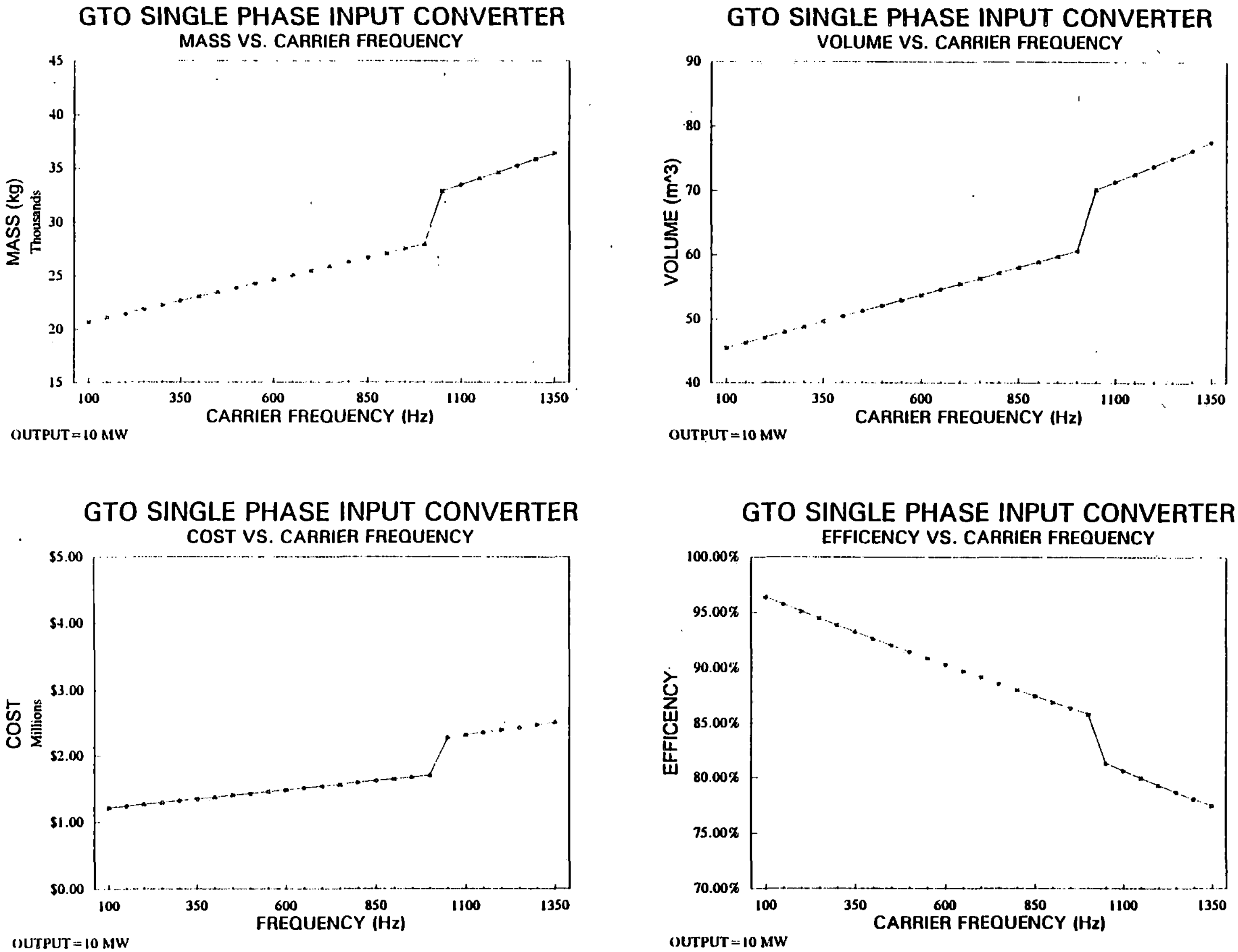


Figure 2-6.2 GTO single phase input converter characteristics vs. carrier frequency.

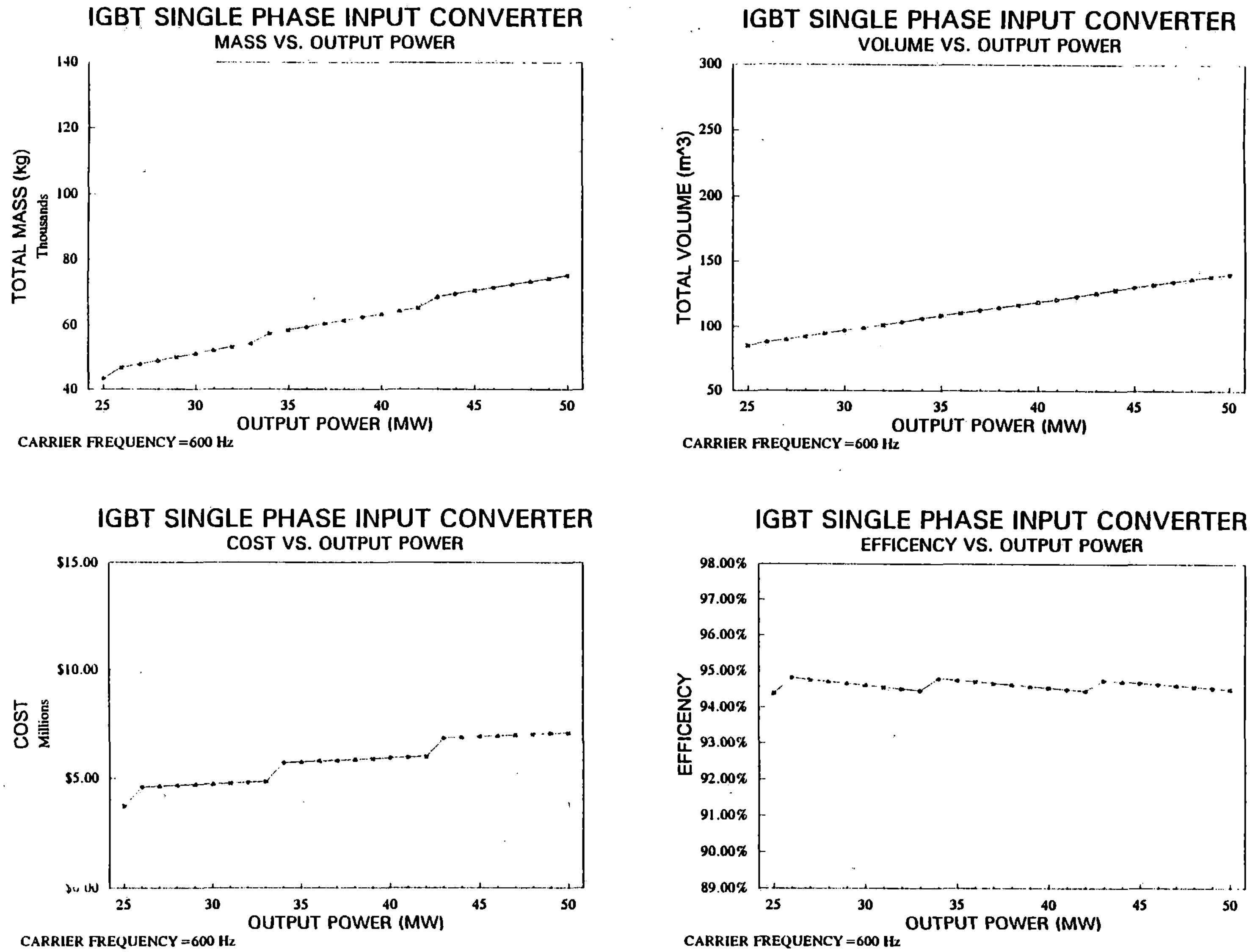


Figure 2-7.1 IGBT single phase input covnerter characteristics vs. output power.

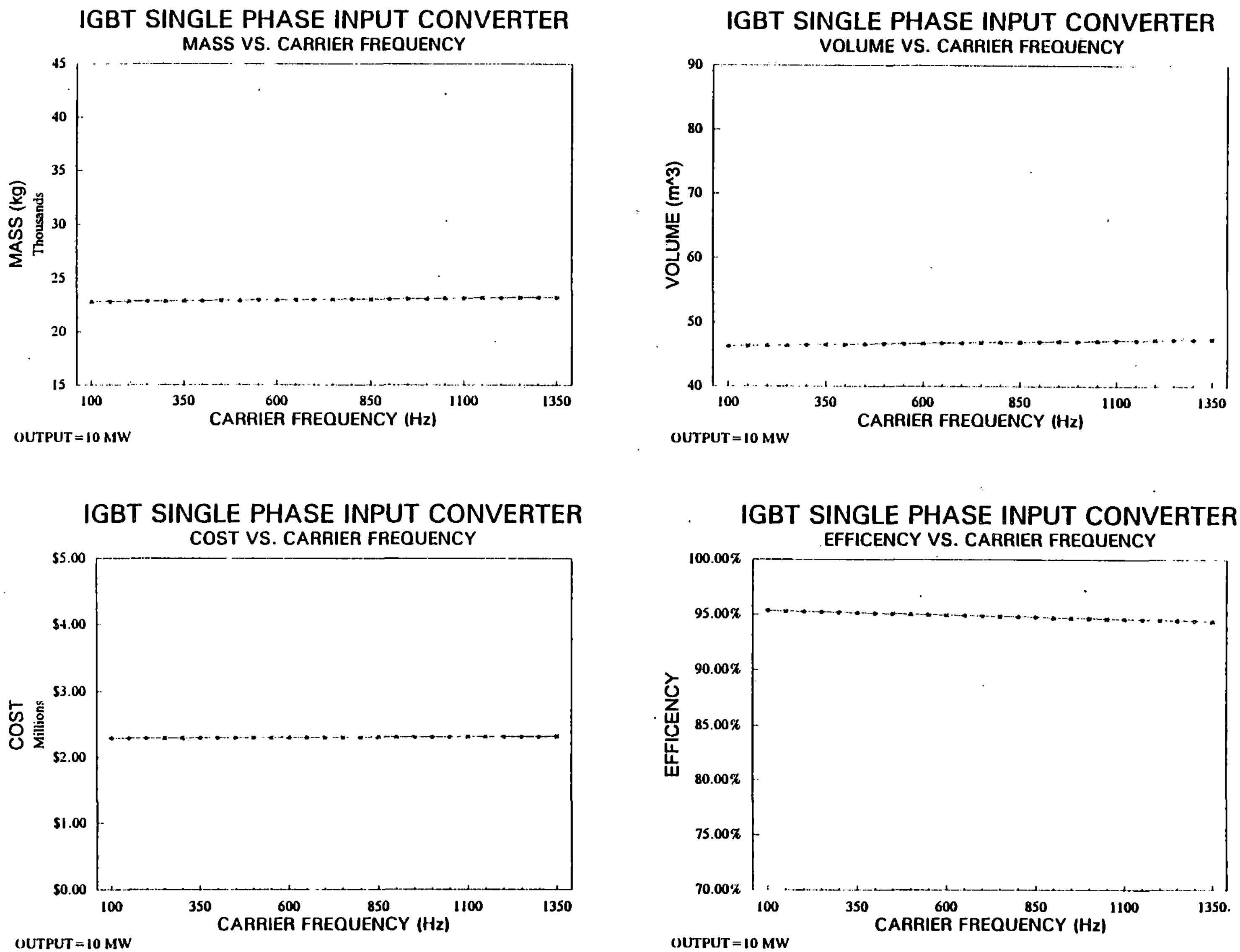


Figure 2-7.2 IGBT single phase input converter characteristics vs. carrier frequency.

2.3.1.3 Three Phase AC to DC Converter

This converter for input power conditioning converts three phase 60 Hz ac source power to dc output power for the traction/levitation motor drive and the auxiliary power system. A schematic of this approach is shown in Figure 2-8. Three phase high voltage ac feeds are connected to the primary of a step-down transformer with several secondaries, each of which feeds a single phase full wave bridge converter. The outputs of the converters are tied in parallel to achieve the required output current for the traction drive. Although not shown, separate lower voltage secondaries and converters are included for the auxiliary power loads.

The graphical results of the spreadsheet analysis for the three phase converter are presented in Figures 2-9, 2-10, and 2-11 for BJT, GTO and IGBT converter topologies.

2.3.2 Traction/Levitation Subsystem

The traction and levitation subsystem is comprised of power conditioning equipment that modulates a dc input from the input power conditioning subsystem into a three phase ac motor drive. In this case we have assumed that the maximum ac output frequency is 60 Hz. Requirements typical for traction and levitation inverters are listed in Table 2-5.

TABLE 2-5
TRACTION/LEVITATION REQUIREMENTS

PARAMETER	REQUIREMENT
Input Voltage	7 kVdc - 35 kVdc
Output Voltage	0-5 kVac three phase, line to line variable frequency
Output Power	5 MVA - 25 MVA per vehicle for an active vehicle system. 25 MVA - 50 MVA per guideway section for a passive vehicle system.
Cooling	Liquid cooling with liquid to air heat exchanger.

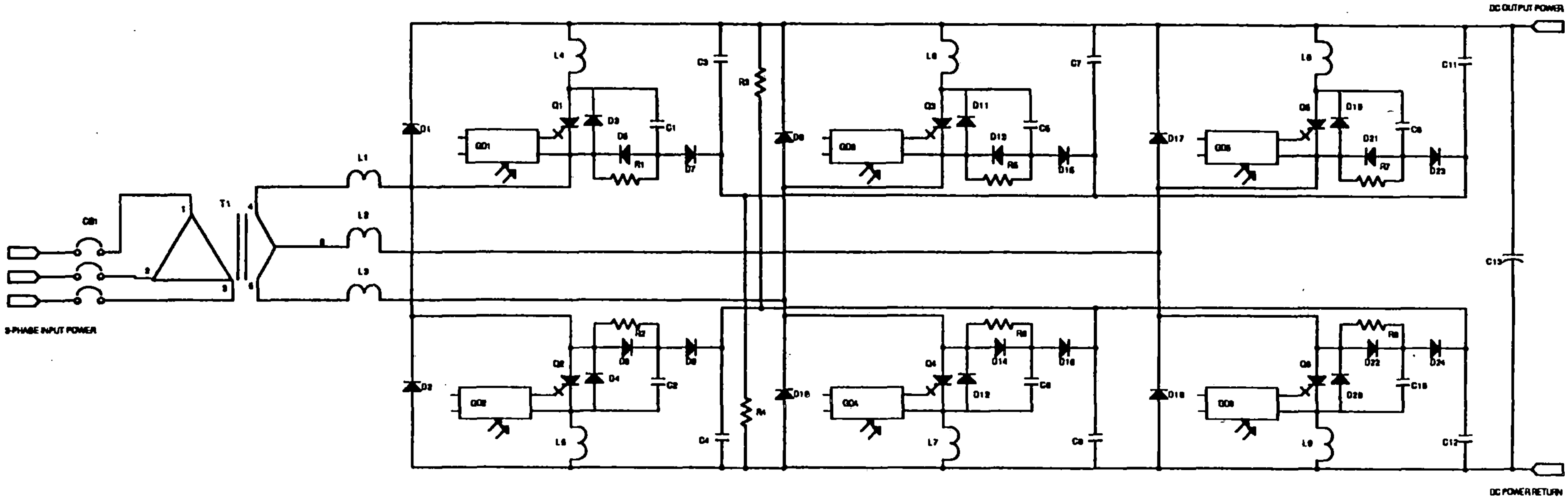


Figure 2-8. Input power conditioning system from three phase distribution system.

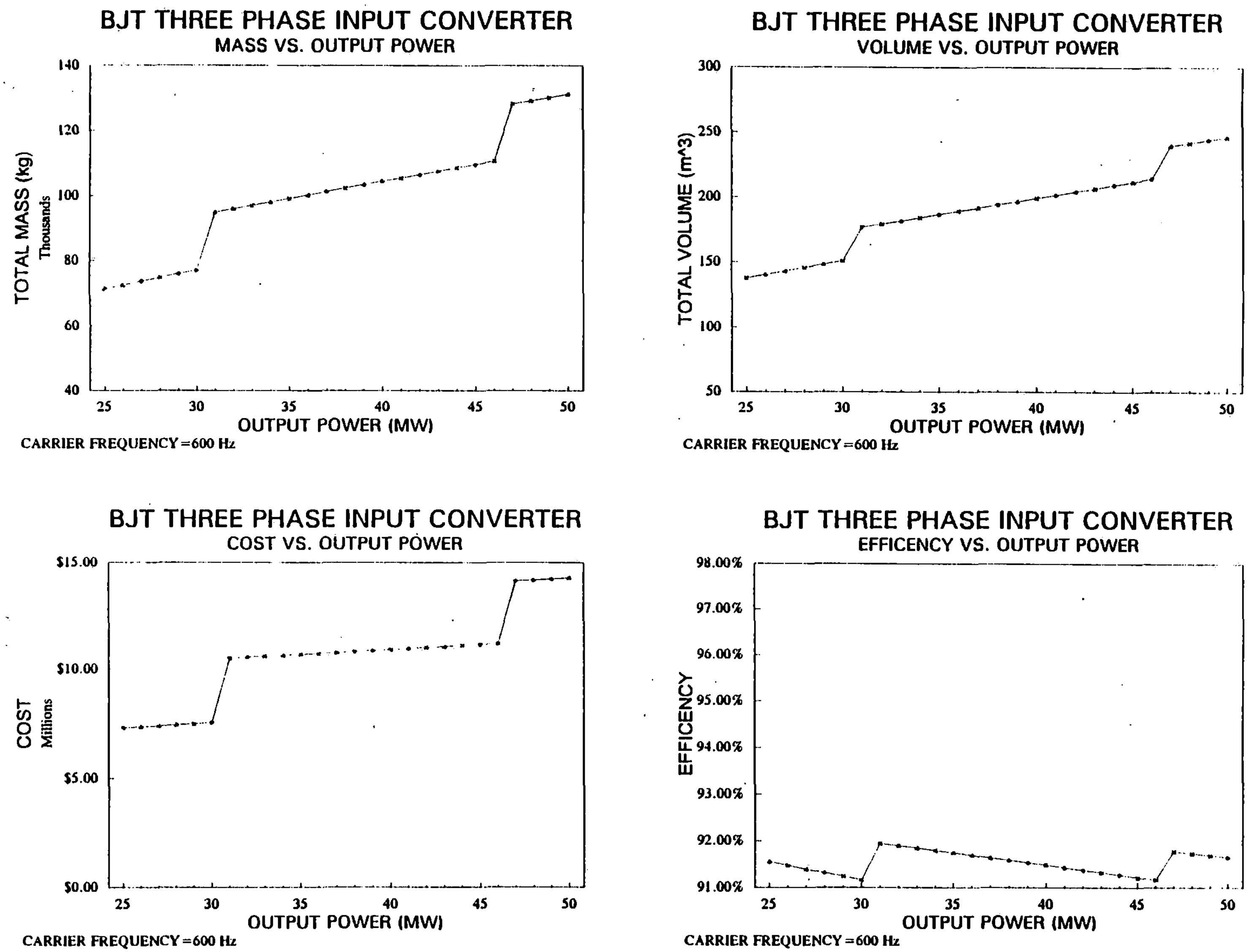


Figure 2-9.1 BJT three phase input converter characteristics vs. output power.

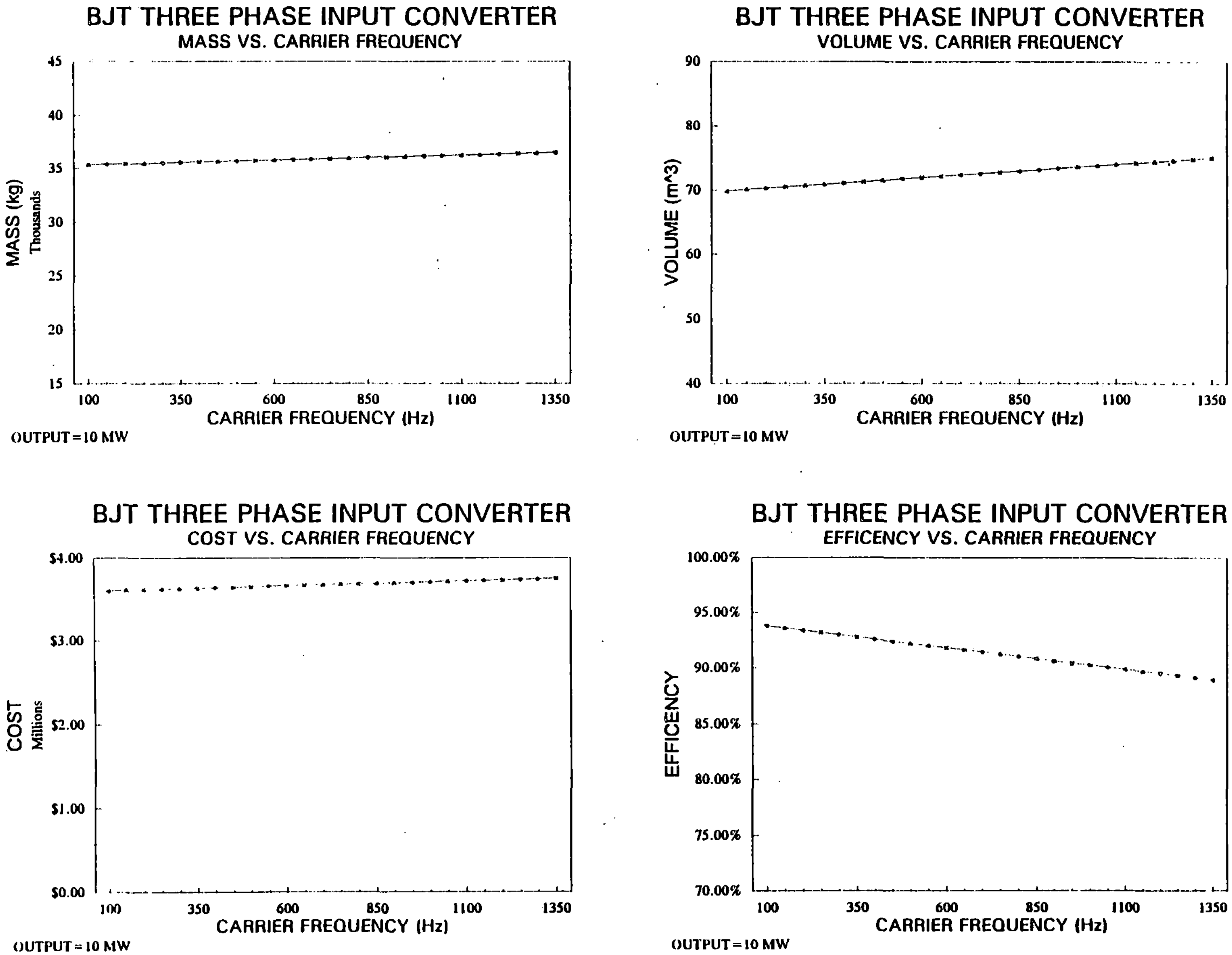


Figure 2-9.2 BJT three phase input converter characteristics vs. carrier frequency.

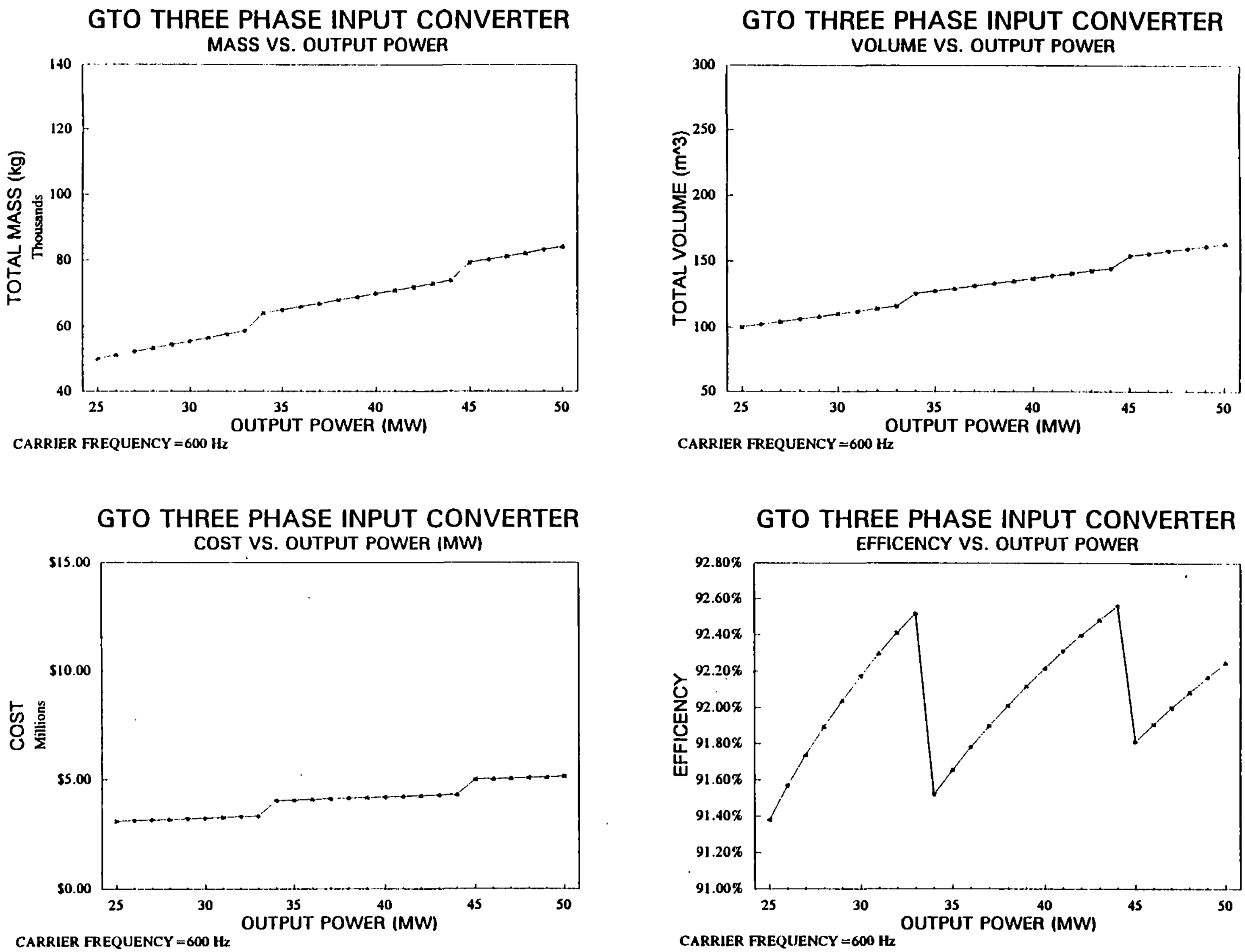


Figure 2-10.1 GTO three phase input converter characteristics vs. output power.

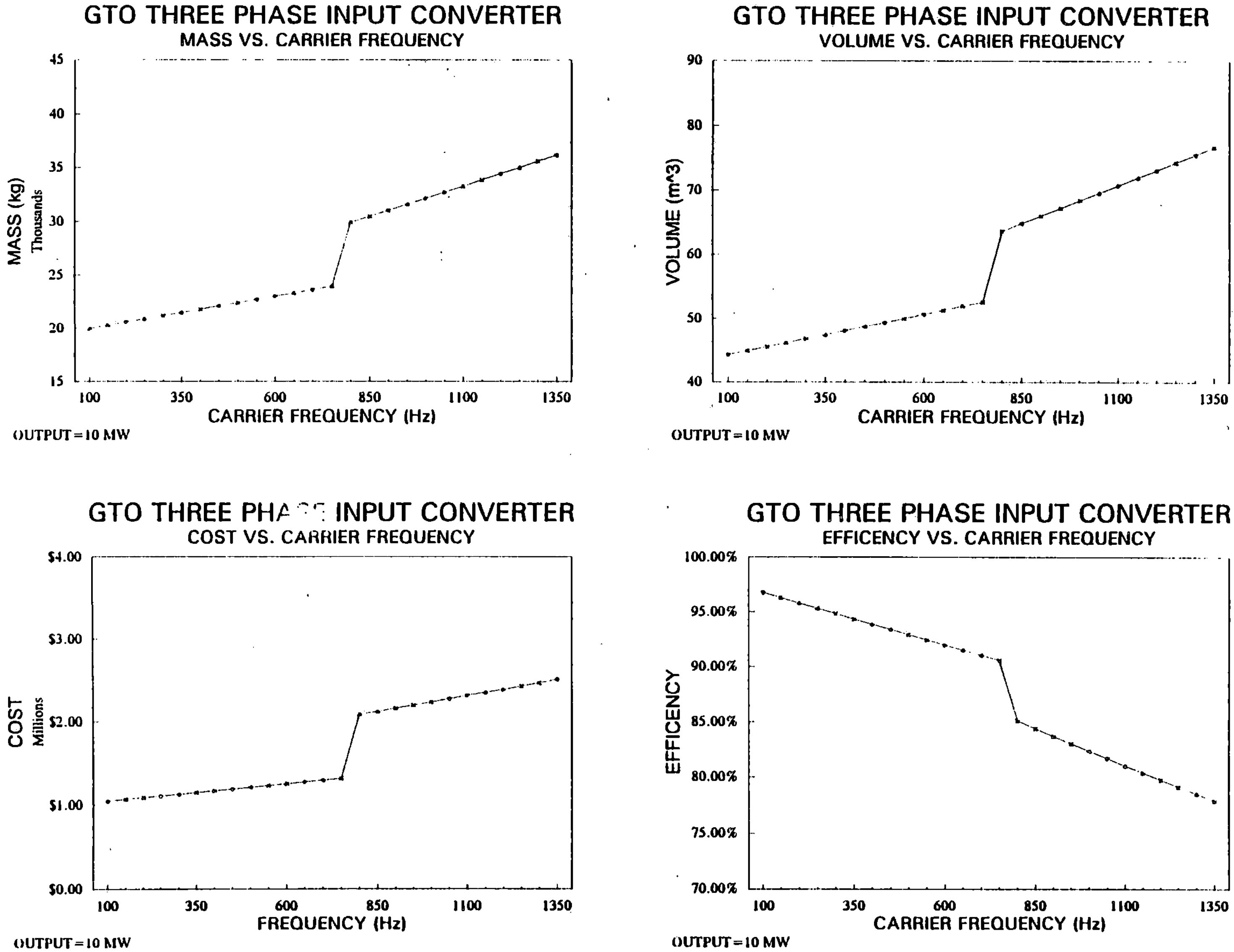


Figure 2-10.2 GTO three phase input converter characteristics vs. carrier frequency.

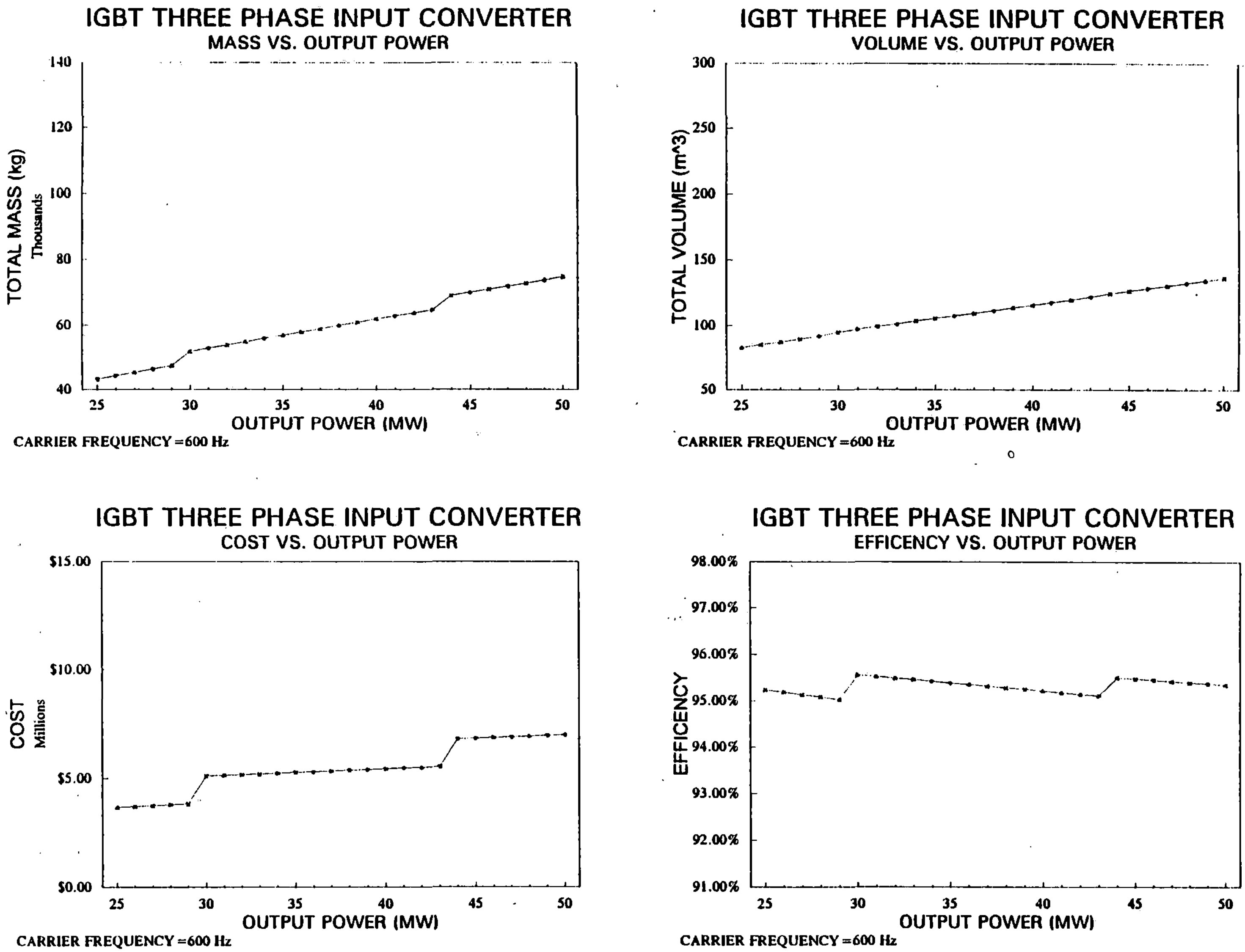


Figure 2-11.1 IGBT three phase input converter characteristics vs. output power.

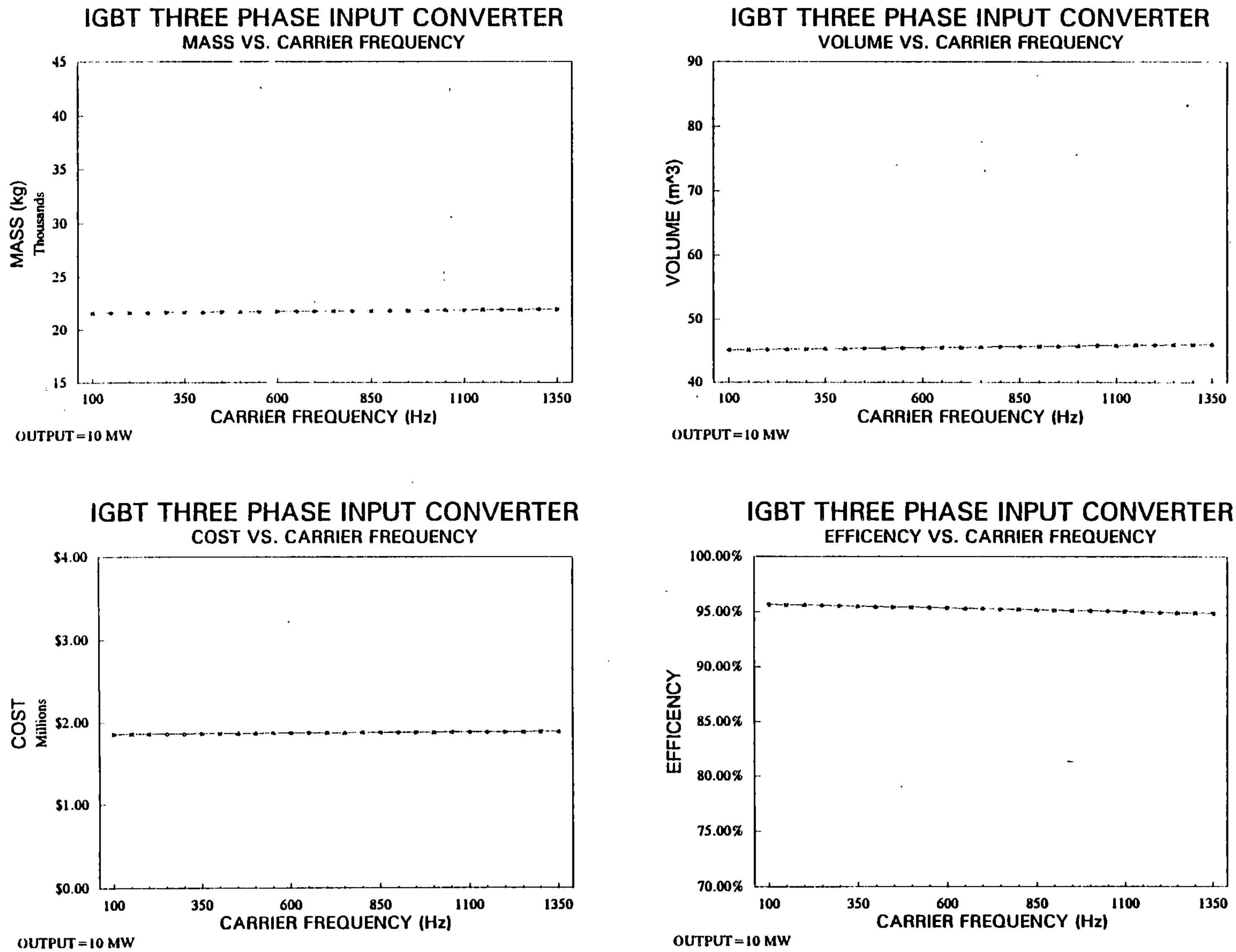


Figure 2-11.2 IGBT three phase input converter characteristics vs. carrier frequency.

2.3.2.1 DC Input Three Phase Motor Drive

This drive for traction or levitation applications converts the dc output from the input power conditioning circuits via pulse width modulation (PWM) into three phase output power. Spreadsheets have been developed which estimate the mass, size, volume, cost and efficiency of a three phase traction drive for a given input voltage, output MVA, and frequency. The electrical, physical and cost parameters of the semiconductor switching device, support electronics, and cooling system are included in the estimate.

The spreadsheet is based on the inverter configuration shown in Figure 2-12. The inverter consists of six switches, a capacitor filter bank and controls. Each switch consists of a driver and a series parallel array of switch modules as shown in Figure 2-13. The switch modules consist of the basic switching element and gate drive as shown in Figure 2-14.

Mass, volume, cost and efficiency of the three phase motor drives are quite sensitive to the inverter PWM carrier frequency. Therefore, graphical data was generated as a function of both frequency and output MVA in Figures 2-15 through 2-17.

The graphical results of the spreadsheet analysis where the carrier frequency is varied from 100 Hz to 1.35 kHz and the output MVA is held constant at 10 MVA are shown for the BJT, GTO, and IGBT cases in Figures 2-15.2, 2-16.2 and 2-17.3, respectively. The discontinuities in the curves reflect points where an additional set of BJT, GTO or IGBT modules is added to meet the desired carrier frequency requirements.

The GTO approach is most sensitive to carrier frequency as shown in Figure 2-16.2. The reason for this is threefold. First, high voltage GTOs have inherently high switching losses which become larger than the conduction loss at about 400 to 600 Hz. Second, each GTO requires a substantial dV/dt snubber that dissipates about 27 watts per Hz. As the carrier frequency increases, the amount of power lost in the snubber circuit increases and causes the mass, volume and cost to go up with a corresponding decrease in efficiency of the inverter. Third, the GTOs have a minimum off time specification of about 170 μs which reduces the maximum duty cycle as the frequency is increased, thus causing higher conduction losses for a given output MVA.

The IGBT approach has lower sensitivity to carrier frequency over the range of frequencies considered as shown in Figure 2-17.2. This is due to the faster switching times of the IGBT and the reduced dV/dt snubber requirements. Figures 2-16.3 and 2-17.3 offer more detail of the

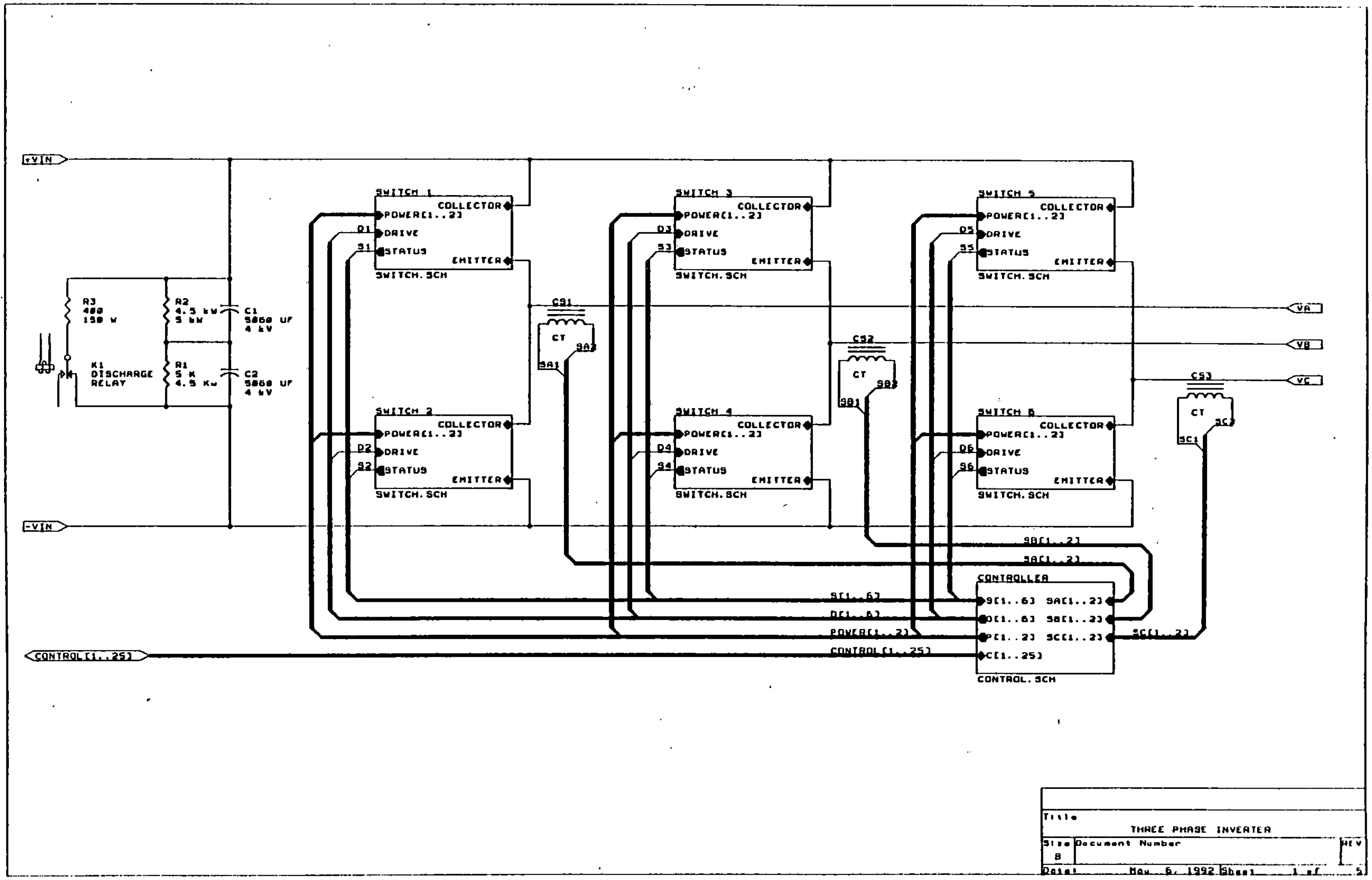


Figure 2-12 Three phase inverter schematic.

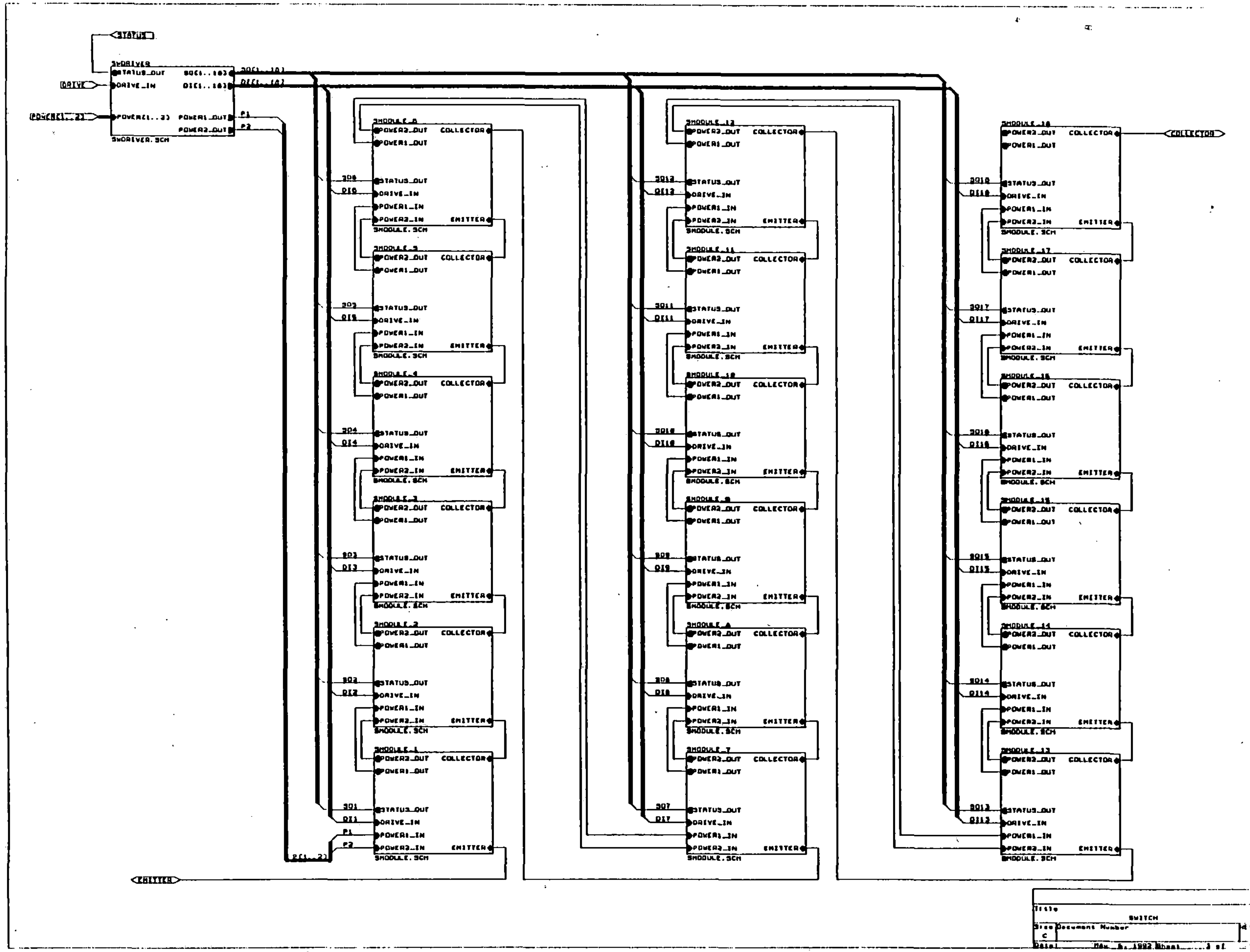


Figure 2-13 Switch schematic.

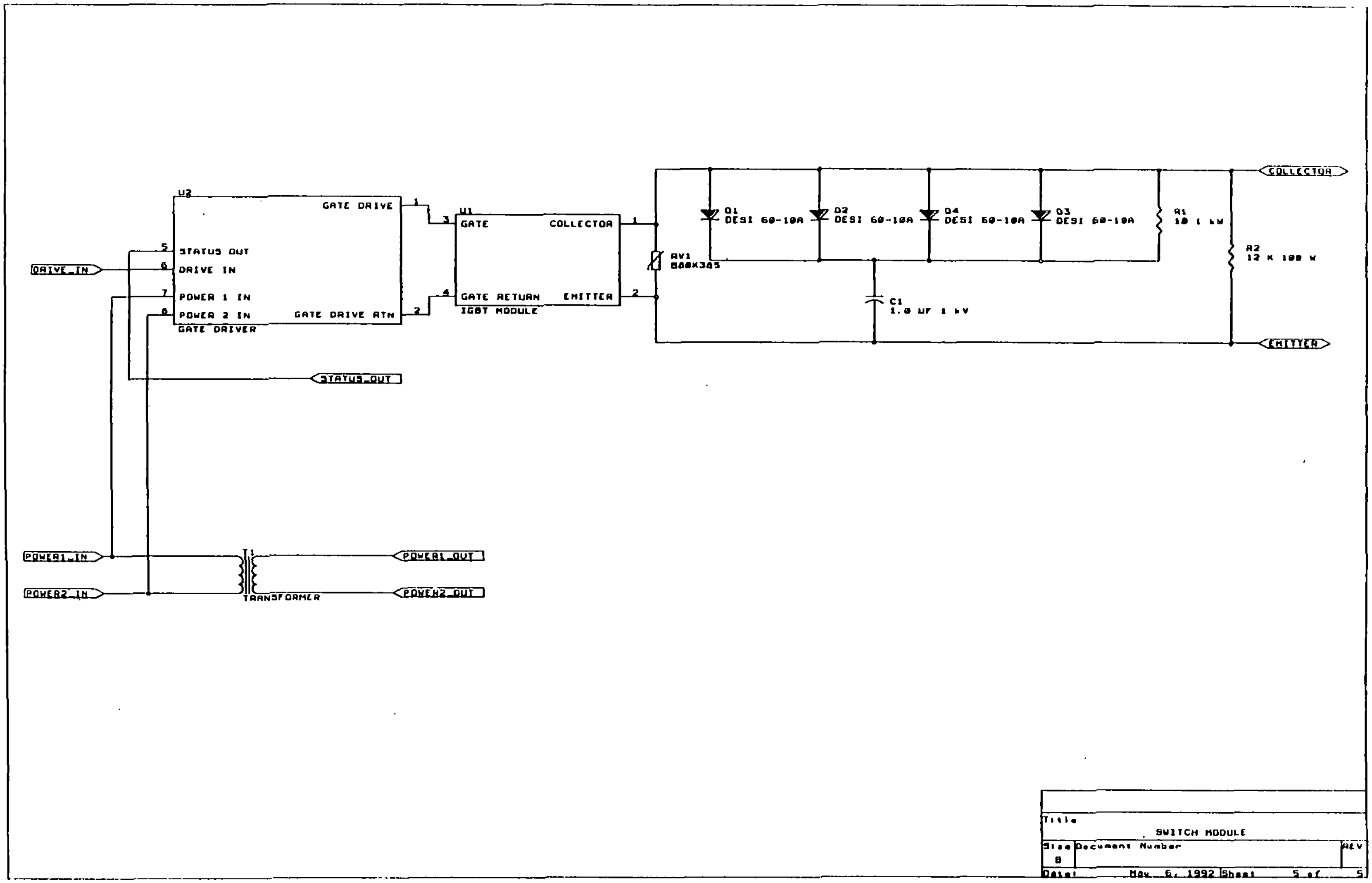


Figure 2-14 Switch module schematic (IGBT case).

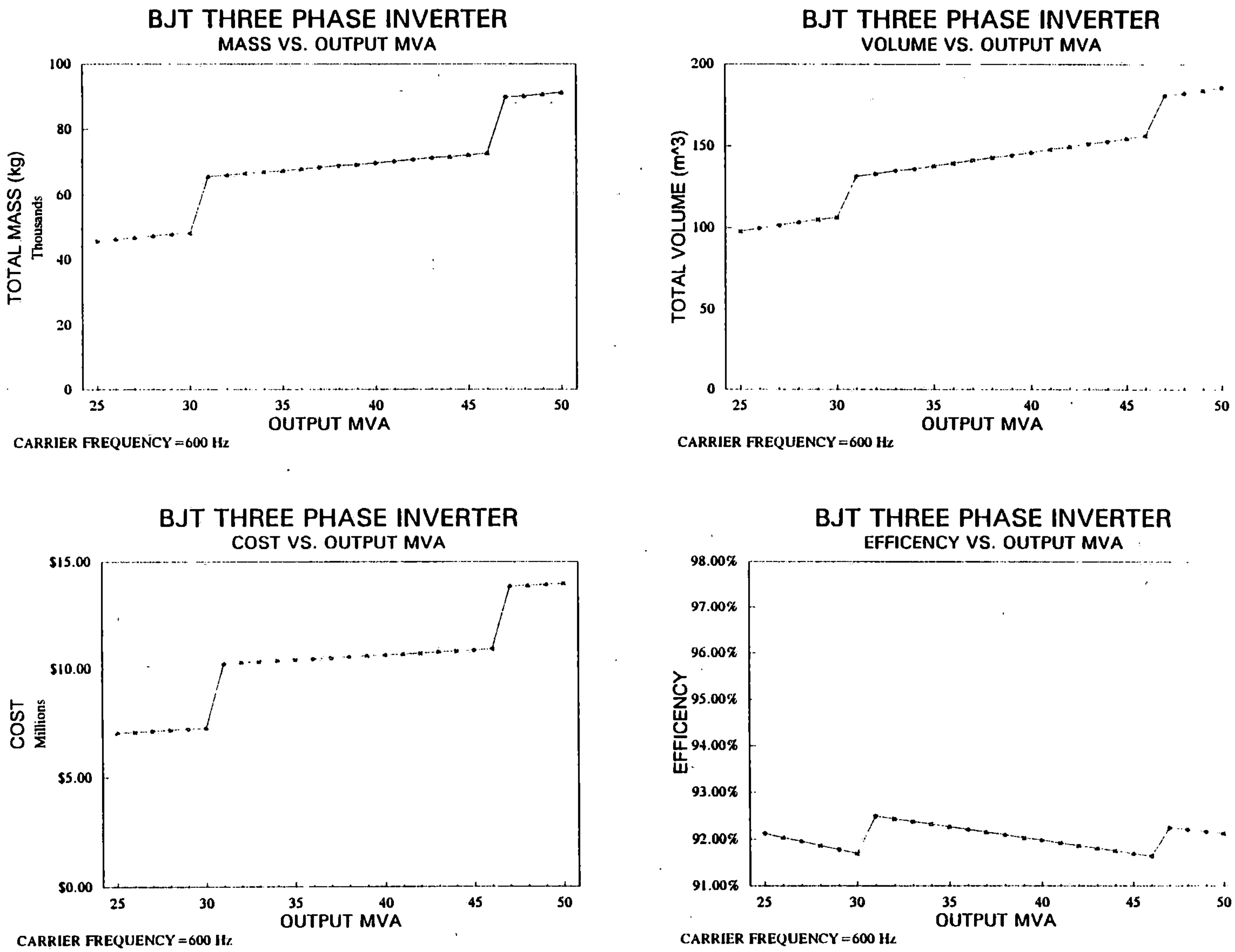


Figure 2-15.1 BJT three phase inverter characteristics vs. output power.

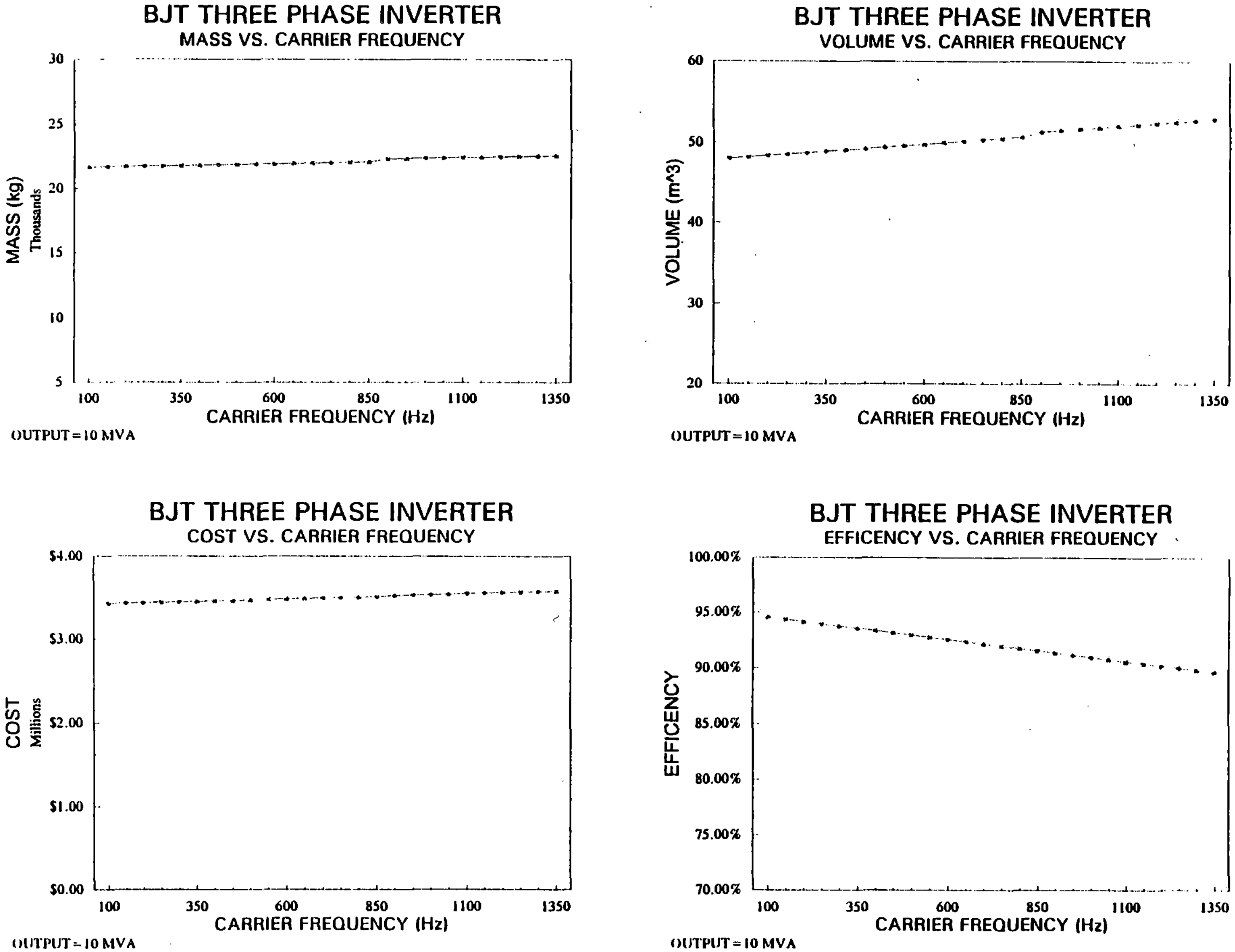


Figure 2-15.2 BJT three phase inverter characteristics vs. carrier frequency.

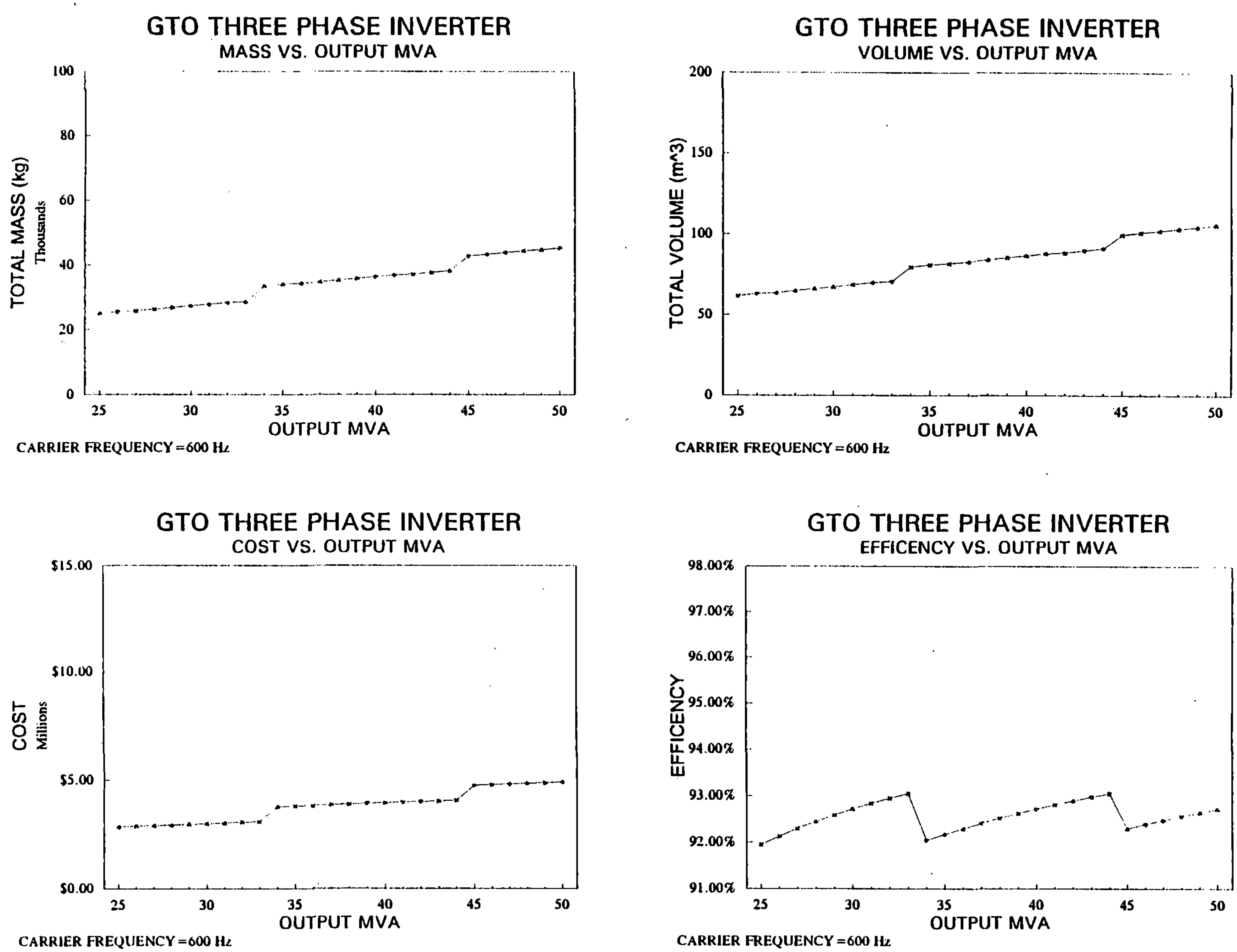


Figure 2-16.1 GTO three phase inverter characteristics vs. output power.

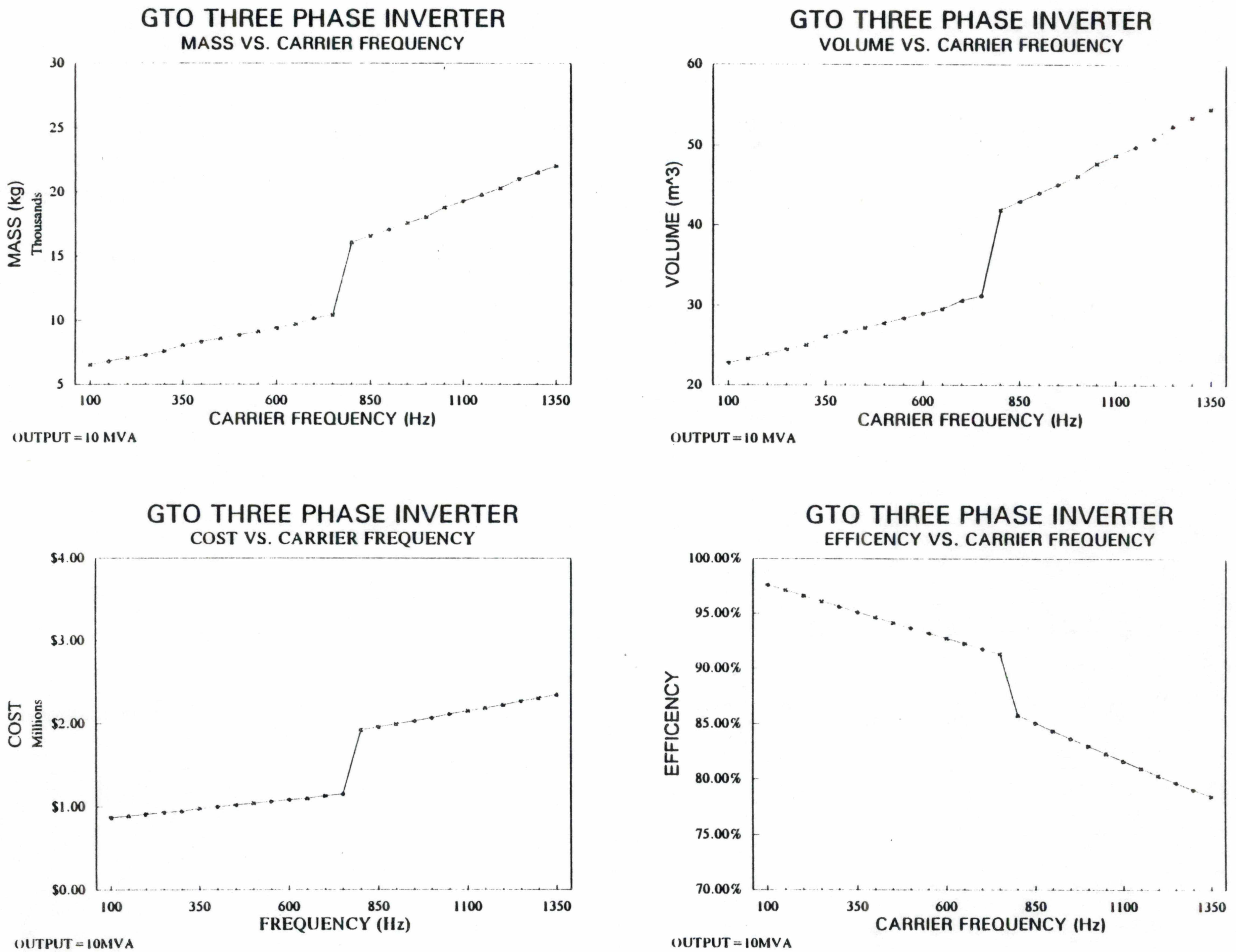


Figure 2-16.2 GTO three phase inverter characteristics vs. carrier frequency.

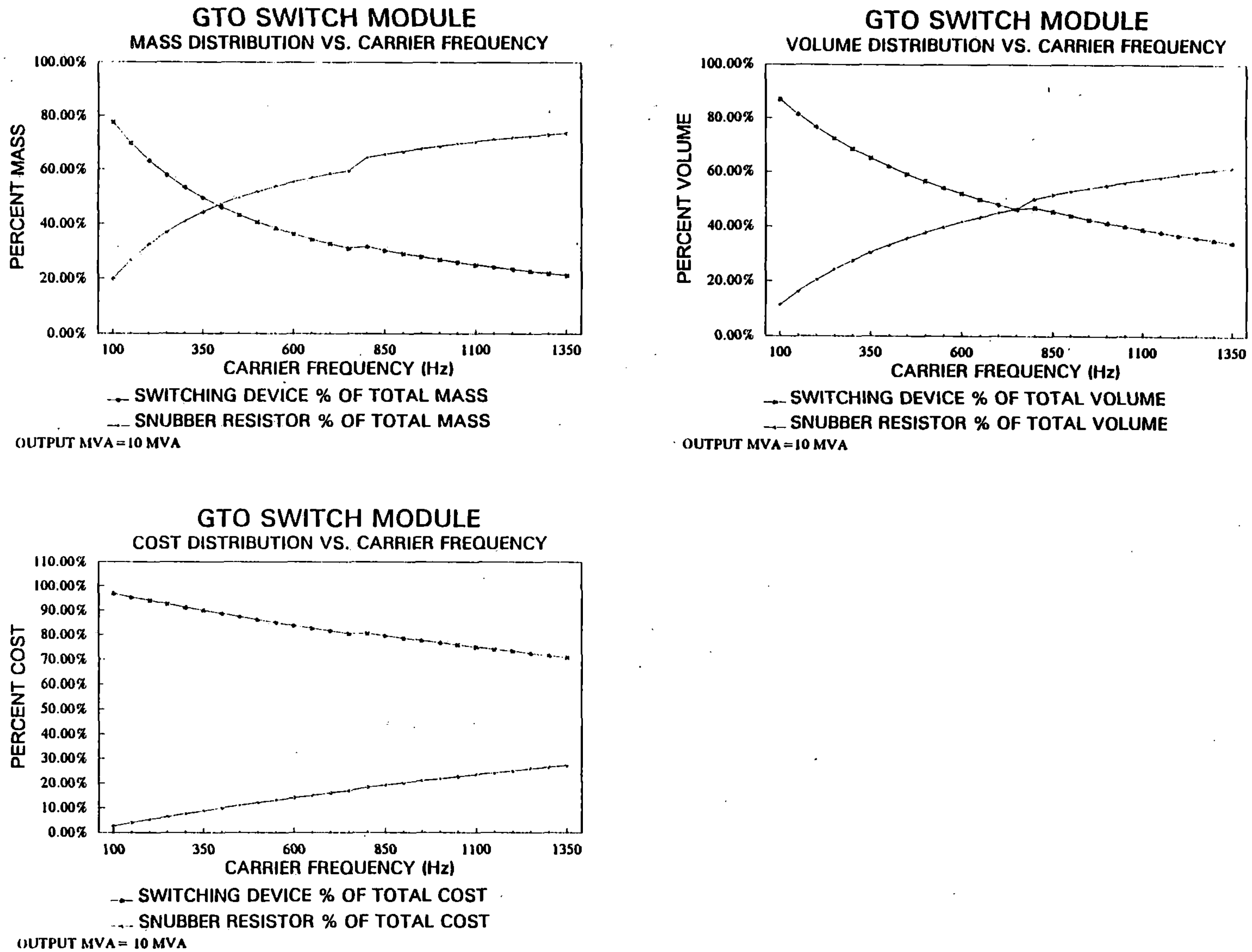


Figure 2-16.3 GTO switch module characteristics vs. carrier frequency.

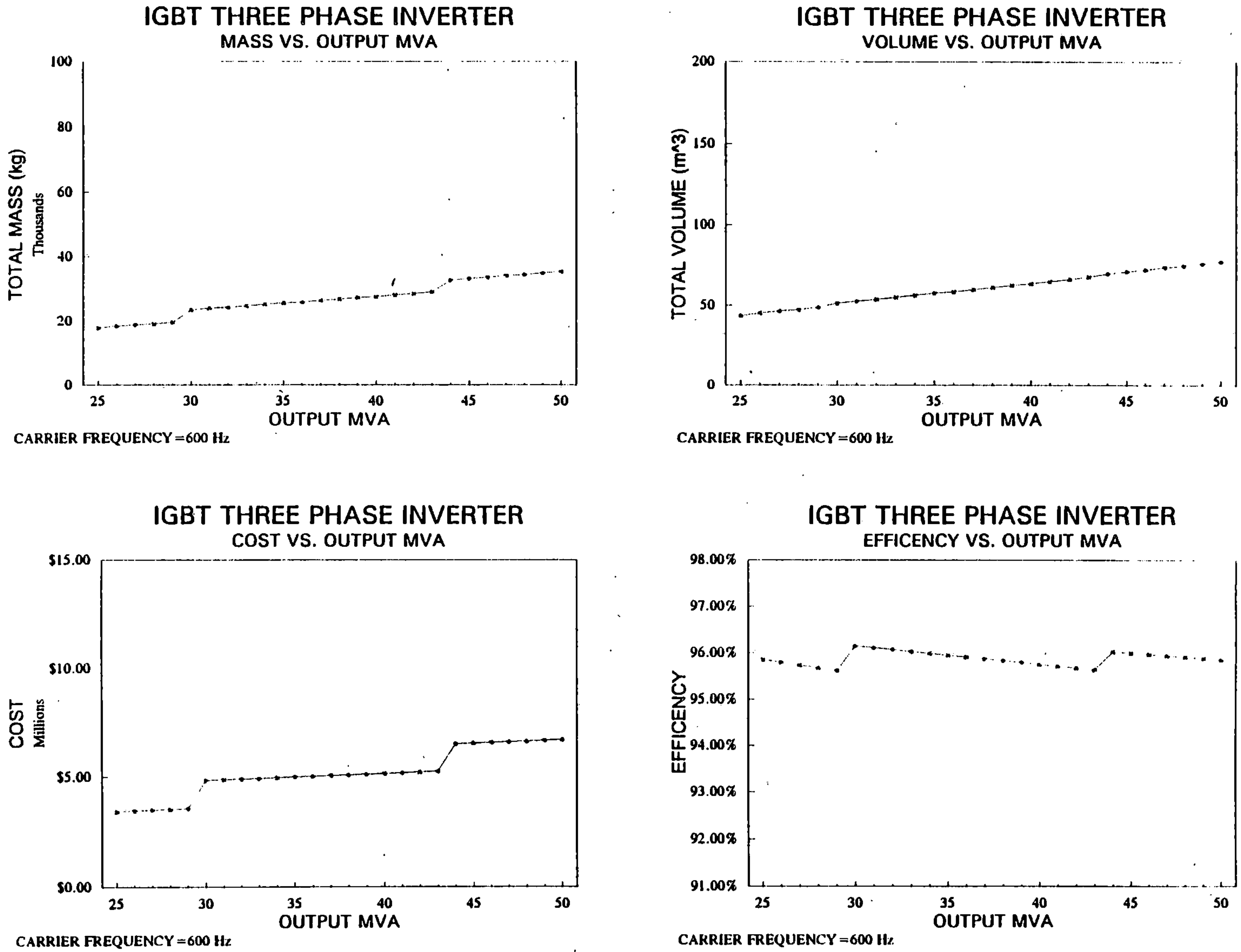


Figure 2-17.1 IGBT three phase inverter characteristics vs. output power.

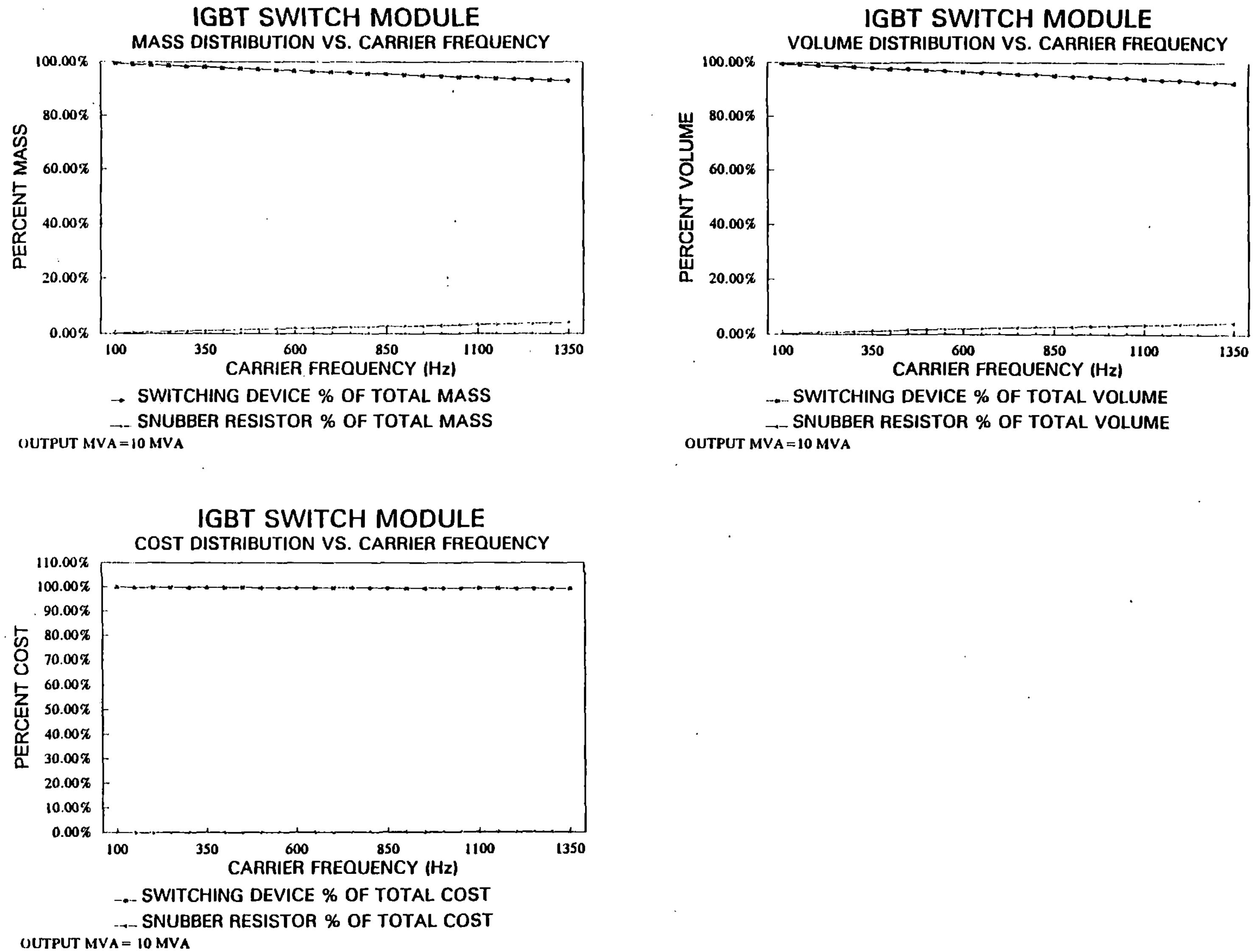


Figure 2-17.2 IGBT three phase inverter characteristics vs. carrier frequency.

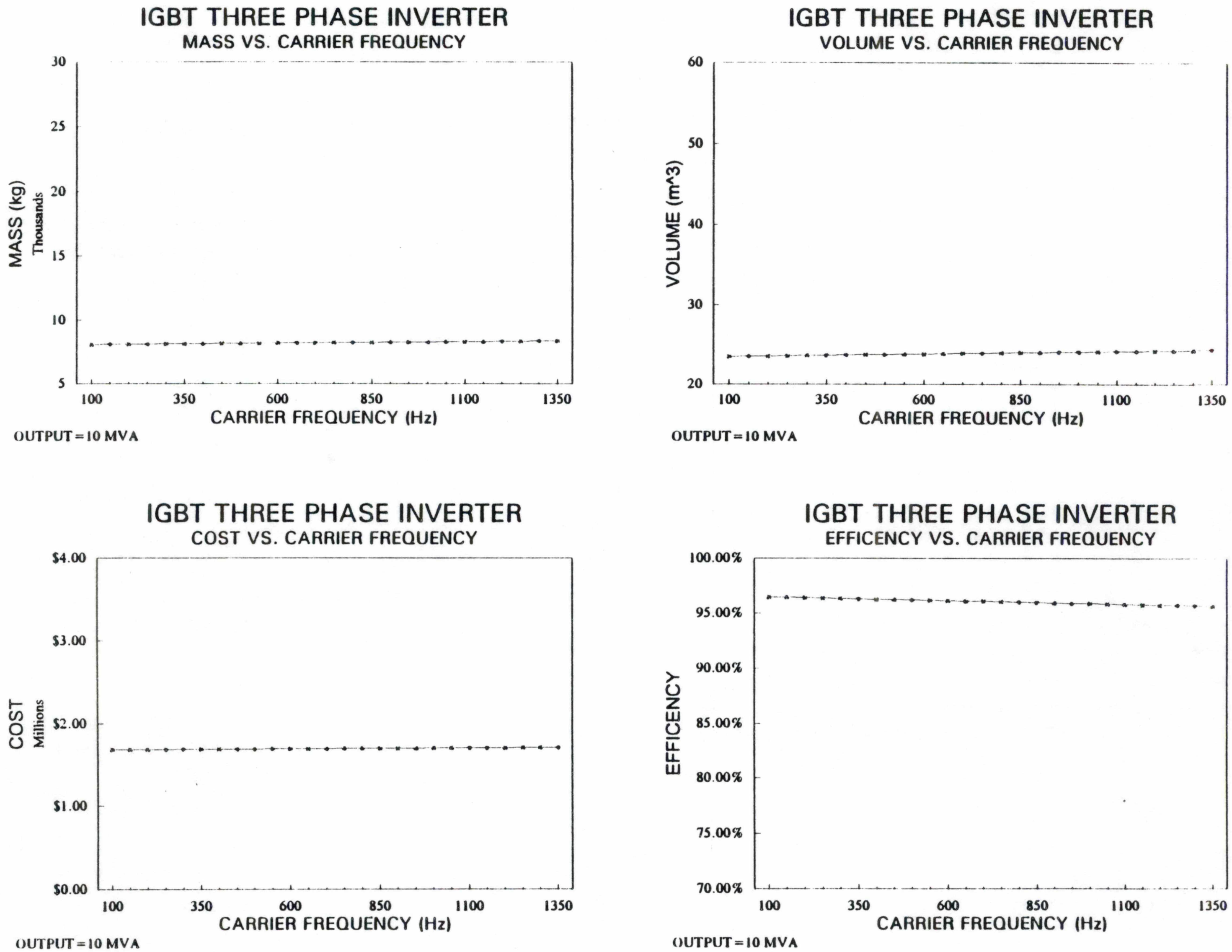


Figure 2-17.3 IGBT switch module characteristics vs. carrier frequency.

parameters vs. switching frequency. For instance, 80% of the mass of the GTO module at high frequency is due to the snubber resistor. In contrast, the IGBT switch mass dominates at all frequencies.

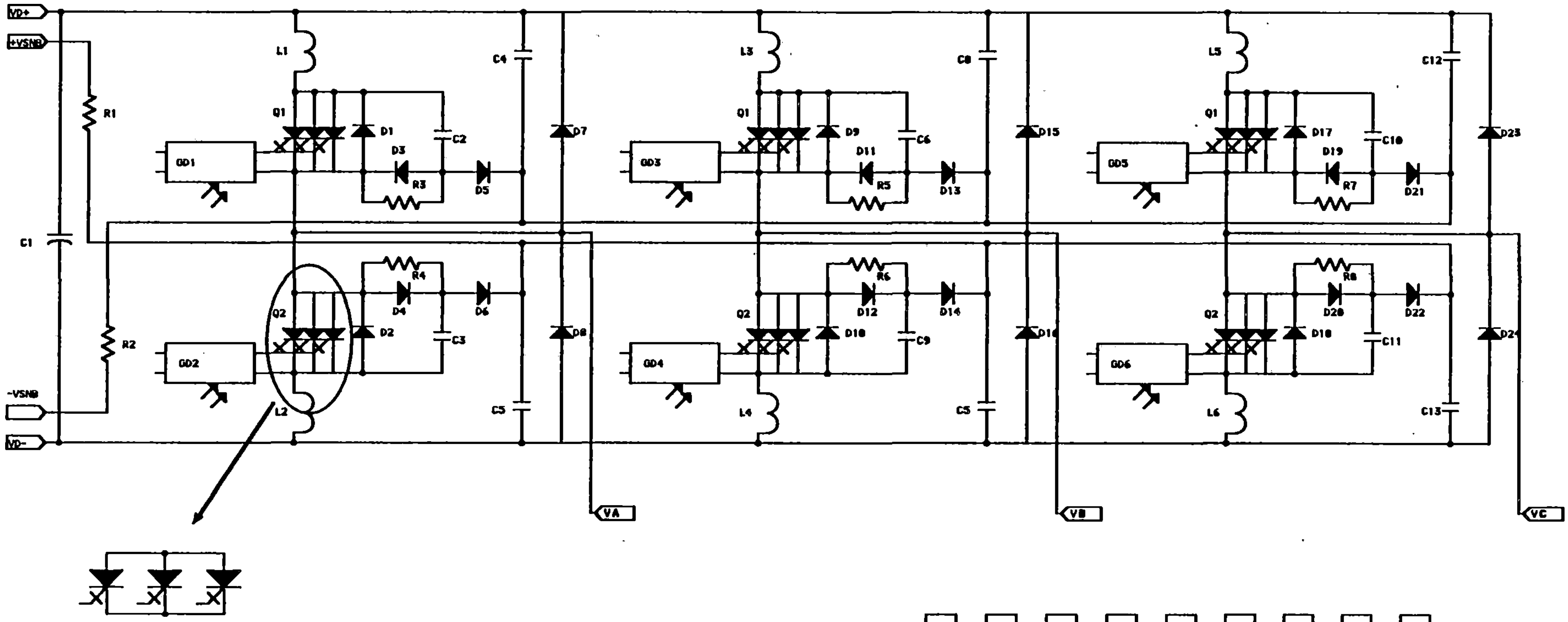
The results of the frequency sensitivity analysis indicate that the GTO approach offers advantages in all categories at low carrier frequencies and that the IGBT approach has advantages at high carrier frequencies. The BJT does not appear to be competitive for application in a traction drive topology.

The graphical results of the spreadsheet analysis where the output MVA is varied from 25 MVA to 50 MVA and the carrier frequency is held constant at 600 Hz are shown for the GTO case in Figure 2-16.1 and for the IGBT case in Figure 2-17.1. The discontinuities in the curves reflect points where an additional set of GTO or IGBT modules is added to meet the power requirements. Graphical results for the BJT approach are shown in Figure 2-15.1.

2.3.2.2 DC-AC Three Phase, Staggered Switch Firing Inverter

As an alternative approach for increasing the carrier frequency in a GTO-based inverter, the circuit shown in Figure 2-18 could be used. The higher bandwidth of this circuit is realized by gating parallel GTOs sequentially instead of concurrently, thus obtaining a factor of bandwidth multiplication proportional to the number of devices in parallel. A single GTO is capable of short bursts of pulses at several kilohertz, but the high losses during the turn-off process limit the average frequency to one where the heat can be effectively removed, which is less than 500 Hz. This circuit yields a higher net switching frequency than the operating frequency of the individual GTOs.

This circuit does increase the inverter carrier frequency, which might allow GTOs to be used in a system where increased bandwidth is required due to tight tolerances in air gap control between the motor and the reaction rail. There are some limitations to this circuit, however. The addition of more parallel devices beyond two does not yield a higher power output. This is because the peak current rating becomes the limitation instead of the average power. Also, the parallel but sequentially fired devices all share the same snubber circuitry. Since the power dissipation in the snubber is directly proportional to the carrier frequency, the snubber must be sized accordingly. Evaluation of this approach may be made by scaling the data presented in the previous section.



Sequencial firing of GTOs A, B, and C increases the frequency capability of a GTO inverter. Maximum pulse current is still limited by the maximum turn-off capability of a single GTO (e.g. 4000 A). Maximum frequency is limited by the junction recovery caracteristics of the GTO (e.g. 6 kHz). A reduction in the peak to average current ratio reduces optimal silicon utilization above two sequential devices.

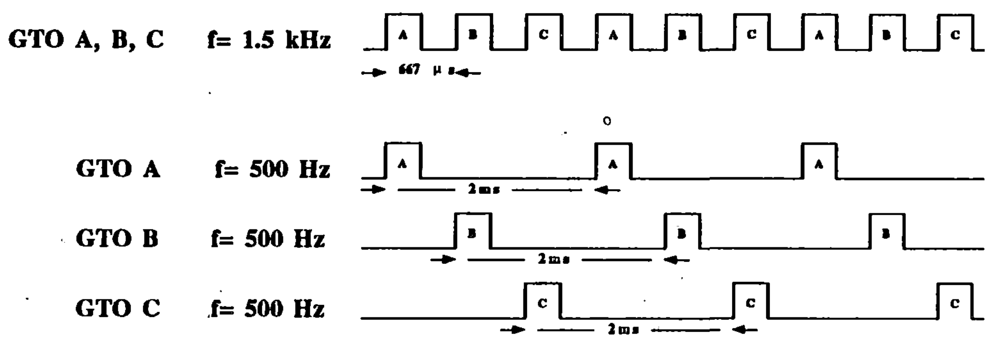


Figure 2-18 GTO power inverter for high frequency operation.

2.3.3 Braking Chopper Subsystem

The braking chopper provides a load for regenerated ower whenever the power rail or grid is not receptive. The chopper maintains the dc input voltage to the inverter system at a safe level, typically between 25 and 50% above the maximum dc source voltage at no load. The braking resistor is not included in the analysis because it is application specific, and is considered mature technology. As an example, in order to decelerate a 100 metric ton vehicle from 135 m/s to stop at 1.9 m/s^2 a braking resistor must be rated to handle approximately 900 MJ.

2.3.3.1 DC Braking Chopper

A schematic of the braking chopper is shown in Figure 2-19. The circuit is comprised of a GTO thyristor, Q1, with auxiliary loads and a load resistor. Normally, regenerated power from deceleration or braking is returned to the power grid or rail system. There are, however, occasions when the power source grid or rail may be nonreceptive. These occurrences may be caused by rail gaps, or lack of other power users. In such an event, the braking chopper will cause the inverter dc input voltage to be maintained at a safe level by gating the regenerated power into the braking resistor. A PWM controller for this circuit will regulate the amount of dissipation needed in the load resistor to meet the operating conditions.

A GTO-based design was determined to match the operating requirements the best. The GTO is the device with the highest voltage rating, and in a low frequency, low duty cycle application is by far the best device. The spreadsheet analysis results are presented in Figure 2-20. The steps in the graph are a result of adding parallel devices as the power requirement is increased.

2.3.4 Auxiliary Power Subsystem

This type of inverter operates from a dc voltage provided by the input conditioning circuits and inverts this dc into three phase ac power. The expected provisions for auxiliary loads on the vehicle with battery backup are:

Housekeeping (Hotel):	100 kVA - 250 kVA 120/208 Vac three phase 60 Hz.
Superconducting Power:	100 kVA 0-100 Vdc, 0-3000 A, variable voltage for superconducting coils.


+ DC BUS
- DC BUS

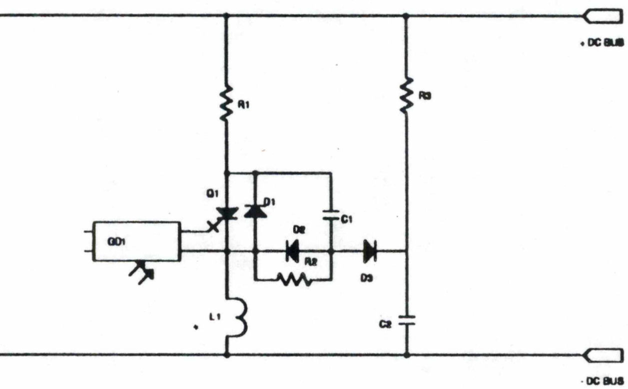


Figure 2-19   GTO braking chopper.

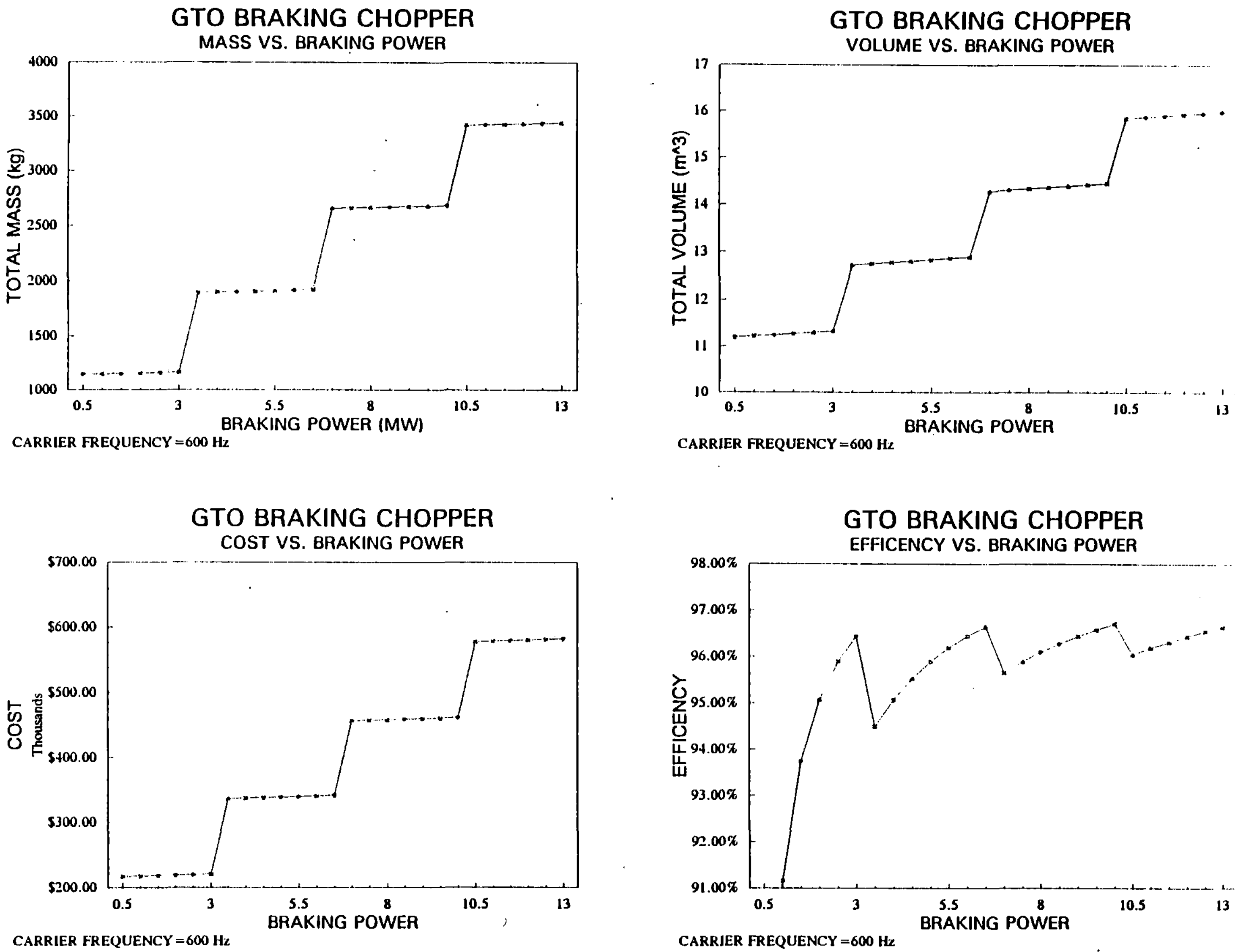


Figure 2-20.1 GTO braking chopper characteristics vs. braking power.

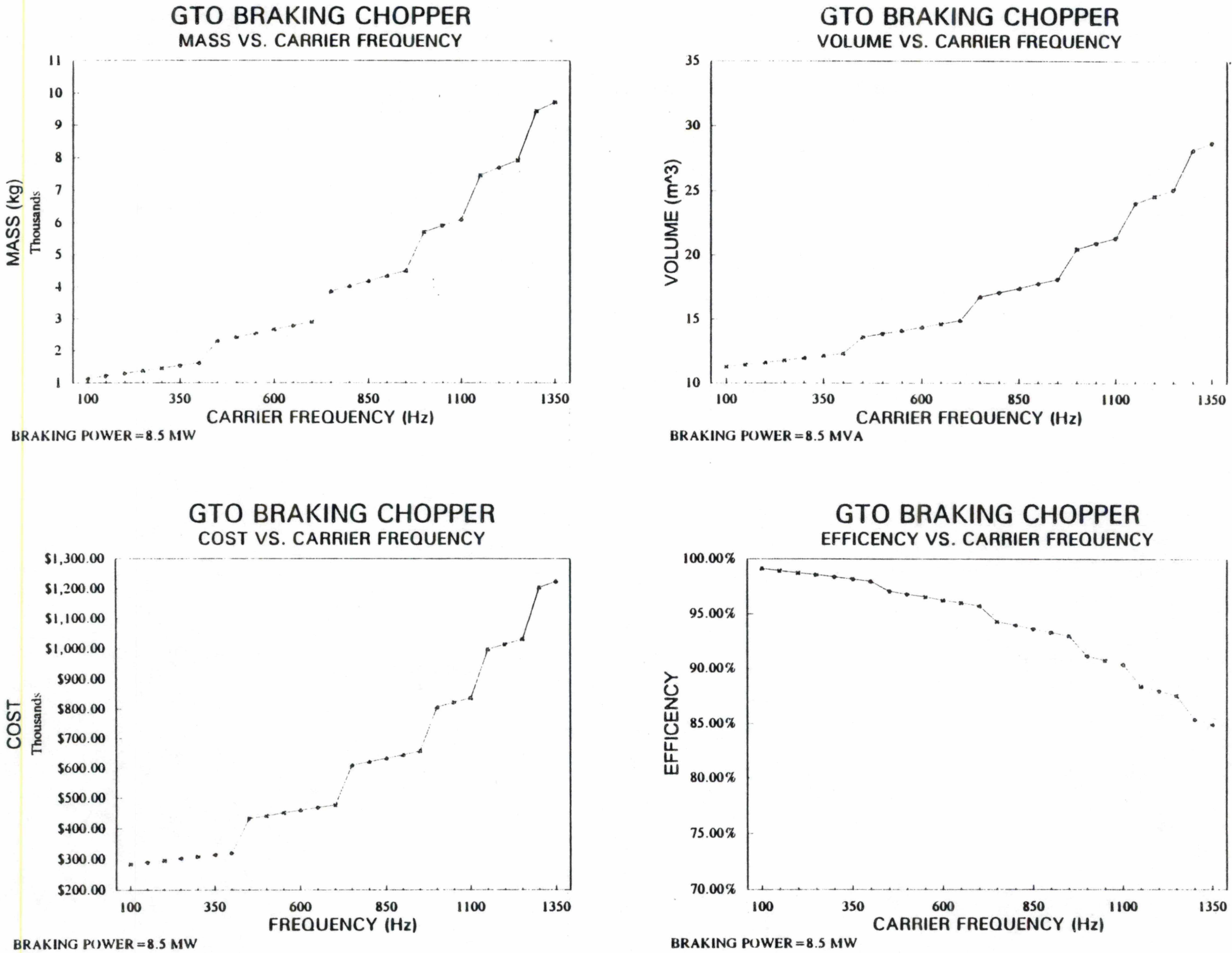


Figure 2-20.2 GTO braking chopper characteristics vs. carrier frequency.

2.3.4.1 Auxiliary Power Three Phase Inverter

An auxiliary power inverter circuit using IGBTs is diagrammed in Figure 2-21. The spreadsheet analysis is a modified version of the one used for the traction/levitation drive with the addition of the isolation transformer. The results of the spreadsheet analysis of the auxiliary power inverter are shown in Figures 2-22 to 2-24. In comparison to the traction drive, at this lower output MVA, the GTO becomes least competitive. The auxiliary power requirements favor the use of the IGBT or BJT because of the low input voltage and modest output power requirement. The IGBT will offer some slight advantages over the BJT because of its simpler, lower power gate drive requirement. At this output MVA, which is much lower than that required for traction drive, the GTO is the least attractive of the three devices.

2.3.4.2 Power Converter for Superconducting Coils

A superconducting magnet can be used as an energy storage device which can regenerate power to the source. A schematic of the power converter to charge and discharge a superconducting coil is shown in Figure 2-25. The low voltage input and low power output indicate that IGBTs are the device of choice for this converter. The input power for this converter is drawn from the vehicle auxiliary power, three phase converter, nominally 120 V/208 V. The input power is rectified to provide approximately 290 Vdc in a diode bridge comprised of D1 through D6. Filtering is provided via inductor L1 and capacitor C1. IGBTs Q1 and Q2 operate in a PWM fashion to cause a current to flow in the superconducting coil SC1. Freewheeling diodes D9 and D10 provide the current path during the interval the IGBTs are not conducting. The duty ratio is limited to provide a maximum of 100 Vdc equivalent output to the coil during charging. During normal operation, the duty ratio of the IGBT conduction is adjusted to a lower value (approximately 50%). IGBT Q3 is operated in a chopper configuration with resistor R2 to dissipate the stored energy in the superconducting coil when discharging of the coil is necessary.

The spreadsheet for this converter is scaled from other spreadsheets. The resulting analysis shows that mass, volume and cost of a 100 kW converter are not sensitive to switching frequency in the range considered (0-25 Hz). The mass of this converter is ~290 kg, the volume is ~0.75 m^3, and the cost is estimated at $58,000.

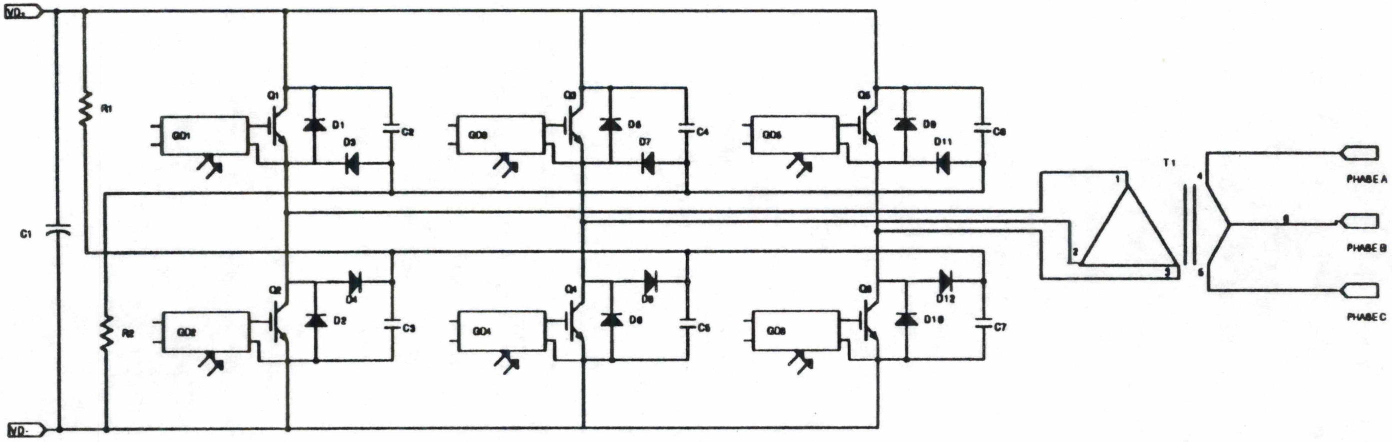


Figure 2-21 Power conditioner for auxiliary loads (hotel power).

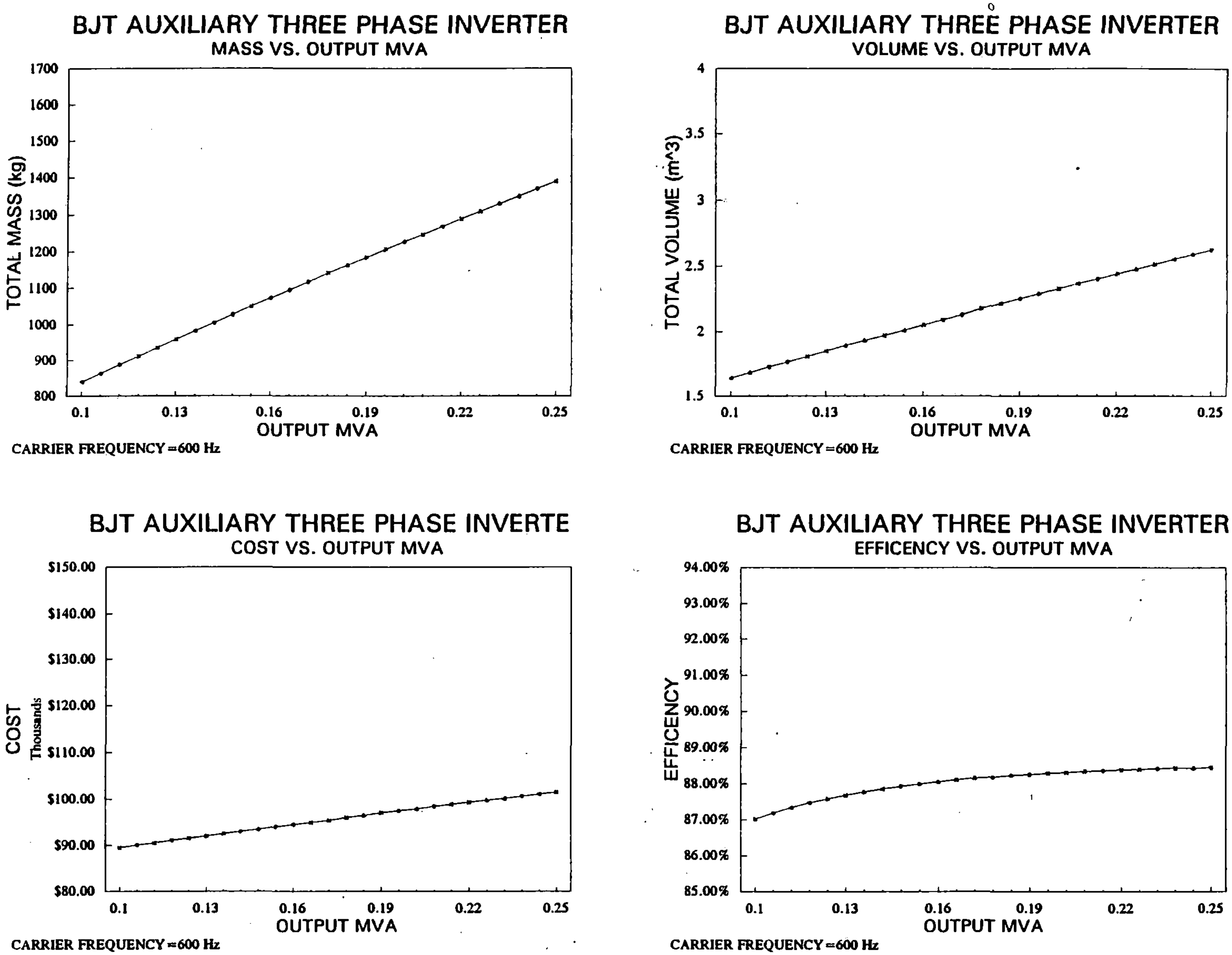


Figure 2-22.1 BJT three phase auxiliary power inverter characteristics vs. output power.

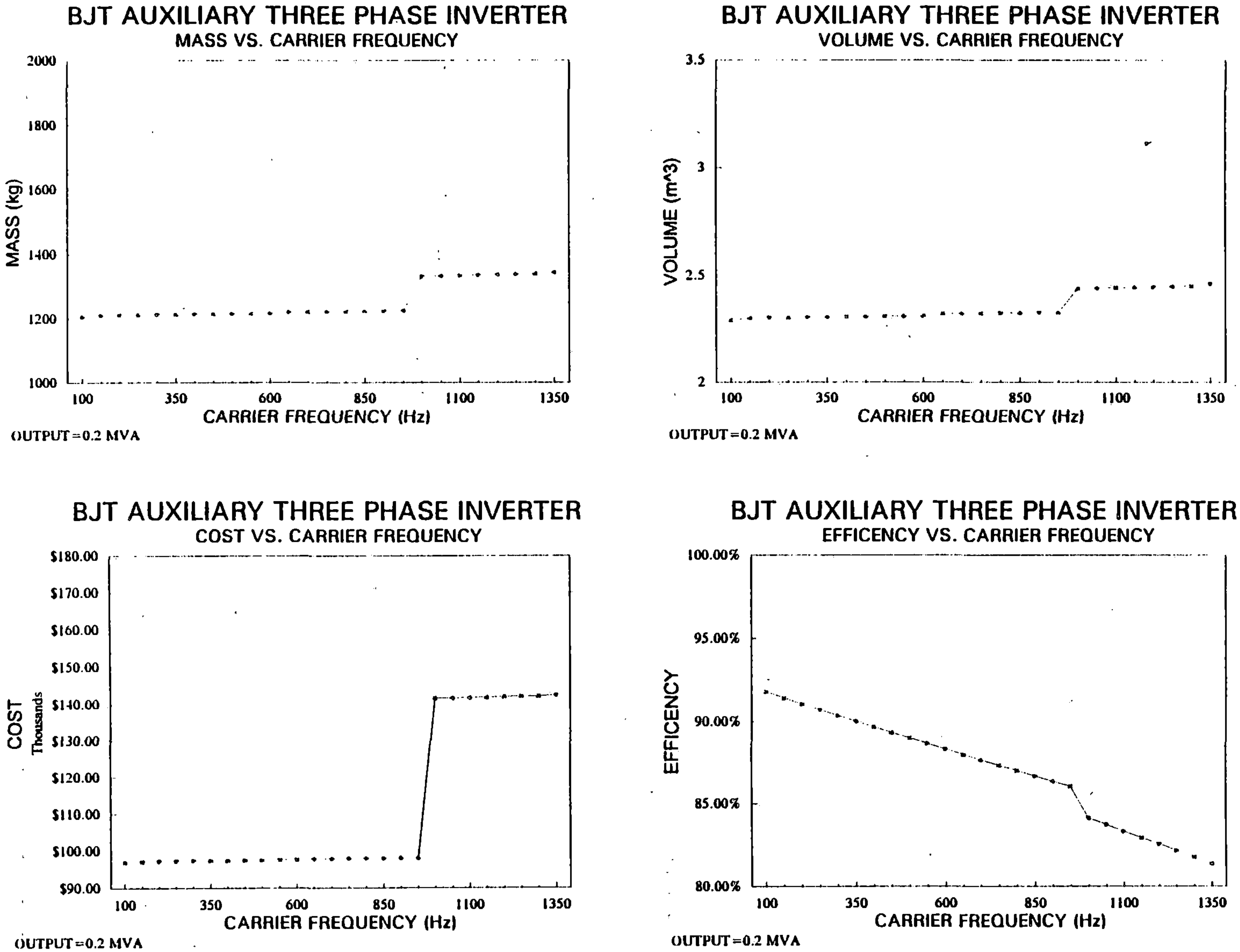


Figure 2-22.2 BJT three phase auxiliary power inverter characteristics vs. carrier frequency.

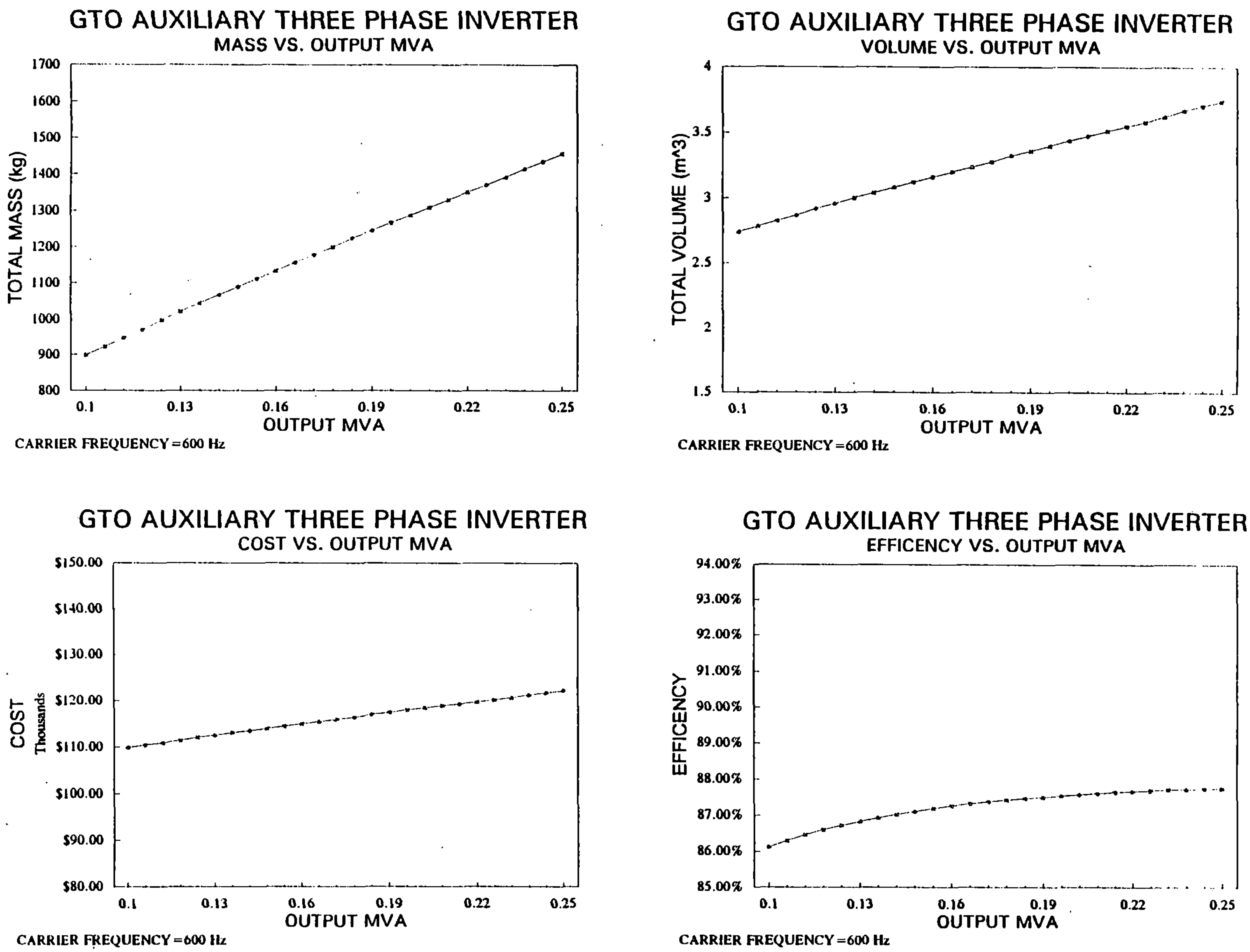


Figure 2-23.1 GTO three phase auxiliary power inverter characteristics vs. output power.

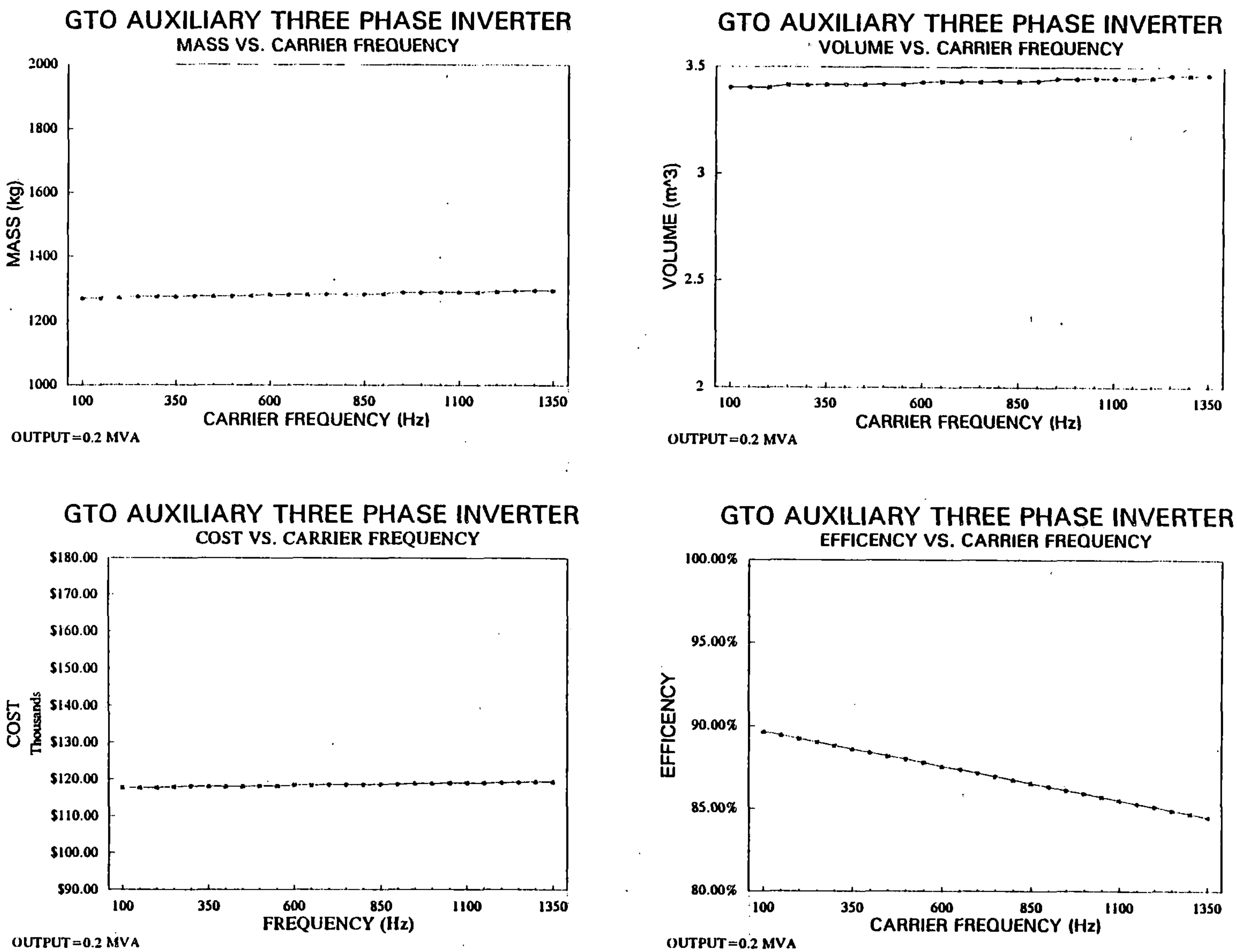


Figure 2-23.2 GTO three phase auxiliary power inverter characteristics vs. carrier frequency.

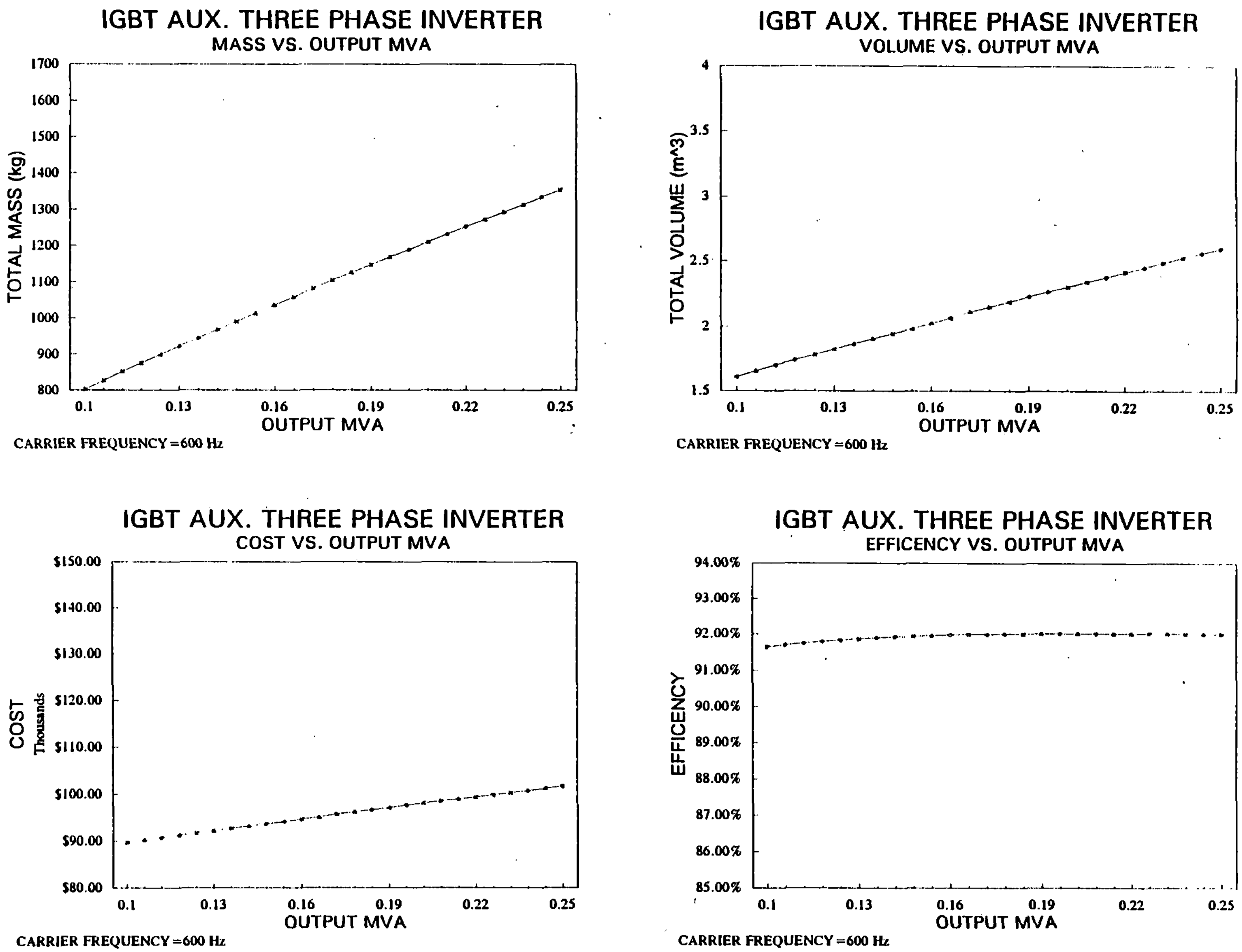


Figure 2-24.1 IGBT three phase auxiliary power inverter characteristics vs. output power.

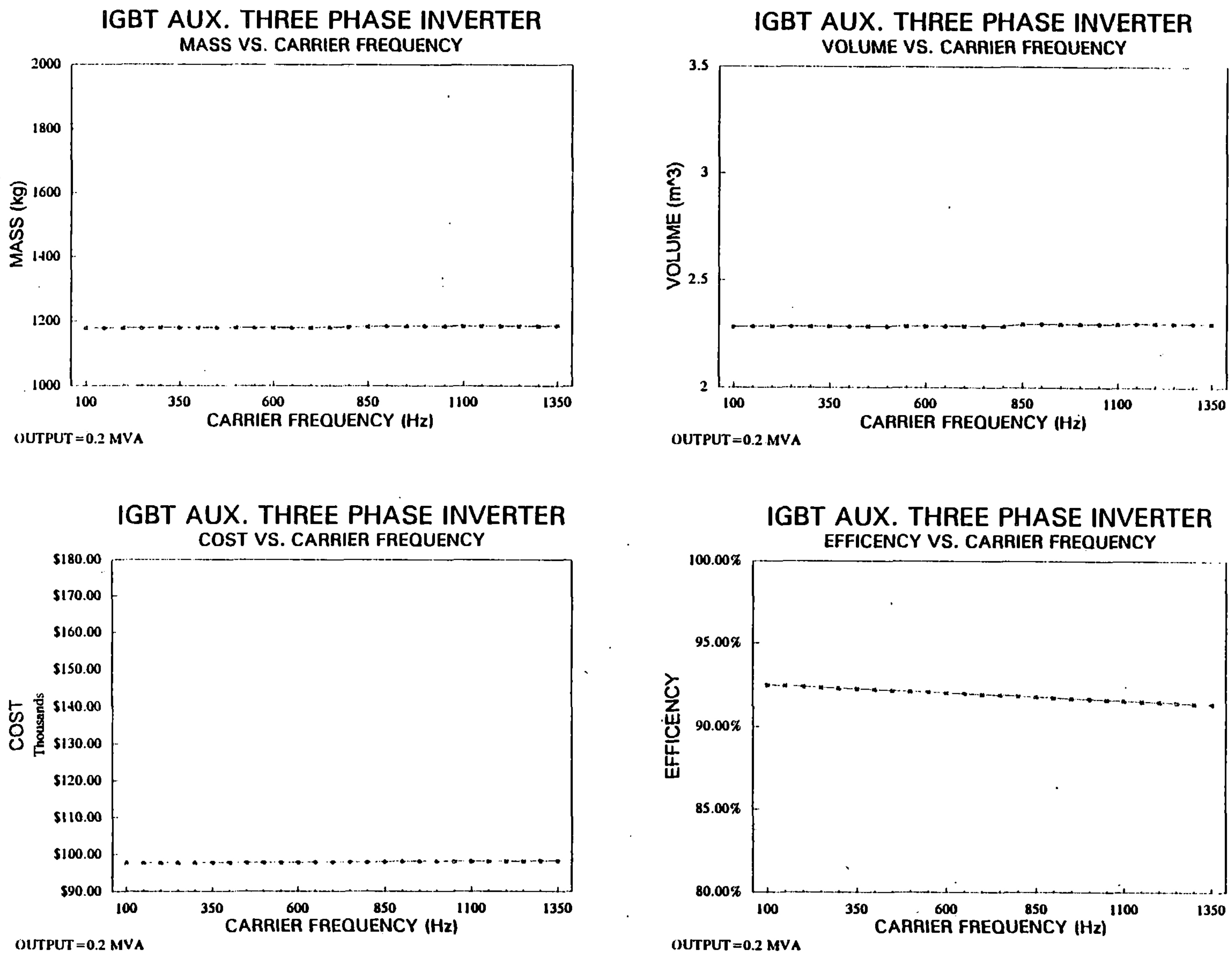


Figure 2-24.2 IGBT three phase auxiliary power inverter characteristics vs. carrier frequency

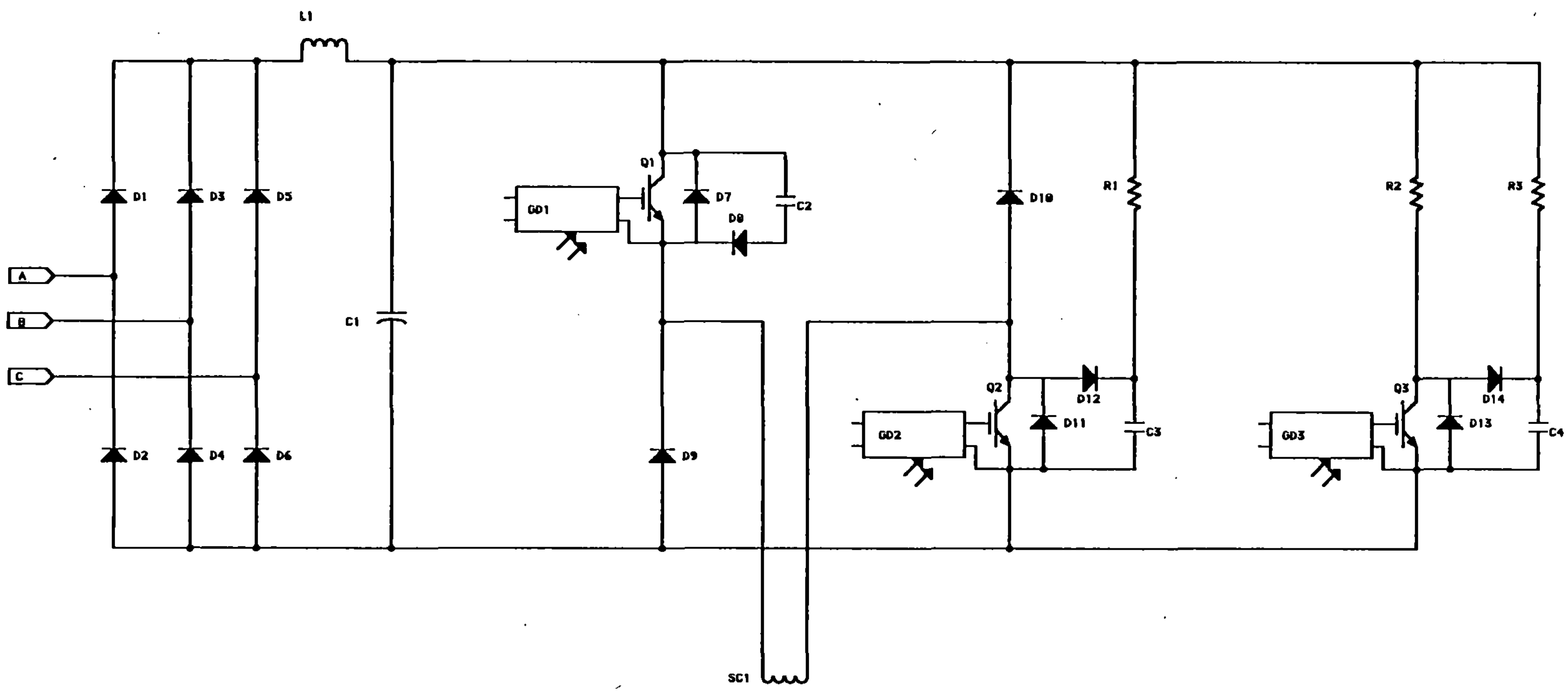


Figure 2-25 Power converter for superconducting coils.

3. DETAILED ANALYSIS

3.1 TRACTION/LEVITATION DRIVE AND HOTEL POWER ANALYSIS

3.1.1 Spreadsheet Description

A spreadsheet has been developed which estimates the mass, size, volume, cost and efficiency of a three phase traction drive for a given input voltage, output MVA, and frequency. The electrical, physical and cost parameters of the semiconductor switching device, support electronics and cooling system are included in the estimate.

The spreadsheet is based on the inverter configuration shown in Figure 3-1. The inverter consists of six switches, a capacitor filter bank and controls. Each switch consists of a driver and a series parallel array of switch modules as shown in Figure 3-2. The switch modules consist of the basic switching element and gate drive as shown in Figure 3-3. Unipolar PWM (pulse width modulation) is assumed in all cases.

The spreadsheet estimates the number of switch modules in series and in parallel required by the input voltage, output MVA, switching frequency, switch element electrical characteristics and thermal requirements. The power dissipation of all of the major heat generating components is calculated based upon the estimated switch series-parallel configuration. The mass, volume and cost of the entire switch, including buswork and frame, is estimated based upon the number of switch modules required.

The number of capacitors required for the input filter capacitor bank is estimated based upon the input voltage, output MVA and switch power loss. The switch and capacitor filter bank mass, volume, cost and loss are summed along with allowances for the overall buswork and frame estimates to arrive at the inverter estimates. The total inverter losses are used to size a liquid cooling system including refrigeration whose characteristics are combined with those of the inverter to estimate the mass, volume, cost and efficiency of the entire system.

Two sets of spreadsheets are provided in Appendix H for each type of switching device considered. The first set covers the case where the inverter carrier frequency is varied and the output is held constant at 10 MVA. The second set covers the case where the output

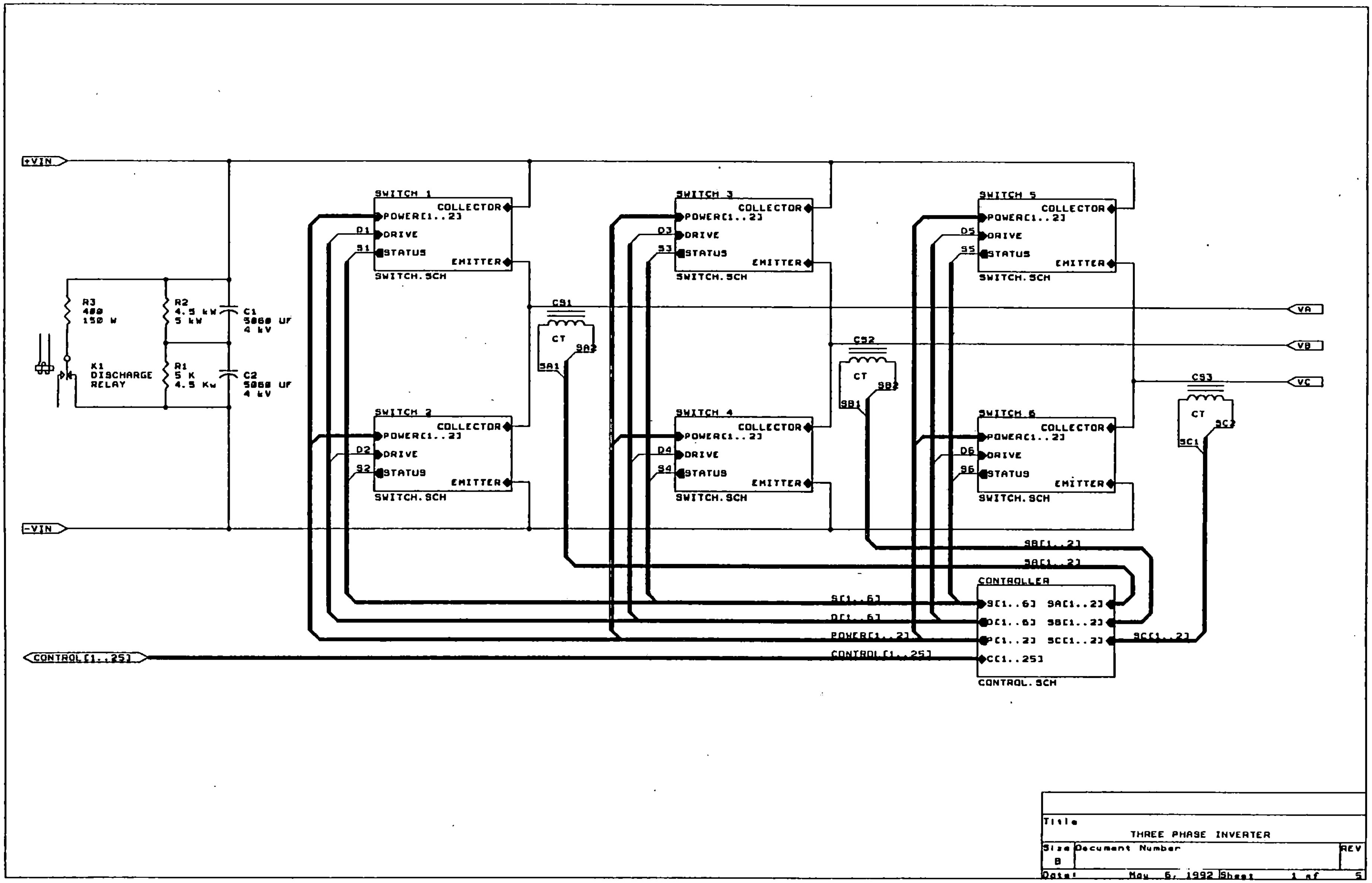
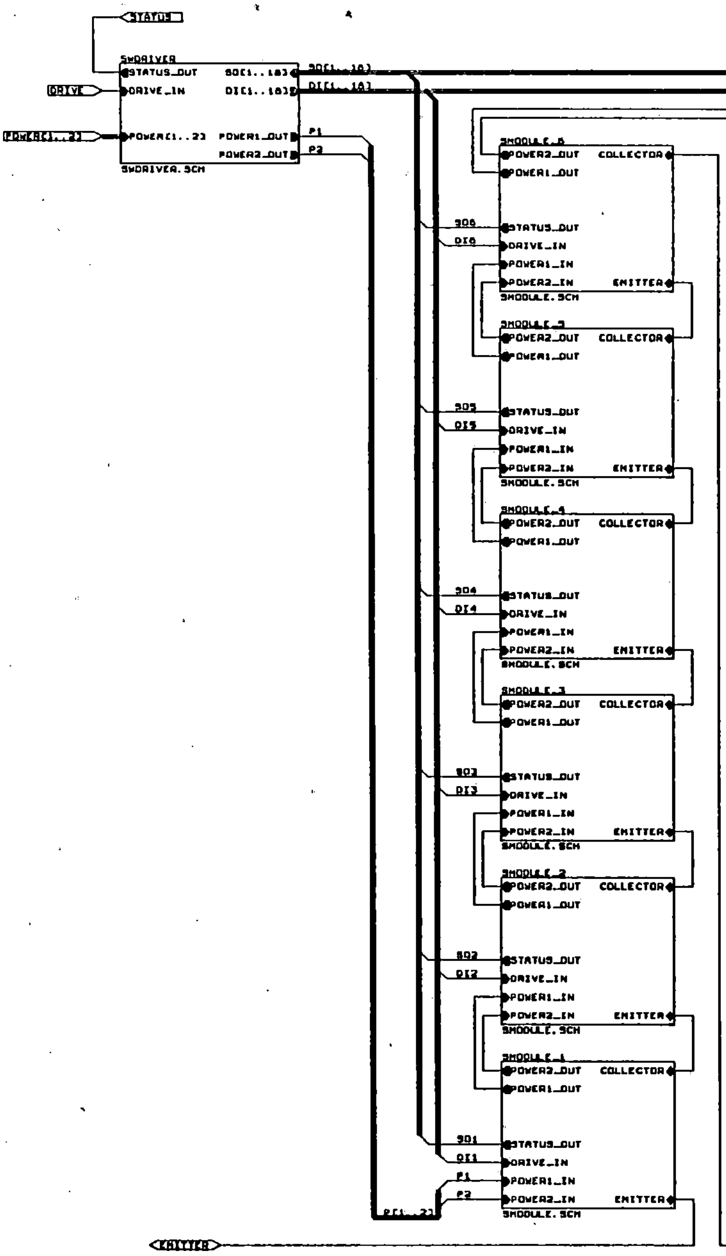


Figure 3-1. Three phase inverter.


STATUS
SWDRIVER
STATUS_OUT
DRIVE_IN
POWER[1..2]
SO[1..18]
DI[1..18]
POWER1_OUT
POWER2_OUT
P1
P2
SWDRIVER.SCH
DRIVE
SMODULE_6
SMODULE_5
SMODULE_4
SMODULE_3
SMODULE_2
SMODULE_1
POWER2_OUT
POWER1_OUT
COLLECTOR
STATUS_OUT
DRIVE_IN
POWER1_IN
POWER2_IN
EMITTER
SMODULE.SCH
SO6
DI6
SO5
DI5
SO4
DI4
SO3
DI3
SO2
DI2
SO1
DI1
P[1..2]
EMITTER

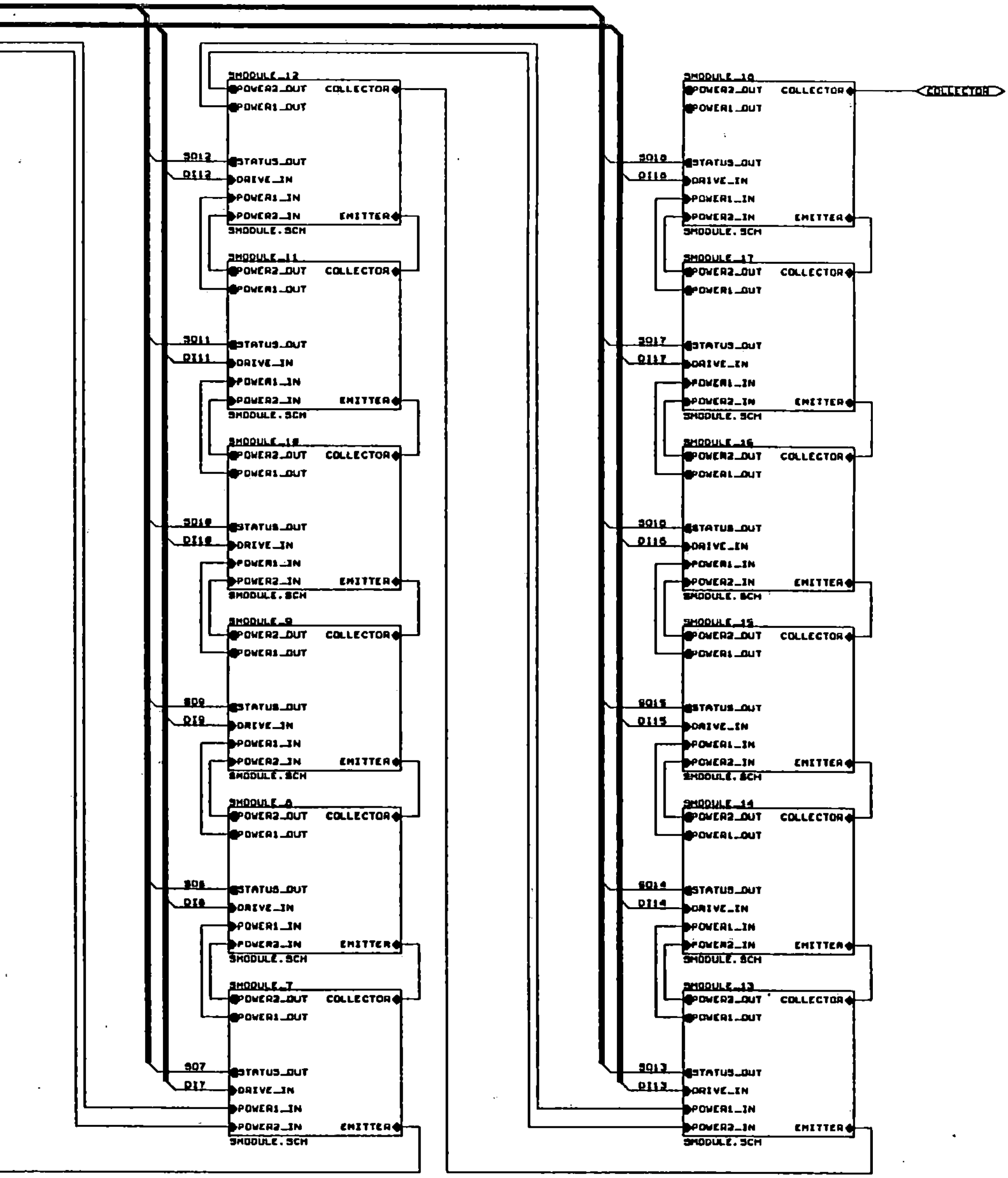


Figure 3-2. Switch.

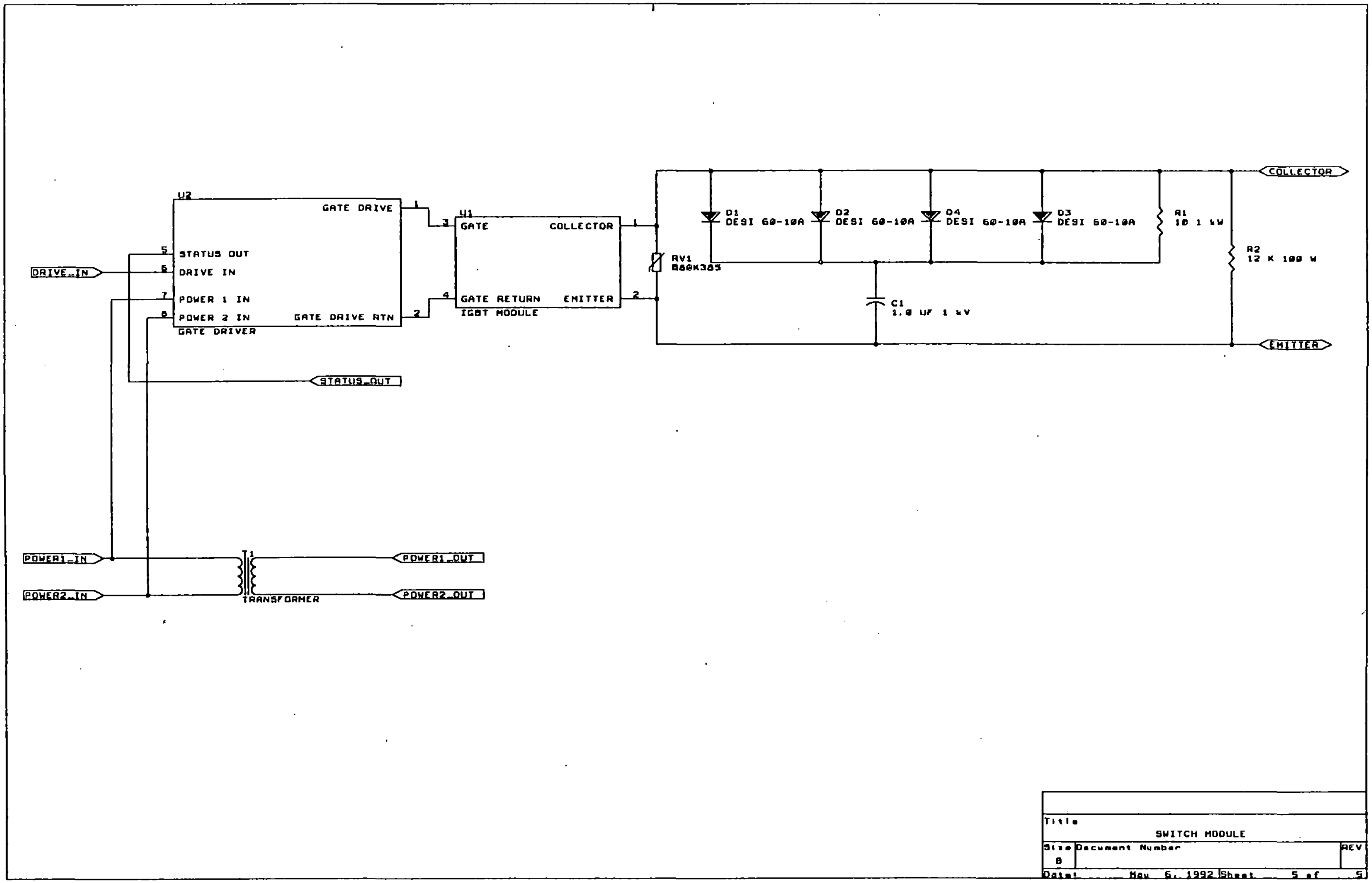


Figure 3-3. Switch module.

MVA is varied and the inverter carrier frequency is held constant at 600 Hz. The structure of the spreadsheets and the basis for the input parameters assumed are discussed in Section 3.1.2. The completed spreadsheets for GTO, IGBT, and BJT switching devices used in traction/levitation drives are shown in Figures H-1, H-2, and H-3, respectively, in Appendix H. Spreadsheets showing data for GTO, IGBT and BJT switching devices when used in auxiliary power conditioning applications are presented in Figures H-4 through H-6.

3.1.2 Detailed Description of Spreadsheet for Traction Drive and Hotel Power

The spreadsheet consists of four sheets arranged as follows. The title of each sheet is shown in the upper left-hand corner. The top half of each sheet consists of a series of blocks which contain the parameters of the various inverter components. The bottom half of the sheet consists of a large block split into "Input Parameters" and "Calculated Results" The input parameters are a group of cells which contain the desired input voltage, output MVA and switching frequency. The calculated results are the estimates generated by the spreadsheet. The input parameters from the first page are copied to the remaining three sheets for convenience. The four sheets are described as follows:

3.1.2.1 Inverter Summary

This is the top level sheet. The desired input parameters are loaded into the appropriate columns and the total estimated mass, volume, cost and efficiency including heat exchanger are displayed in the "Calculated Results" columns. The detailed description of each block is as follows:

Inverter Parameters

This block sets the number of switches in the inverter based upon the number of phases desired.

Number of Phases: Input - unprotected
Sets the inverter configuration. Acceptable values are 3 and 1.

Number of switches: Output - protected
Indicates the number of switches in the inverter based on the number of phases selected.

Heat Exchanger Parameters

This block contains the basis of cost, prime power, mass and volume estimates for the cooling system. The values used are from quoted prices for a 100 kW and a 200 kW refrigerated cooling system from Electro Impulse Inc. , a manufacturer.

Fixed Cost: Input - unprotected
Y intercept of the cooling system cost vs. thermal power graph based upon manufacturer's data.

Cost per kW Loss ($/kW): Input - unprotected
Slope of the graph of cooling system cost vs. thermal power based on manufacturer's data.

Prime Power (kVA/kW Loss): Input - unprotected
The ratio of the input prime power required by the cooling system to the inverter power loss.

Fixed Mass (kg): Input - unprotected
Y intercept of the graph of cooling system mass vs. thermal power.

Mass per kW Loss (kg/kW): Input - unprotected
Slope of the graph of cooling system mass vs. thermal power based upon manufacturer's data.

Fixed Volume (m^3): Input - unprotected
Y intercept of the graph of cooling system volume vs. thermal power.

Volume/kW Loss (m^3/kW): Input - unprotected
Slope of the graph of cooling system volume vs. thermal power based upon manufacturer's data.

Controller

This block contains the controller mass and volume estimates. The values used are based on existing controllers manufactured by General Atomics.

Mass (kg): Input - unprotected

Estimated mass of the controller.

Volume (m^3): Input - unprotected

Estimated volume of the controller.

Buswork & Frame Estimates

This block contains the buswork and frame estimates as a percentage of the mass and volume of the individual switches, capacitor filter bank, and controller.

% Increase in Total Mass: Input - unprotected

Buswork and frame mass estimate expressed as a percent of the sum of the individual component masses.

% Increase in Total Volume: Input - unprotected

Buswork and frame volume estimate expressed as a percent of the sum of the individual inverter component volumes.

Cost Estimates

This block contains the cost estimates for the controller, buswork and frame. Prices were obtained from manufacturer's quotes or price lists.

Controller Fixed Cost: Input - unprotected

Y intercept of the controller cost vs. number of switches graph.

Controller Cost/Switch: Input - unprotected

Slope of the controller cost vs. number of switches graph based on the number of switches in the inverter.

Bus & Frame % Inc in Cost: Input - unprotected

Buswork and frame cost estimate expressed as a percent of the sum of the individual inverter component costs.

Labor and Service Estimates (% of Total Cost)

This block contains the typical cost distribution of an inverter which provides the basis to estimate the total inverter cost from the material cost. These estimates are obtained from General Atomics' manufacturing experience.

Material: Input - unprotected
Material cost estimate expressed as percentage of the total inverter cost.

Fab Labor: Input - unprotected
Fabrication labor cost expressed as a percentage of the total inverter cost.

Fab Services: Input - unprotected
Fabrication services cost as a percentage of the total inverter cost.

Test Labor: Input - unprotected
Test labor cost as a percentage of the total inverter cost.

Input Parameters

This block contains the desired inverter parameters for the spreadsheet to generate an estimate.

Input Voltage (kVDC): Input - unprotected
Inverter input voltage.

Output MVA: Input - unprotected
Inverter output MVA.

Switch Freq (Hz): Input - unprotected
Inverter switching frequency.

Calculated Results

This block contains the inverter parameter estimates calculated by the spreadsheet program.

Mass (kg): Output - protected

Total inverter plus cooling system mass estimated from the following equation:

$$MASS = (M_{SW}*N+M_F+M_C)*(1+K_{MBW})+b_{MHEX}+(m_{MHEX}*P)$$

where:

MASS	= Total inverter mass estimate in kg.
M_{SW}	= Mass estimate of individual switch in kg from sheet 2.
N	= Number of switches.
M_F	= Mass of capacitor filter bank in kg from sheet 4.
M_C	= Mass estimate of controller in kg.
K_{MBW}	= % increase in total mass due to the inverter buswork & frame.
b_{MHEX}	= Cooling system fixed mass estimate in kg.
m_{MHEX}	= Cooling system mass per kW inverter loss estimate in kg/kW.
P	= Total estimated inverter loss in kW.

Volume (m^3): Output - protected

Total inverter plus cooling system volume estimated from the following equation:

$$VOLUME = (V_{SW}*N+V_F+V_C)*(1+K_{VBW})+b_{VHEX}+(m_{VHEX}*P)$$

where:

VOLUME	= Total inverter volume estimate in m^3.
V_{SW}	= Volume estimate of individual switch in m^3 from sheet 2.
N	= Number of switches.
V_F	= Volume of capacitor filter bank in m^3 from sheet 4.
V_C	= Volume estimate of controller in m^3.
K_{VBW}	= % increase in total volume due to the inverter buswork & frame.
bVHEX	= Cooling system fixed volume estimate in m^3.
mVHEX	= Cooling system volume per kW inverter loss estimate in m^3/kW.
P	= Total estimated inverter loss in kW.

Cost: Output - protected

Total inverter plus heat exchanger cost estimated from the following equation:

$$COST = \frac{(\$_{SW}*N+\$_F+b\$_C+m\$_C*N)*(1+K\$_{BW})+b\$_{HEX}+(m\$_{HEX}*P)}{K\$_{MAT}}$$

where:

COST	= Total inverter plus heat exchanger cost.
$\$_{SW}$	= Cost estimate of individual switch from sheet 2.
N	= Number of switches.
$\$_F$	= Cost estimate of capacitor filter bank from sheet 4.
$b\$_C$	= Controller fixed cost.
$m\$_C$	= Controller cost per switch.
$K\$_{BW}$	= % increase in total cost due to inverter buswork and frame.
$b\$_{HEX}$	= Cooling system fixed cost estimate.
$m\$_{HEX}$	= Cooling system cost per kW inverter loss estimate.
P	= Total estimated inverter loss in kW.
$K\$_{MAT}$	= Material % of total cost.

Inverter Loss (kW): Output - protected

Total inverter loss estimated from the following equation:

$$P = (P_{SW}*N+P_F)$$

where:

P	= Total estimated inverter loss in kW.
P_{SW}	= Loss estimate of individual switch in kW from sheet 2.
N	= Number of switches.
P_F	= Loss estimate of the input filter capacitor bank in kW from sheet 4.

Heat Ex Power (kVA): Output - protected

Total cooling system prime power requirements estimated from the following equation:

$$kVA = P * K_{HEX}$$

where:

kVA = Prime power estimate for the cooling system in kVA.

P = Total estimated inverter loss in kW.

K_{HEX} = Cooling system input prime power required as a function of inverter power loss in kVA/kW loss.

Inverter Efficiency: Output - protected

Inverter efficiency calculated from the following equation:

$$\eta_{INV} = \frac{MVA}{MVA + P_{MW}}$$

where:

η_{INV} = Estimated inverter efficiency in %.

MVA = Desired inverter output power in MVA.

P_{MW} = Estimated inverter loss in MW.

Total Efficiency: Output - protected

Total overall efficiency of the inverter and cooling system calculated from the following equation:

$$\eta_{TOT} = \frac{MVA}{MVA + P_{MW} + MVA_{HEX}}$$

where:

η_{INV} = Estimated inverter efficiency in %.

MVA = Desired inverter output power in MVA.

P_{MW} = Estimated inverter loss in MW.
MVA_{HEX} = Estimated cooling system prime power requirements in MW.

Maximum Duty Cycle: Output - protected

Maximum inverter duty cycle for a given frequency calculated from the following equation:

$$Du = 1 - F * \tau_{OFF}$$

where:

Du = Maximum duty cycle.
F = Switching frequency in Hz.
τ_{OFF} = Minimum switch off time in seconds from sheet 2.

NOTE: In the event that the calculated maximum duty cycle is negative, the spreadsheet will report "freq too high" in the cell.

Maximum MVA: Output- protected

Maximum estimated MVA capability of the inverter for a given input voltage assuming full utilization of the calculated switch series parallel combination calculated from the following equation:

$$MVA_{MAX} = V_{INP} * \sqrt{\frac{2 * Du}{\pi}} * N_P * I\phi_{MAX} * \sqrt{n_\Phi} * 10^{-3}$$

where:

MVA_{MAX} = Maximum estimated MVA capacity.
V_{INP} = DC input voltage in kV.
Du = Maximum estimated duty cycle.
N_P = Number of switch modules in parallel from sheet 2.
$I\phi_{MAX}$ = Maximum estimated phase current per switch module in amperes from sheet 2.

n_ϕ = Number of phases

3.1.2.2 GTO/IGBT/BJT Switch Quantity Characterization

This sheet estimates the number of series and parallel switch modules required per switch for the given input voltage, output MVA and switching frequency. In the case of the GTO spreadsheet, one Toshiba SG3000JX24 GTO per switch module is assumed. For the IGBT spreadsheet, 10 Advanced Power Technology APT200G100BFN IGBT chips per module are assumed. For the BJT spreadsheet, 2 GEC Plessey (Marconi) DT600-550 NPN power bipolar transistors per module are assumed. Lower power devices are used for auxiliary (hotel) power. In the case of the GTO spreadsheet, one Toshiba SG1200R23 GTO per switch module is assumed. For the IGBT spreadsheet, 5 Advanced Power Technology APT200G100BFN IGBT chips per module are assumed. For the BJT spreadsheet, a single Powerex KS621K60 Darlington transistor module is assumed. The detailed description of each block is as follows:

GTO/IGBT/BJT Parameters

This block contains the electrical parameters of the switching device.

Voltage Rating (kV): Input - unprotected
Device breakdown voltage in kV.

Power Diss per GTO/IGBT/BJT (W): Input - unprotected
Maximum power dissipation of the individual GTO, IGBT, or BJT chip in watts based upon a maximum junction temperature of 100 °C for the GTO and 125 °C for the IGBT and BJT, the package and heat sink thermal resistance and the cooling system capacity.

V Threshold (Volts): Input - unprotected
Y intercept of the graph of device conduction voltage drop versus forward current.

Dynamic r (Ohms): Input - unprotected
Slope of the graph of device conduction voltage drop versus forward current.

Inc. Sw Loss Per Amp (J/A): Input - unprotected

Slope of the graph of device total switching energy loss in joules versus forward current.

Fixed Sw Loss: Input - unprotected

Y intercept of the graph of device total switching energy loss in joules versus forward current.

Minimum Off Time (s): Input - unprotected

Switching device minimum off time in seconds.

Maximum Itgq (A): Input - unprotected

Switching device maximum controllable current in amperes.

Switch Module Parameters

This block contains the physical parameters of the individual switch modules.

Fixed Mass (kg): Input - unprotected

Y intercept of the graph of switch module mass vs. dv/dt snubber loss.

Mass per Snub Loss (kg/kW); Input - unprotected

Slope of the graph of switch module mass vs. dv/dt snubber loss..

Fixed Vol (m^3): Input - unprotected

Y intercept of the graph of switch module volume vs. dv/dt snubber loss..

Vol per Snub Loss (m^3/kW): Input - unprotected

Slope of the graph of switch module volume vs. dv/dt snubber loss.

Buswork & Frame Estimates

This block contains the factors used to estimate the mass and volume of the buswork and frame.

% Increase in Total Mass: Input - unprotected

Buswork and frame mass estimate expressed as a percent of the sum of the individual switch module and driver masses.

% Increase in Total Volume: Input - unprotected

Buswork and frame volume estimate expressed as a percent of the sum of the individual switch module and driver volumes.

Cost Estimates

This block contains the factors used to estimate the cost for the switch modules, driver, buswork and frame.

Fixed Cost per Module: Input - unprotected

Y intercept of the graph of switch module cost vs. dv/dt snubber loss

Cost per dv/dt Loss ($/kW): Input - unprotected

Slope of the graph of switch module cost vs. dv/dt.

Driver Fixed Cost: Input - unprotected

Y intercept of the graph of driver cost vs. number of switch modules in the switch.

Driver Cost per Module: Input - unprotected

Slope of the graph of driver cost vs. number of switch modules in the switch.

Bus & Frame % Inc in Cost: Input - unprotected

Buswork and frame cost estimate expressed as a percent of the sum of the individual switch component costs.

Input Parameters

This block contains the desired inverter parameters copied from sheet 1.

Input Voltage (kVDC): Input - protected

Inverter input voltage.

Output MVA: Input - protected
Inverter output MVA.

Switch Freq (Hz): Input - protected
Inverter switching frequency.

Calculated Results

This block contains the switch parameter estimates calculated by the spreadsheet.

Total Est Mass (kg): Output - protected
Total switch mass estimated from the following equation:

$$M_{SW} = \left[N_{SM} * \left(b_{MSM} + m_{MSM} * P_{SNUB}\right)\right] * \left(1 + K_{SBWM}\right)$$

where:

M_{SW}	= Total switch mass estimate in kg.
NSM	= Number of switch modules.
b_{MSM}	= Switch module fixed mass estimate in kg/kW.
m_{MSM}	= Switch module mass per dv/dt and di/dt snubber loss estimate in kg/kW.
P_{SNUB}	= Estimated dv/dt and di/dt snubber power loss in kW from sheet 3.
K_{SBWM}	= % increase in total switch mass due to the buswork & frame.

Total Est Volume (m^3): Output - protected
Total switch volume estimate based on the following equation:

$$V_{SW} = \left[N_{SM} * \left(b_{VSM} + m_{VSM} * P_{SNUB}\right)\right] * \left(1 + K_{SBWV}\right)$$

where:

V_{SW} = Total switch volume estimate in m^3.
N_{SM} = Number of switch modules.
b_{VSM} = Switch module fixed volume estimate in (m^3/kW).
m_{VSM} = Switch module volume per dv/dt and di/dt snubber loss estimate in (m^3/kW).
P_{SNUB} = Estimated dv/dt and di/dt snubber power loss in kW from sheet 3.
K_{SBWV} = % increase in total switch volume due to the buswork & frame.

Total Est Mat'l Cost: Output - protected

Total switch cost estimated from the following equation:

$$\$_{SW} = \left[N_{SM}*\left(b\$_{SM}+m\$_{SM}*P_{SNUB}\right)+b\$_{D}+m\$_{D}*N_{SM}\right]*\left(1+K\$_{SBW}\right)$$

where:

$\$_{SW}$ = Total switch material cost estimate.
N_{SM} = Number of switch modules.
$b\$_{SM}$ = Switch module fixed cost estimate.
$m\$_{SM}$ = Switch module cost per dv/dt and di/dt snubber loss estimate in (\$/kW).
P_{SNUB} = Estimated dv/dt and di/dt snubber power loss in kW from sheet 3.
$K\$_{SBW}$ = % increase in total switch cost due to the buswork & frame.

Total Est Sw Loss (kW): Output - protected

Total power loss of the entire switch estimated from the following equation:

$$P_{SW} = N_{SM}*P_{SM}$$

where:

P_{SW} = Total switch loss estimate in kW.

N_{SM}	= Number of switch modules.
P_{SM}	= total switch module power loss estimate in kW.

Maximum Peak Current: Output - protected

Maximum peak switching device current in amperes estimated from the following equation:

$$I_{PKMAX} = -\frac{b}{2} + \sqrt{\left(\frac{b}{2}\right)^2 - c}$$

where:

$$c = \frac{(E_{SW} * F - 2P_{DISS}) * \pi}{2 * r_{DYNAMIC} * Du}$$

$$b = \frac{V_{THRESHOLD} + e_{sw} * F}{r_{DYNAMIC}}$$

and:

I_{PKMAX}	= Maximum estimated peak switching device current in amperes.
$V_{THRESHOLD}$	= Switching device threshold voltage in volts.
e_{SW}	= Incremental switching energy loss per ampere in J/A.
F	= Switching frequency in Hz.
$r_{DYNAMIC}$	= Switching device dynamic resistance in ohms.
E_{SW}	= Switching device fixed switching energy loss in J.
P_{DISS}	= Switching device maximum power dissipation in W.
Du	= Maximum estimated duty cycle.

NOTES:

1. In the event that the calculated maximum peak switching device current exceeds the specified maximum Itgq, the maximum Itgq value is loaded into the cell.
2. In the event that the calculated maximum peak switching device current is negative, the message "freq too high" is loaded into the cell.

Max Phase Cur Parallel (Arms): Output - protected

Calculates the maximum rms phase current per parallel set of switch modules from the following equation:

$$I_{RMSMAX} = I_{PKMAX} * \sqrt{\frac{2*Du}{\pi}}$$

where:

I_{RMSMAX} = Maximum estimated phase current per parallel set of switch modules in rms amperes.
I_{PKMAX} = Maximum estimated peak switching device current in amperes.
Du = Maximum estimated duty cycle.

Parallel Modules Req: Output - protected

Estimates the number of switch modules in parallel for a given output MVA rating by the following scheme:

Let:

$$A_P = \frac{MVA}{V_{INP} * \sqrt{\frac{2*Du}{\pi}} * I_{RMSMAX} * \sqrt{n_\phi}}$$

where:

A_P = Ratio of the desired output MVA to the MVA capacity of a single switch module operating at maximum rated current.
MVA = Desired inverter output power in MVA.

V_{INP}	=	DC input voltage in volts.
Du	=	Maximum estimated duty cycle.
I_{RMSMAX}	=	Maximum estimated phase current per parallel set of switch modules in rms amperes.
$n\phi$	=	Number of phases.

If A_P is exactly a integer, then the spreadsheet loads A_P into the cell. Otherwise, the spreadsheet loads the integer of A_P+1 into the cell.

Series Modules Req: Output - protected

Estimates the number of switch modules in series for a given input voltage using the following scheme:

Let:

$$A_S = \frac{V_{INP}}{V_{DMAX}/2.5}$$

where:

A_S	=	Ratio of the desired input voltage to the voltage capacity of a single switch module.
V_{INP}	=	DC input voltage in kV.
V_{DMAX}	=	Maximum switching device voltage rating in kV.
2.5	=	Device voltage derating factor.

If A_S is exactly an integer, then the spreadsheet loads A_S into the cell. Otherwise, the spreadsheet loads the integer of A_S+1 into the cell.

Total Modules Req: Output - protected

Estimates the total number of switch modules for the switch from the following equation:

$$N_{SM} = N_P * N_S$$

where:

N_{SM} = Number of switch modules per switch.
N_P = Number of switch modules in parallel.
N_S = Number of switch modules in series.

3.1.2.3 Switch Loss Estimation

This sheet calculates the losses of all of the switch module components under actual operating conditions. In the case of the GTO spreadsheet, one Toshiba 800GXHH21 anti-parallel diode per switch module is assumed. In the case of the IGBT spreadsheet, 34 IXYS DESI 60-10A diodes per switch module are assumed. In the case of the BJT spreadsheet, 2 each International Rectifier R38BF6A diodes per switch module are assumed. In the case of the BJT spreadsheet, 2 International Rectifier R38BF6A diodes per switch module are assumed. The detailed description of each block is as follows:

Snubber Parameters

This block contains the electrical parameters of the switch module dv/dt and di/dt snubber components.

dv/dt Snubber Capacitor (uF): Input - unprotected
Capacitance value of the dv/dt snubber capacitor in microfarads.

di/dt Snubber Inductor (uH): Input - unprotected
Inductance value of the di/dt snubber inductor in microhenries.

Anti-Parallel Diode Parameters

This block contains the electrical characteristics of the anti-parallel diode.

Diode VT (V): Input - unprotected
Y intercept of the graph of diode conduction voltage drop versus forward current.

Diode r (Ohms): Input - unprotected

Slope of the graph of diode conduction voltage drop versus forward current.

Diode Irr (Amps): Input - unprotected

Diode reverse recovery current.

Input Parameters

This block contains the desired inverter parameters copied from sheet 1.

Input Voltage (kVDC): Input - protected

Inverter input voltage.

Output MVA: Input - protected

Inverter output MVA.

Switch Freq (Hz): Input - protected

Inverter switching frequency.

Calculated Results

Total Est Mod Loss (kW): Output - protected

Total power loss for the entire switch module estimated from the following equation:

$$P_{SM} = P_{SD}+P_{AD}+P_{dvdt}+P_{didt}+P_{COND}$$

where:

P_{SM}	= Total estimated switch module power loss in kW.
P_{SD}	= Total estimated module switching device power loss in kW.
P_{AD}	= Total module anti-parallel diode estimated power loss in kW.
P_{dvdt}	= Total dv/dt snubber power loss in kW.
P_{didt}	= Total di/dt snubber power loss in kW.
P_{COND}	= Total module conduction loss in kW.

Module Peak Current (A): Output - protected

Switch module peak forward current for the given number of parallel modules and the desired output MVA from the following equation:

$$I_{PK} = \frac{MVA}{N_P * V_{INP} * \left(\frac{2*Du}{\pi}\right) * \sqrt{n_\phi}} * 10^3$$

where:

IPK	= Switch module peak forward current estimate in A.
MVA	= Desired inverter output power in MVA.
N_P	= Number of switch modules in parallel.
V_{INP}	= DC input voltage in kV.
Du	= Maximum estimated duty cycle.
n_ϕ	= Number of phases.

Module Cond Loss (kW): Output - protected

Switch module forward conduction power loss estimated from the following equation:

$$P_{SCOND} = \left[\left(\frac{r_{DYNAMIC}}{N_{SDEV}}\right) * I_{PK}^2 + V_{THRESHOLD} * I_{PK}\right] * \left(\frac{Du}{\pi}\right) * 10^{-3}$$

where:

P_{SCOND}	= Estimated switch module forward conduction power loss in kW.
$r_{DYNAMIC}$	= Switching device dynamic resistance in ohms.
N_{SDEV}	= Number of switching devices per module.
I_{PK}	= Estimated switch module peak forward current in A.
$V_{THRESHOLD}$	= Switching device threshold voltage in volts.
Du	= Maximum estimated duty cycle.

Module Switch Loss (kW): Output - protected

Switch module switching power loss estimated from the following equation:

$$P_{SWITCHING} = \frac{\left[e*\left(\frac{I_{PK}}{N_{SDEV}}\right)*\left(\frac{2*Du}{\pi}\right)+E\right]*N_{SDEV}*F}{2}*10^{-3}$$

where:

$P_{SWITCHING}$	= Estimated switch module switching power loss in kW.
e	= Incremental switching loss per amp per switching device in J/A.
IPK	= Estimated switch module peak forward current in A.
N_{SDEV}	= Number of switching devices per module.
Du	= Maximum estimated duty cycle.
E	= Fixed switching loss per switching device in J.
F	= Switching frequency in Hz.

Total Module Loss (kW): Output - protected

Sum of switch module switching device conduction and switching power loss calculated from the following equation:

$$P_{SD} = P_{SCOND} + P_{SWITCHING}$$

where:

P_{SD}	= Total estimated module switching device power loss in kW.
P_{SCOND}	= Switch module forward conduction power loss estimate in kW.
$P_{SWITCHING}$	= Switch module switching power loss estimate in kW.

Anti-Parallel Loss (kW): Output - protected

Total switch module anti-parallel diode power loss estimated from the following equation:

$$P_{AD}=\frac{\left(r_{ADDYNAMIC}*I_{PK}^2+V_{ADTHRESHOLD}*I_{PK}\right)*\left(\frac{2*Du}{\pi}\right)}{2}*10^{-3}$$

where:

P_{AD} = Total module anti-parallel diode estimated power loss in kW.
$r_{ADDYNAMIC}$ = Anti-parallel diode dynamic resistance in ohms.
IPK = Estimated switch module peak forward current in A.
$V_{ADTHRESHOLD}$ = Anti-parallel diode threshold voltage in volts.
Du = Maximum estimated duty cycle.

dv/dt Snubber Loss (kW): Output - protected

Total power loss of the dv/dt snubber estimated from the following equation:

$$P_{dvdt} = \frac{1}{2}*C*\left[\frac{V_{DMAX}}{2}\right]^2*F*10^{-3}$$

where:

P_{dvdt} = Total dv/dt snubber power loss in kW.
C = Total estimated snubber capacitance in microfarads.
V_{DMAX} = Maximum switching device voltage rating in kV.
F = Switching frequency in Hz.

di/dt Snubber Loss (kW): Output - protected

Total power loss of the di/dt snubber estimated from the following equation:

$$P_{didt} = \frac{1}{2}*L*\left(I_{PK}+I_{rr}\right)^2*F*10^{-9}$$

where:

P_{didt} = Total di/dt snubber power loss in kW.
L = Total estimated snubber inductance in microhenries.
I_{PK} = Estimated switch module peak forward current in A.
I_{rr} = Anti-parallel diode reverse recovery current in A.
F = Switching frequency in Hz.

Conductor Loss (kW): Output - protected

Total power loss in the switch module conductor in series with the transistor that is sized to cause a large enough voltage drop to assure current sharing among parallel modules is estimated from the following equation:

$$P_{COND} = \frac{I_{PK} * \left(\frac{2*Du}{\pi}\right) * V_{drop} * 10^{-3}}{2}$$

where:

P_{COND} = Total module power loss in the conductor in kW.
I_{PK} = Estimated switch module peak forward current in A.
Du = Maximum estimated duty cycle.
V_{drop} = Total switch module conductor voltage drop required for sharing in V.

3.1.2.4 Input Filter Sizing

This sheet estimates the number of series and parallel input capacitors for the inverter for a given input voltage, output MVA switching frequency, and inverter efficiency. The estimated losses in the capacitors and bleeder resistors are also calculated. The detailed description of each block is as follows:

Capacitor Parameters

This block contains the electrical and physical parameters of the selected filter capacitor.

Capacitance (uF): Input - unprotected
Capacitor capacitance in microfarads.

Voltage (kV): Input - unprotected
Capacitor rated DC voltage.

RMS Ripple Current (A): Input - unprotected
Maximum capacitor rms ripple current.

Voltage Derating: Input - unprotected
Capacitor voltage derating factor.

Current Derating: Input - unprotected
Capacitor ripple current derating factor.

Max ESR (ohms): Input - unprotected
Maximum capacitor equivalent series resistance.

Bleeder Res (ohms): Input - unprotected
Capacitor bleeder resistor value.

Mass (kg): Input - unprotected
Capacitor mass including allowances for the bleeder resistor and brackets.

Volume (m^3): Input - unprotected
Capacitor volume including allowances for the bleeder resistor, brackets, and unused volume due to non-rectangular form factors.

Buswork & Frame Estimates

This block contains the buswork and frame estimates for the input filter as a percentage increase in mass and volume of the individual capacitors. The capacitor energy dump circuit is considered part of this allowance.

% Increase in Total Mass: Input - unprotected

Buswork and frame mass estimate expressed as a percent of the sum of the masses of the individual capacitors.

% Increase in Total Volume: Input - unprotected
Buswork and frame volume estimate expressed as a percent of the sum of the volumes of the individual capacitors.

Cost Estimates

This block contains the cost estimates for the capacitors, dump, buswork and frame.

Cap & Bleeder Cost per Cap: Input - unprotected
Cost of a single capacitor with bleeder resistor.

Dump Cost per kJ: Input - unprotected
Slope of the graph of the input filter energy dump circuit cost versus stored energy.

Bus & Frame % Inc in Cost: Input - unprotected
Buswork and frame cost estimate expressed as a percent of the sum of the individual capacitor and bleeder resistor costs.

Input Parameters

This block contains the desired inverter parameters copied from sheet 1.

Input Voltage (kVDC): Input - protected
Inverter input voltage.

Output MVA: Input - protected
Inverter output MVA.

Switch Freq (Hz): Input - protected
Inverter switching frequency.

Calculated Results

This block contains the input filter parameters calculated by the spreadsheet.

Total Est Mass (kg): Output - protected

Total input filter capacitor bank mass estimated from the following equation:

$$M_F = M_{CP}*N_{CP}*(1+K_{FBWM})$$

where:

MF = Total input filter capacitor bank mass estimate in kg.

MCP = Mass estimate of individual capacitor and bleeder resistor in kg.

N_{CP} = Total number of capacitors in the input filter bank.

K_{FBWM} = % increase in total input filter mass due to the capacitor bank bus-work and frame.

Total Est Volume (m^3): Output - protected

Total input filter capacitor bank volume estimated from the following equation:

$$V_F = V_{CP}*N_{CP}*(1+K_{FBWV})$$

where:

V_F = Total input filter capacitor bank volume estimate in m^3.

V_{CP} = Volume estimate of individual capacitor and bleeder resistor in m^3.

N_{CP} = Total number of capacitors in the input filter bank.

K_{FBWV} = % increase in total input filter volume due to the capacitor bank buswork and frame.

Total Est Cost: Output - protected

Total input filter capacitor bank cost estimated from the following equation:

$$\$_F = (N_{CP}*\$_{CP}+E_F*m\$_{EF})*(1+K\$_{FBW})$$

where:

$\$_F$ = Total input filter capacitor bank cost estimate.
N_{CP} = Total number of capacitors in the input filter bank.
$\$_{CP}$ = Cost estimate of individual capacitor and bleeder resistor.
E_F = Total estimated stored energy in the input filter bank in kJ.
$m\$_{EF}$ = Energy dump cost per kJ.
$K\$_{FBW}$ = % increase in total input filter cost due to the capacitor bank buswork and frame.

Total Est Loss (kW): Output - protected

Total input filter capacitor bank power loss estimated from the following equation:

$$P_F = P_{CP}*N_{CP}*10^{-3}$$

where:

P_F = Power loss estimate of the input filter capacitor bank in kW.
P_{CP} = Estimated power loss per capacitor with bleeder resistor in W.
N_{CP} = Total number of capacitors in the input filter bank.

RMS Filter Current (A): Output - protected

Total input filter capacitor bank ripple current estimated from the following equation:

$$I_{FRMS} = \frac{MVA+P_{SW}*N*10^{-3}}{V_{INP}*\sqrt{\frac{2*Du}{\pi}}}*10^3$$

where:

I_{FRMS} = Total estimated input filter capacitor bank rms current in A.

MVA	=	Desired inverter output power in MVA.
P_{SW}	=	Loss estimate of individual switch in kW from sheet 2.
N	=	Number of switches from sheet 1.
VINP	=	DC input voltage in kV.
Du	=	Maximum estimated duty cycle from sheet 1.

Loss per Capacitor (W): Output - protected

Power loss per capacitor including bleeder resistor power loss estimated from the following equation:

$$P_{CP} = \left[\frac{I_{FRMS}}{N_{CPP}}\right]^2 * ESR + \left[\frac{V_{INP} * 10^3}{N_{CPS}}\right]^2 * \frac{1}{R_B}$$

where:

P_{CP}	=	Estimated power loss per capacitor with bleeder resistor in W.
I_{FRMS}	=	Total estimated input filter capacitor bank rms current in A.
N_{CPP}	=	Number of parallel capacitor strings in the input filter bank.
ESR	=	Capacitor equivalent series resistance in ohms.
V_{INP}	=	DC input voltage in kV.
N_{CPS}	=	Number of capacitors in series in the input filter bank.
R_B	=	Bleeder resistance in ohms.

Total Stored Energy (J): Output - protected

Total stored energy in the input filter capacitor bank estimated from the following equation:

$$E_F = \frac{1}{2} * \left[\frac{V_{INP}}{N_{CPS}}\right]^2 * C * N_{CP} * 10^{-3}$$

where:

E_F	=	Total estimated stored energy in the input filter bank in kJ.

V_{INP} = DC input voltage in kV.
N_{CPS} = Number of capacitors in series in the input filter bank.
C = Capacitance of individual capacitor in uF.
N_{CP} = Total number of capacitors in the input filter bank.

Parallel Caps Req: Output - protected

Number of parallel strings, N_{CPP} , of capacitors required to meet the current requirements estimated from the following equation:

Let:

$$A_{CPP} = \frac{I_{FRMS}}{I_{RIPPLE} * D_{CURRENT}}$$

where:

A_{CPP} = Ratio of input filter rms current to the rms current rating of a single capacitor.
I_{FRMS} = Total estimated input filter capacitor bank rms current in A.
I_{RIPPLE} = Maximum capacitor rms ripple current in A.
$D_{CURRENT}$ = Capacitor ripple current derating factor.

If A_{CPP} is exactly an integer, then the spreadsheet loads A_{CPP} into the cell. Otherwise, the spreadsheet loads the integer of $A_{CPP} + 1$ into the cell.

Series Capacitors Req: Output - protected

Number of capacitors in series, N_{CPS} , required to meet the desired input voltage requirements estimated from the following equation:

Let:

$$A_{CPS} = \frac{V_{INP}}{V_{CP} * D_{VOLTAGE}}$$

where:

A_{CPS}	= Ratio of the desired input voltage to the voltage rating of a single capacitor.
V_{INP}	= DC input voltage in kV.
V_{CP}	= Capacitor voltage rating in kV.
$D_{VOLTAGE}$	= Capacitor voltage derating factor.

If A_{CPS} is exactly an integer, then the spreadsheet loads A_{CPS} into the cell. Otherwise, the spreadsheet loads the integer of $A_{CPS} + 1$ into the cell.

Total Caps Req: Output - protected

The total number of capacitors required for the input filter bank estimated from the following equation:

$$N_{CP} = N_{CPP} * N_{CPS}$$

where:

N_{CP}	= Total number of capacitors in the input filter bank.
N_{CPP}	= Number of parallel capacitor strings in the input filter bank.
N_{CPS}	= Number of capacitors in series in the input filter bank.

3.2 INPUT POWER CONDITIONING ANALYSIS

3.2.1 Spreadsheet Description

A spreadsheet has been developed which estimates the mass, size, volume, cost and efficiency of a one or three phase input power conditioning converter for a given input voltage and output power. The electrical, physical and cost parameters of the semiconductor switching device, support electronics and heat removal system are included in the estimate.

The input converter consists of either four or six switches, an input transformer and controls. Each switch consists of a driver and a series parallel array of switch modules. The switch modules consist of the basic switching element and gate drive. Unipolar PWM (pulse width modulation) is assumed in all cases.

The spreadsheet estimates the number of switch modules in series and in parallel based upon the input voltage, output power, switch element electrical characteristics and thermal requirements. The power dissipation of all of the major heat generating components is calculated for the estimated switch series-parallel configuration. The mass, volume and cost of the entire switch including buswork and frame is estimated for the number of switch modules required.

The number of capacitors required for the output filter capacitor bank is estimated based upon the output voltage, output power and switch power loss. The switch and capacitor filter bank mass, volume, cost and loss are summed with allowances for the overall buswork and frame estimates to arrive at the converter estimates. The total converter losses are used to size a refrigerated heat removal system. Its parameters are combined with those of the converter to estimate the total mass, volume, cost and efficiency of the system.

Two sets of spreadsheets are provided in Appendix H for each type of switching device considered. The structure of the spreadsheets and the basis for the input parameters assumed are discussed in Section 3.2.2. The completed spreadsheet for GTO, IGBT, and BJT switching devices in a single phase input converter are shown in Figures H-7, H-8, and H-9 in Appendix H. Figures H-10, H-11, and H-12 show spreadsheets for three phase input power converters with GTO, IGBT and BJT switching devices, respectively.

3.2.2 Detailed Description of Spreadsheet for Power Conditioning

The spreadsheet consists of four sheets arranged as follows. The title of the sheet is shown in the upper left hand corner. The top half of each sheet consists of a series of blocks which contain the parameters of the various converter components. The bottom half of the sheet consists of a large block split into "Input Parameters" and "Calculated Results" The input parameters are a group of cells which contain the desired input voltage and output power and line frequency. The calculated results are the estimates generated by the spreadsheet. The input results are from the first page are copied to the remaining four sheets for convenience. The first three sheets have the same cell equations as described in Section 3.1.2. The last sheet estimates the size of the input transformer based on standard equations.

3.2.2.1 Transformer Sizing

This sheet estimates the size of the transformer. The transformer mass, volume, cost and loss were scaled as a function of MVA from catalog parameters of a given transformer. Standard transformer scaling equations found in chapter 10 of Fink, Donald G., and Beaty, H. Wayne (eds.) Standard Handbook for Electrical Engineers, 11th edition, McGraw Hill, 1978, were used.

Basis Transformer Parameters

This block contains parameters for the catalogue transformer used as a basis for scaling.

MVA Rating 50% Duty Cycl: Input-unprotected
MVA rating of transformer

Mass (kg): Input-unprotected
Mass of transformer

Volume (m^3): Input - unprotected
Volume of transformer

Frequency (Hz): Input - unprotected
Frequency of transformer

Full Load Power Loss (kW): Input - unprotected
Power loss of transformer at full load

Estimated Cost: Input - unprotected
Cost of transformer

Transformer Power Factor

Rectification Power Factor (PF): Input - unprotected
Ratio of output power from rectifier to transformer MVA rating

Input Parameters

This block contains the desired transformer parameters

Output Voltage (kVDC): Input - protected
Required output voltage from the power conditioning copied from sheet 1.

Output Power (MW): Input - protected
Required output power from the power conditioning copied from sheet 1

Line Freq (Hz): Input - protected
Input line frequency (assumed to be 60 Hz).

Calculated Results

This block contains the transformer parameter estimates calculated by the spreadsheet.

Total Est Mass (kg): Output - protected
Total transformer mass estimated from the following equation:

$$M_{TR} = M_{TRB} * \left[\frac{MVA_{TR}}{MVA_{TRB}}\right]^{3/4}$$

where:

M_{TR} = Total transformer mass estimate in kg.
M_{TRB} = Mass of transformer used as a basis.
MVA_{TR} = Transformer MVA rating.
MVA_{TRB} = MVA rating of transformer used as a basis.

Total Est Volume (m^3): Output - protected
Total transformer volume estimated from the following equation:

$$V_{TR} = V_{TRB} \left[\frac{MVA_{TR}}{MVA_{TRB}}\right]^{3/4}$$

where:

V_{TR} = Total transformer volume in m^3
V_{TRB} = Volume of transformer used as a basis in m^3

Total Est Cost: Output - protected
Total transformer cost estimated from the following equation:

$$\$_{TR} = \$_{TRB} \left[\frac{MVA_{TR}}{MVA_{TRB}}\right]^{3/4}$$

where

$\$_{TR}$ = Total transformer material cost estimate.
$\$_{TRB}$ = Cost of transformer used as a basis.

Total Est Loss (kW): Output - protected
Total power loss in the transformer estimated from the following equation:

$$P_{TR} = P_{TRB} \left[\frac{MVA_{TR}}{MVA_{TRB}} \right]^{3/4}$$

where

P_{TR} = Total transformer loss estimate in kW.

P_{TRB} = Power loss in the transformer used as a basis in kW.

Transformer MVA Rating: Output - protected

Transformer MVA rating calculated from the following equation

$$MVA_{TR} = MW/PF$$

where:

MVA_{TR} = Transformer MVA rating

MW = Required output power

PF = Rectification power factor

3.3 BRAKING CHOPPER ANALYSIS

3.3.1 Spreadsheet Description

A spreadsheet has been developed which estimates the mass, size, volume, cost and efficiency of a braking chopper for a given input voltage, braking power, and frequency. The electrical, physical and cost parameters of the semiconductor switching device, support electronics and heat exchanger are included in the estimate. The estimate does not include the actual braking resistor.

The spreadsheet is based on the braking chopper configuration shown in Figure 2-19. The braking chopper is a large switch consisting of a series parallel array of switch modules and controls.

The spreadsheet estimates the number of switch modules in series and in parallel based upon the input voltage, braking power, switching frequency, switch element electrical characteristics and thermal requirements. The power dissipation of all of the major heat generating components is calculated based upon the estimated switch series-parallel configuration. The mass, volume and cost of the entire switch is estimated based upon the number of switch modules required along with buswork and frame estimates.

The total braking chopper losses are used to size a liquid cooling system including refrigeration which is combined with the braking chopper estimates to generate the total estimated mass, volume, cost and efficiency of the system.

Two sets of spreadsheets are provided in Appendix H. The first set, Figures H-13.1 to H-13.3, covers the case where the braking chopper carrier frequency is varied and the braking power is held constant at 8.5 MW. The second set, Figures H-13.4 to H-13.6, covers the case where the braking power is varied and the braking chopper carrier frequency is held constant at 600 Hz.

3.3.2 Detailed Description of Braking Chopper Spreadsheet

The spreadsheet consists of three sheets arranged as follows. The title of the sheet is shown in the upper left-hand corner. The top half of each sheet consists of a series of blocks which contain the parameters of the various braking chopper components. The bottom half of the sheet consists of a large block split into "Input Parameters" and "Calculated Results" The input parameters are a group of cells which contain the desired input voltage, braking power in MW and switching frequency. The calculated results are the estimates generated by the spreadsheet. The input results from the first page are copied to the remaining three sheets for convenience. The four sheets are described as follows:

3.3.2.1 Braking Chopper Summary

This is the top level sheet. The desired input parameters are loaded into the appropriate columns and the total estimated mass, volume, cost and efficiency including the cooling system are displayed in the calculated results columns. The detailed description of each block is as follows:

Heat Exchanger Parameters

This block contains the basis for cost, prime power, mass and volume estimates for the heat exchanger.

Fixed Cost: Input - unprotected
Y intercept of the heat exchanger cost vs. power graph based upon manufacturer's data.

Cost per kW Loss ($/kW): Input - unprotected
Slope of the heat exchanger cost vs. power graph based on manufacturer's data.

Prime Power (kVA/kW Loss): Input - unprotected
Prime power required for cooling including refrigeration per unit power loss in the braking chopper.

Fixed Mass (kg): Input - unprotected
Y intercept of the cooling system mass vs. power loss graph.

Mass per kW Loss (kg/kW): Input - unprotected
Slope of the cooling system mass vs. power loss graph based upon manufacturer's data.

Fixed Volume (m^3): Input - unprotected
Y intercept of the cooling system volume vs. power loss graph.

Volume/kW Loss: Input - unprotected
Slope of the cooling system volume vs. power loss graph based upon manufacturer's data.

Controller

This block contains the controller mass and volume estimates.

Mass (kg): Input - unprotected
Estimated mass of the controller.

Volume (m^3): Input - unprotected
Estimated volume of the controller.

Buswork & Frame Estimates

This block contains the buswork and frame mass and volume estimates expressed as a percentage of the mass and volume of the individual switches, capacitor filter bank and controller.

% Increase in Total Mass: Input - unprotected
Buswork and frame mass estimate expressed as a percentage of the sum of the individual component masses.

% Increase in Total Volume: Input - unprotected
Buswork and frame volume estimate expressed as a percentage of the sum of the individual braking chopper component volumes.

Cost Estimates

This block contains the cost estimates for the controller, buswork and frame.

Controller Fixed Cost: Input - unprotected
Controller cost assumed.

Bus & Frame % Inc in Cost: Input - unprotected
Buswork and frame cost expressed as a percentage of the sum of the individual braking chopper component costs.

Labor and Service Estimates (% of Total Cost)

This block contains the typical cost distribution of a braking chopper which provides the basis to extrapolate the total braking chopper cost based upon the material cost.

Material: Input - unprotected
Material cost as percentage of the total braking chopper cost.

Fab Labor: Input - unprotected

Fabrication labor cost as a percentage of the total braking chopper cost.

Fab Services: Input - unprotected

Fabrication services cost as a percentage of the total braking chopper cost.

Test Labor: Input - unprotected

Test labor cost as a percentage of the total braking chopper cost.

Input Parameters

This block contains the desired braking chopper parameters for the spreadsheet to generate an estimate.

Input Voltage (kVDC): Input - unprotected

Braking chopper input voltage.

Braking Power (MW): Input - unprotected

Braking chopper braking power.

Switch Freq (Hz): Input - unprotected

Braking chopper switching frequency.

Calculated Results

This block contains the braking chopper parameter estimates calculated by the spreadsheet.

Mass (kg): Output - protected

Total braking chopper plus cooling system mass estimated from the following equation:

$$MASS = (M_{SW}+M_C)*(1+K_{MBW})+b_{MHEX}+(m_{MHEX}*P)$$

where:

MASS	=	Total braking chopper mass estimate in kg.
M_{SW}	=	Mass estimate of individual switch in kg from sheet 2.
M_C	=	Mass estimate of controller in kg.
K_{MBW}	=	% increase in total mass due to the braking chopper buswork & frame.
b_{MHEX}	=	Cooling system fixed mass estimate in kg.
m_{MHEX}	=	Cooling system mass per kW braking chopper loss estimate in kg/kW.
P	=	Total estimated braking chopper loss in kW.

Volume (m^3): Output - protected

Total braking chopper plus cooling system volume estimated from the following equation:

$$VOLUME = (V_{SW}+V_C)*(1+K_{VBW})+b_{VHEX}+(m_{VHEX}*P)$$

where:

VOLUME	=	Total braking chopper volume estimate in m^3.
V_{SW}	=	Volume estimate of individual switch in m^3 from sheet 2.
V_C	=	Volume estimate of controller in m^3.
K_{VBW}	=	% increase in total volume due to the braking chopper buswork & frame.
b_{VHEX}	=	Cooling system fixed volume estimate in m^3.
m_{VHEX}	=	Cooling system volume per kW braking chopper loss estimate in m^3/kW.
P	=	Total estimated braking chopper loss in kW.

Cost: Output - protected

Total braking chopper plus heat exchanger cost estimate based on the following equation:

$$COST = \frac{(\$_{SW}+\$_C)*(1+K\$_{BW})+b\$_{HEX}+(m\$_{HEX}*P)}{K\$_{MAT}}$$

where:

COST	= Total cost of braking chopper plus cooling system cost.
$\$_{SW}$	= Cost estimate of individual switch from sheet 2.
$\$_F$	= Cost estimate of capacitor filter bank from sheet 4.
$\$_C$	= Controller fixed cost.
$K\$_{BW}$	= % increase in total cost due to braking chopper buswork and frame.
$b\$_{HEX}$	= Cooling system fixed cost estimate.
$m\$_{HEX}$	= Cooling system cost per kW braking chopper loss estimate.
P	= Total estimated braking chopper loss in kW.
$K\$_{MAT}$	= Material % of total cost.

Braking chopper Loss (kW): Output - protected

Total braking chopper loss estimated from the following equation:

$$P = P_{SW}$$

where:

P	= Total estimated braking chopper loss in kW.
P_{SW}	= Loss estimate of individual switch in kW from sheet 2.

Heat Ex Power (kVA): Output - protected

Total estimated cooling system prime power requirements based on the following equation:

$$kVA = P*K_{HEX}$$

where:

kVA = Prime power estimate for the heat exchanger in kVA.
P = Total estimated braking chopper loss in kW.
K_{HEX} = Cooling system input prime power required as a function of braking chopper power loss in kVA/kW loss.

Braking chopper Efficiency: Output - protected

Braking chopper efficiency based on the following equation:

$$\eta_{INV} = \frac{MW}{MW+P_{MW}}$$

where:

η_{INV} = Estimated efficiency of braking chopper including cooling system in %.
MW = Desired braking chopper output power in MW.
P_{MW} = Estimated braking chopper loss in MW.

Total Efficiency: Output - protected

Total overall efficiency of the braking chopper and cooling system based on the following equation:

$$\eta_{TOT} = \frac{MW}{MW+P_{MW}+MW_{HEX}}$$

where:

η_{TOT} = Estimated efficiency of braking chopper including cooling system in %.
MW = Desired braking chopper output power in MW.
P_{MW} = Estimated braking chopper loss in MW.
MW_{HEX} = Estimated cooling system prime power requirements in MW.

Maximum Duty Cycle: Output - protected

Maximum braking chopper duty cycle for a given frequency based on the following equation:

$$Du = 1 - F * \tau_{OFF}$$

where:

Du	= Maximum duty cycle.
F	= Switching frequency in Hz.
τ_{OFF}	= Minimum switch off time in seconds from sheet 2.

NOTE: In the event that the calculated maximum duty cycle is negative, the spreadsheet will report "freq too high" in the cell.

Maximum MW: Output- protected

Maximum MW capability of the braking chopper for a given input voltage assuming full utilization of the calculated switch series parallel combination estimated from the following equation:

$$MW_{MAX} = V_{INP} * Du * N_P * I_{PKMAX} * 10^{-3}$$

where:

MW_{MAX}	= Maximum estimated MW capacity.
V_{INP}	= DC input voltage in kV.
Du	= Maximum estimated duty cycle.
N_P	= Number of switch modules in parallel from sheet 2.
I_{PKMAX}	= Maximum peak current per switch module in amperes from sheet 2.

3.3.2.2 <u>GTO Switch Quantity Characterization</u>

This sheet estimates the number of series and parallel switch modules required per switch for the given input voltage, braking power in MW and switching frequency. One Toshiba SG3000JX24 GTO per switch module is assumed. The detailed description of each block is as follows:

GTO Parameters

This block contains the electrical parameters of the GTO.

Voltage Rating (kV): Input - unprotected
Device breakdown voltage in kV.

Power Diss per GTO (W): Input - unprotected
Maximum power dissipation of the individual GTO in watts based upon a maximum junction temperature of 100 °C for the GTO, the package and heat sink thermal resistance and the cooling system capacity.

V Threshold (Volts): Input - unprotected
Y intercept of the graph of device conduction voltage drop versus forward current.

Dynamic r (Ohms): Input - unprotected
Slope of the graph of device conduction voltage drop versus forward current.

Inc. Sw Loss Per Amp: Input - unprotected
Slope of the graph of device total switching energy loss versus forward current.

Fixed Switching Loss (J): Input - unprotected
Y intercept of the graph of device total switching energy loss versus forward current.

Minimum Off Time (s): Input - unprotected
GTO minimum off time.

Maximum Itgq (A): Input - unprotected
GTO maximum controllable current.

Switch Module Parameters

This block contains the physical parameters of the individual switch modules.

Fixed Mass (kg): Input - unprotected

Y intercept of the graph of switch module mass vs. snubber power loss.

Mass per Snub Loss (kg/kW); Input - unprotected
Slope of the graph of switch module mass vs. snubber power loss.

Fixed Vol (m^3): Input - unprotected
Y intercept for the switch module volume vs. snubber power loss.

Vol per Snub Loss (m^3/kW): Input - unprotected
Slope of the graph of switch module volume vs. snubber power loss.

Buswork & Frame Estimates

This block contains the buswork and frame mass and volume estimates for the switch as a percentage of the mass and volume of the individual switch modules and driver.

% Increase in Total Mass: Input - unprotected
Buswork and frame mass estimate as a percentage of the sum of the individual switch module and driver masses.

% Increase in Total Volume: Input - unprotected
Buswork and frame volume estimate as a percentage of the sum of the individual switch module and driver volumes.

Cost Estimates

This block contains the cost estimates for the switch modules, driver, buswork and frame.

Fixed Cost per Module: Input - unprotected
Y intercept of the graph of switch module cost vs. number of switch modules.

Cost per Snub Loss ($/kW): Input - unprotected
Slope of the graph of switch module cost vs. snubber power loss.

Driver Fixed Cost: Input - unprotected

Y intercept of the graph of driver cost vs. number of switch modules.

Driver Cost per Module: Input - unprotected

Slope of the graph of driver cost vs. number of switch modules.

Bus & Frame % Inc in Cost: Input - unprotected

Buswork and frame cost as a percentage of the sum of the individual switch component costs.

Input Parameters

This block contains the desired braking chopper parameters copied from sheet 1.

Input Voltage (kVDC): Input - protected

Braking chopper input voltage.

Braking Power (MW): Input - protected

Braking chopper braking power in MW.

Switch Freq (Hz): Input - protected

Braking chopper switching frequency.

Calculated Results

This block contains the switch parameter estimates calculated by the spreadsheet.

Total Est Mass (kg): Output - protected

Total switch mass estimate based on the following equation:

$$M_{SW} = \left[N_{SM} * \left(b_{MSM} + m_{MSM} * P_{SNUB}\right)\right] * \left(1 + K_{SBWM}\right)$$

where:

M_{SW} = Total switch mass estimate in kg.
N_{SM} = Number of switch modules.
b_{MSM} = Switch module fixed mass estimate in (kg/kW).
m_{MSM} = Switch module mass per dv/dt and di/dt snubber loss estimate in (kg/kW).
P_{SNUB} = Estimated dv/dt and di/dt snubber power loss in kW from sheet 3.
K_{SBWM} = % increase in total switch mass due to the buswork & frame.

Total Est Volume (m^3): Output - protected

Total switch volume estimate based on the following equation:

$$V_{SW} = \left[N_{SM} * \left(b_{VSM} + m_{VSM} * P_{SNUB}\right)\right] * \left(1 + K_{SBWV}\right)$$

where:

V_{SW} = Total switch volume estimate in m^3.
N_{SM} = Number of switch modules.
b_{VSM} = Switch module fixed volume estimate in (m^3/kW).
m_{VSM} = Switch module volume per dv/dt and di/dt snubber loss estimate in (m^3/kW).
P_{SNUB} = Estimated dv/dt and di/dt snubber power loss in kW from sheet 3.
K_{SBWV} = % increase in total switch volume due to the buswork & frame.

Total Est Mat'l Cost: Output - protected

Total switch cost estimate based on the following equation:

$$\$_{SW} = \left[N_{SM} * \left(b\$_{SM} + m\$_{SM} * P_{SNUB}\right) + b\$_D + m\$_D * N_{SM}\right] * \left(1 + K\$_{SBW}\right)$$

where:

$\$_{SW}$ = Total switch material cost estimate.
N_{SM} = Number of switch modules.
$b\$_{SM}$ = Y intercept of the graph of switch module cost vs. snubber power loss.

$m\$_{SM}$ = Slope of the graph of switch module cost vs. dv/dt and di/dt snubber loss in ($/kW).

P_{SNUB} = Estimated dv/dt and di/dt snubber power loss in kW from sheet 3.

$b\$_{D}$ = Y intercept of the graph of driver cost vs. number of switch modules.

$m\$_{D}$ = Slope of the graph of driver cost vs. number of switch modules.

$K\$_{SBW}$ = % increase in total switch cost due to the buswork & frame.

Total Est Sw Loss (kW): Output - protected

Total estimated power loss of the entire switch based on the following equation:

$$P_{SW} = N_{SM} * P_{SM}$$

where:

P_{SW} = Total switch loss estimate in kW.

N_{SM} = Number of switch modules.

Maximum Peak Current (A): Output - protected

Maximum peak GTO current based upon the following equation:

$$I_{PKMAX} = -\frac{b}{2} + \sqrt{\left(\frac{b}{2}\right)^2 - c}$$

where:

$$c = \frac{E_{SW} * F - P_{DISS}}{r_{DYNAMIC} * Du}$$

$$b = \frac{V_{THRESHOLD} + e_{sw} * F}{r_{DYNAMIC} * Du}$$

and:

I_{PKMAX}	= Maximum estimated peak GTO current in amps.
$V_{THRESHOLD}$	= GTO threshold voltage in volts.
e_{SW}	= Incremental switching energy loss per amp in J/A.
F	= Switching frequency in Hz.
$r_{DYNAMIC}$	= GTO dynamic resistance in ohms.
E_{SW}	= GTO fixed switching energy loss in J.
P_{DISS}	= GTO maximum power dissipation in W.
Du	= Maximum estimated duty cycle.

NOTES:

1. In the event that the calculated maximum peak GTO current exceeds the specified maximum Itgq, the maximum Itgq value is loaded into the cell.

2. In the event that the calculated maximum peak GTO current is negative, the message "freq too high" is loaded into the cell.

Max Current/Parallel (Arms): Output - protected

Calculates the maximum rms current per parallel set of switch modules based on the following equation:

$$I_{RMSMAX} = I_{PKMAX} * \sqrt{Du}$$

where:

I_{RMSMAX}	= Maximum estimated current per parallel set of switch modules in rms amperes.
I_{PKMAX}	= Maximum estimated peak GTO current in amperes.
Du	= Maximum estimated duty cycle.

Parallel Modules Req: Output - protected

Estimates the number of switch modules in parallel for a given braking power in MW rating based upon the following scheme:

Let:

$$A_p = \frac{MW}{V_{INP} * \sqrt{Du} * I_{RMSMAX}}$$

where:

A_P = Ratio of the desired braking power in MW to the MW capacity of a single switch module operating at maximum rated current.

MW = Desired braking chopper output power in MW.

V_{INP} = DC input voltage in volts.

Du = Maximum estimated duty cycle.

I_{RMSMAX} = Maximum estimated phase current per parallel set of switch modules in rms amperes.

If A_P is exactly an integer, then the spreadsheet loads A_P into the cell. Otherwise, the spreadsheet loads the integer of A_P+1 into the cell.

Series Modules Req: Output - protected

Estimates the number of switch modules in series for a given input voltage using the following scheme:

Let:

$$A_S = \frac{V_{INP}}{V_{DMAX}/2.5}$$

where:

A_S = Ratio of the desired input voltage to the voltage capacity of a single switch module.

V_{INP} = DC input voltage in kV.

V_{DMAX} = Maximum GTO voltage rating in kV.

2.5 = Device voltage derating factor.

If A_S is exactly an integer, then the spreadsheet loads A_S into the cell. Otherwise, the spreadsheet loads the integer of $A_S + 1$ into the cell.

Total Modules Req: Output - protected

Calculates the total number of switch modules for the switch from the following equation:

$$N_{SM} = N_P * N_S$$

where:

N_{SM} = Number of switch modules per switch.

N_P = Number of switch modules in parallel.

N_S = Number of switch modules in series.

3.3.2.3 Switch Loss Estimation

This sheet calculates the losses of all of the switch module components under actual operating conditions. One Toshiba 800GXHH21 anti-parallel diode per switch module is assumed. The detailed description of each block is as follows:

Snubber Parameters

This block contains the electrical parameters of the switch module dv/dt and di/dt snubber components.

dv/dt Snubber Capacitor (uF): Input - unprotected

Capacitance value of the dv/dt snubber capacitor.

di/dt Snubber Inductor (uH): Input - unprotected

Inductance value of the di/dt snubber inductor.

Anti-Parallel Diode Parameters

This block contains the electrical characteristics of the anti-parallel diode.

Diode VT (V): Input - unprotected

Y intercept of the graph of diode conduction voltage drop versus forward current.

Diode r (Ohms): Input - unprotected

Slope of the graph of diode conduction voltage drop versus forward current.

Diode Irr (Amps): Input - unprotected

Diode reverse recovery current.

Input Parameters

This block contains the desired braking chopper parameters copied from sheet 1.

Input Voltage (kVDC): Input - protected

Braking chopper input voltage.

Braking Power (MW): Input - protected

Braking chopper braking power in MW.

Switch Freq (Hz): Input - protected

Braking chopper switching frequency.

Calculated Results

Total Est Mod Loss (kW): Output - protected

Total power loss for the entire switch module estimated from the following equation:

$$P_{SM} = P_{SD} + P_{AD} + P_{dvdt} + P_{didt} + P_{COND}$$

where:

P_{SM} = Total estimated switch module power loss in kW.

P_{SD} = Total estimated module GTO power loss in kW.

P_{AD} = Total module anti-parallel diode estimated power loss in kW.

P_{dvdt} = Total dv/dt snubber power loss in kW.

P_{didt}	= Total di/dt snubber power loss in kW.
P_{COND}	= Total module conduction loss in kW.

Module Peak Current (A): Output - protected

Switch module peak forward current for the given number amount of parallel modules and the desired braking power in MW estimated from the following equation:

$$I_{PK} = \frac{MW}{N_P * V_{INP} * Du} * 10^3$$

where:

I_{PK}	= Estimated switch module peak forward current in A.
MW	= Desired braking chopper output power in MW.
N_P	= Number of switch modules in parallel.
V_{INP}	= DC input voltage in kV.
Du	= Maximum estimated duty cycle.

Module Cond Loss (kW): Output - protected

Switch module forward conduction power loss estimated from the following equation:

$$P_{SCOND} = \left(r_{DYNAMIC} * I_{PK}^2 + V_{THRESHOLD} * I_{PK}\right) * Du * 10^{-3}$$

where:

P_{SCOND}	= Estimated switch module forward conduction power loss in kW.
$r_{DYNAMIC}$	= GTO dynamic resistance in ohms.
I_{PK}	= Estimated switch module peak forward current in A.
$V_{THRESHOLD}$	= GTO threshold voltage in volts.
Du	= Maximum estimated duty cycle.

Module Switch Loss (kW): Output - protected

Estimated switch module switching power loss based on the following equation:

$$P_{SWITCHING} = (e*I_{PK}+E)*F*10^{-3}$$

where:

$P_{SWITCHING}$	= Estimated switch module switching power loss in kW.
e	= Incremental switching loss per amp per GTO in J/A.
I_{PK}	= Estimated switch module peak forward current in A.
Du	= Maximum estimated duty cycle.
E	= Fixed switching loss per GTO in J.
F	= Switching frequency in Hz.

Total Module Loss (kW): Output - protected

Sum of switch module GTO conduction and switching power loss based on the following equation:

$$P_{SD} = P_{SCOND}+P_{SWITCHING}$$

where:

P_{SD}	= Total estimated GTO power loss in the module in kW.
P_{SCOND}	= Estimated switch module forward conduction power loss in kW.
$P_{SWITCHING}$	= Estimated switch module switching power loss in kW.

Anti-Parallel Loss (kW): Output - protected

Total switch module anti-parallel diode power loss estimated from the following equation:

$$P_{AD} = \left(r_{ADDYNAMIC}*I_{PK}^{2}+V_{ADTHRESHOLD}*I_{PK}\right)*Du*10^{-3}$$

where:

P_{AD}	= Total module anti-parallel diode estimated power loss in kW.
$r_{ADDYNAMIC}$	= Anti-parallel diode dynamic resistance in ohms.
I_{PK}	= Estimated switch module peak forward current in A.
$V_{ADTHRESHOLD}$	= Anti-parallel diode threshold voltage in volts.

Du = Maximum estimated duty cycle.

dv/dt Snubber Loss (kW): Output - protected

Total power loss of the dv/dt snubber estimated from the following equation:

$$P_{dvdt} = \frac{1}{2} * C * \left[\frac{V_{DMAX}}{2}\right]^2 * F * 10^{-3}$$

where:

- P_{dvdt} = Total dv/dt snubber power loss in kW.
- C = Total estimated snubber capacitance in microfarads.
- V_{DMAX} = Maximum GTO voltage rating in kV.
- F = Switching frequency in Hz.

di/dt Snubber Loss (kW): Output - protected

Total power loss of the di/dt snubber estimated from the following equation:

$$P_{didt} = \frac{1}{2} * L * (I_{PK} + I_{rr})^2 * F * 10^{-9}$$

where:

- P_{didt} = Total di/dt snubber power loss in kW.
- L = Total estimated snubber inductance in microhenries.
- I_{PK} = Estimated switch module peak forward current in A.
- I_{rr} = Anti-parallel diode reverse recovery current in A.
- F = Switching frequency in Hz.

Conductor Loss (kW): Output - protected

Total power loss in the switch module conductor in series with the transistor that is sized to cause a large enough voltage drop to assure current sharing among parallel modules is estimated from the following equation:

$$P_{COND} = I_{PK} * Du * V_{drop} * 10^{-3}$$

where:

P_{COND}	= Total module conduction loss in kW.
I_{PK}	= Estimated switch module peak forward current in A.
Du	= Maximum estimated duty cycle.
V_{drop}	= Total switch module conductor voltage drop required for sharing in V.

3.4 SUPERCONDUCTING COIL CONVERTER ANALYSIS

3.4.1 Spreadsheet Description

A spreadsheet has been developed which estimates the mass, size, volume, cost and efficiency of a superconducting coil converter for a given input voltage, charging power, and frequency. The electrical, physical and cost parameters of the semiconductor switching device, support electronics and heat exchanger are included in the estimate.

The spreadsheet is based on the converter configuration shown in Figure 2-25. The spreadsheet estimates the number of switch modules in series and in parallel based upon the input voltage, charging power, switching frequency, switch element electrical characteristics and thermal requirements. The power dissipation of all of the major heat generating components is calculated based upon the estimated switch series-parallel configuration. The mass, volume and cost of the entire switch, including buswork and frame, is estimated based upon the number of switch modules required.

The total converter losses are used to size a cooling system which is combined with the converter estimates to estimate the total mass, volume, cost and efficiency of the system.

The spreadsheet cell equations are the same as those in the braking chopper description. Ten APT200G100BFN IGBT chips per switch module are assumed. The detailed spreadsheets are provided in Appendix H in Figures H-14.1 to 14.3.

4. COMPUTER MODELLING

Computer models were developed based on three device types; the bipolar junction transistor (BJT), the gate turn-off thyristor (GTO), and the insulated gate bipolar transistor (IGBT). These models were then incorporated into circuitry to verify operation and then finally into an inverter configuration.

The devices chosen for modelling were the maximum volt-amp product devices presently available. Their data sheets are presented in Appendix C. The devices chosen for detailed computer modelling were the Marconi DT600 BJT, the Advanced Power Technology APT200G100BFN IGBT and the Toshiba SG3000JX24 GTO thyristor. A computer device model of the Asea Brown Boveri CS2104 silicon controlled rectifier (SCR) is also provided although no higher level simulations were performed for this device.

The next level of simulation placed the modelled device into a circuit to provide verification of the device characteristics. Finally, each switch type was modelled into an inverter application along with the snubbing circuitry and matching circuitry that would be required. The input voltage and currents of the inverters were set according to the device specifications.

None of the devices are singularly capable of meeting the voltage and current requirements at MW output power levels. Larger series-parallel device arrays are used to build the final inverter. The approach for circuit modelling of large device arrays analyzes the device array as a single device only with the characteristics of the full switch array. The device which represents the whole array is then appropriately scaled as determined by the performance characteristics of the single device.

External components are used to protect the individual semiconductor devices. The values of these external components take into account the mismatch in parameters such as storage time and saturation voltage that must be accounted for when devices are placed in series or in parallel. This is further explained with each topology description.

In developing the circuits, a safety factor of 2.5 for voltage (e.g., device rated V_{CE} ÷ actual voltage in application) was used. Device junction temperatures were maintained at least 25 °C below the maximum rated operating temperatures.

The output list files for the simulation of the inverter circuits are included as Appendix D. These output files include the codes for all subcircuits or models that were developed.

4.1 BIPOLAR JUNCTION TRANSISTOR COMPUTER MODELS

4.1.1 PSpice Semiconductor Model

The BJT model of the DT600 Marconi transistor is included in Figure 4-1.

```
* DT600 model created using Parts version 5.1 on 03/12/92 at 16:14
*
.model DT600    NPN(Is=84.59p Xti=3 Eg=1.11 Vaf=100 Bf=466.9
+      Ise=84.59p Ne=1.192 Ikf=165.3 Nk=.6454 Xtb=1.5 Br=1.004K
+      Isc=4.049n Nc=1.626 Ikr=60.72m Rc=0 Cjc=2p Mjc=.3333
+      Vjc=.75 Fc=.5 Cje=5p Mje=.3333 Vje=.75 Tr=10n Tf=1n Itf=1
+      Xtf=0 Vtf=10)
```

Figure 4-1. PSpice Model of the Marconi DT600 Bipolar Junction Transistor

4.1.2 PSpice Circuit Simulation with BJT Switches

The circuit topology simulation is the leg of a three-phase motor drive inverter shown in Figure 4-2. Because of the comparatively low volt-amp product of the BJT, a switch made up of bipolar transistors will require a series-parallel arrangement of devices. For example, to first order, with a 5 MW, 5000 V input, the required array size of BJTs is 23 x 2.

The manufacturer's data sheet for the Marconi DT600 was consulted to determine the best method of running devices in series and parallel. The variation in storage time between devices affect the ability of parallel BJT devices to share under transient conditions. Experience has shown that having devices selected with similar characteristics is not practical for large scale applications. An antisaturation clamp (Baker clamp) was used to reduce the collector storage time.

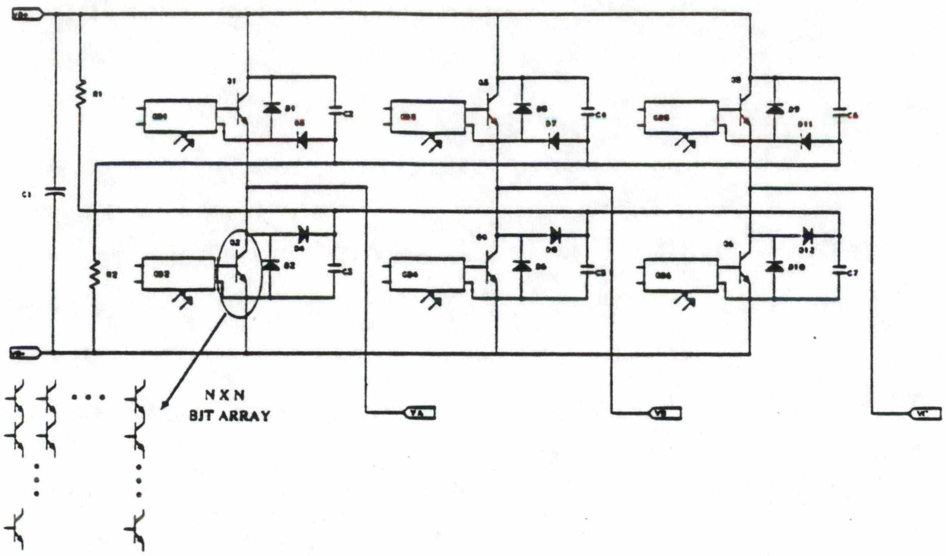


Figure 4-2. Three phase motor drive inverter using BJTs.

the base drive circuit is included. The Baker clamp thus minimizes turn-off time variations between devices. The circuit shown in Figure 4-3 is one cell containing two parallel devices.

The next step was to place the parallel device circuits in series to meet the input voltage requirements. For devices in series, the turn-off time must be controlled or else the first device in the string to turn off will block the most voltage and will be destroyed. To equalize the turn-off times, a snubber circuit is added to the model and is also shown in Figure 4-3. A freewheeling diode is added to the cell to provide a current path needed in operation with an inductive load.

A computer simulation of the circuit in Figure 4-4 was used to verify proper operation. The base drive voltage source in this model is a waveform typical for bipolar transistors where there is a high initial pulse which reaches some nominal drive level once the device is on and then a high reverse pulse and a nominal negative drive when turning off the device. Figure 4-5 shows the sum of the current through the parallel transistors in the upper waveform and the base current in the lower waveform. Figure 4-6 shows the collector current in the upper waveform versus the V_{CE} drop across the transistors in the lower waveform. The labeled data points show a simulated voltage drop of 1.5 V when there is a collector current of 545 A which, when compared to the data sheet, is a reasonable value.

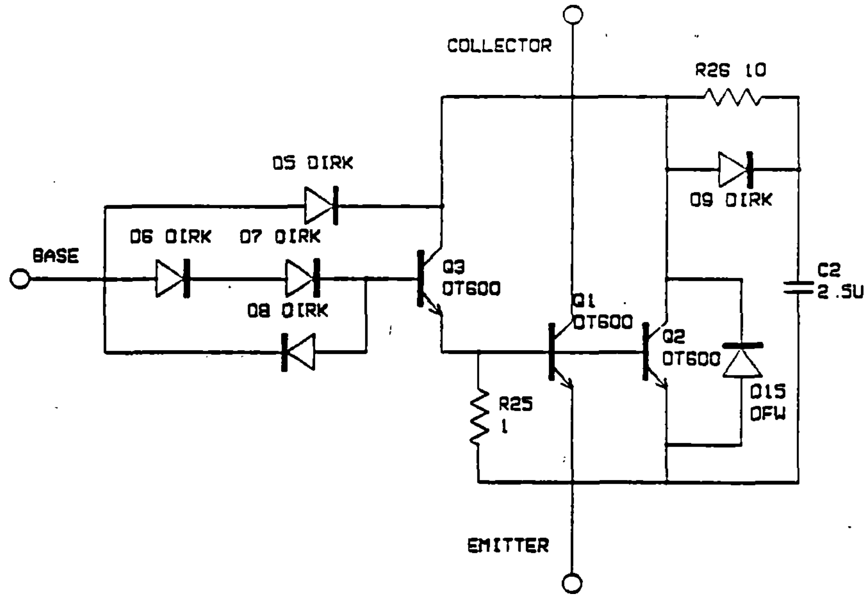


Figure 4-3. A cell comprised of two DT600 BJTs in parallel.

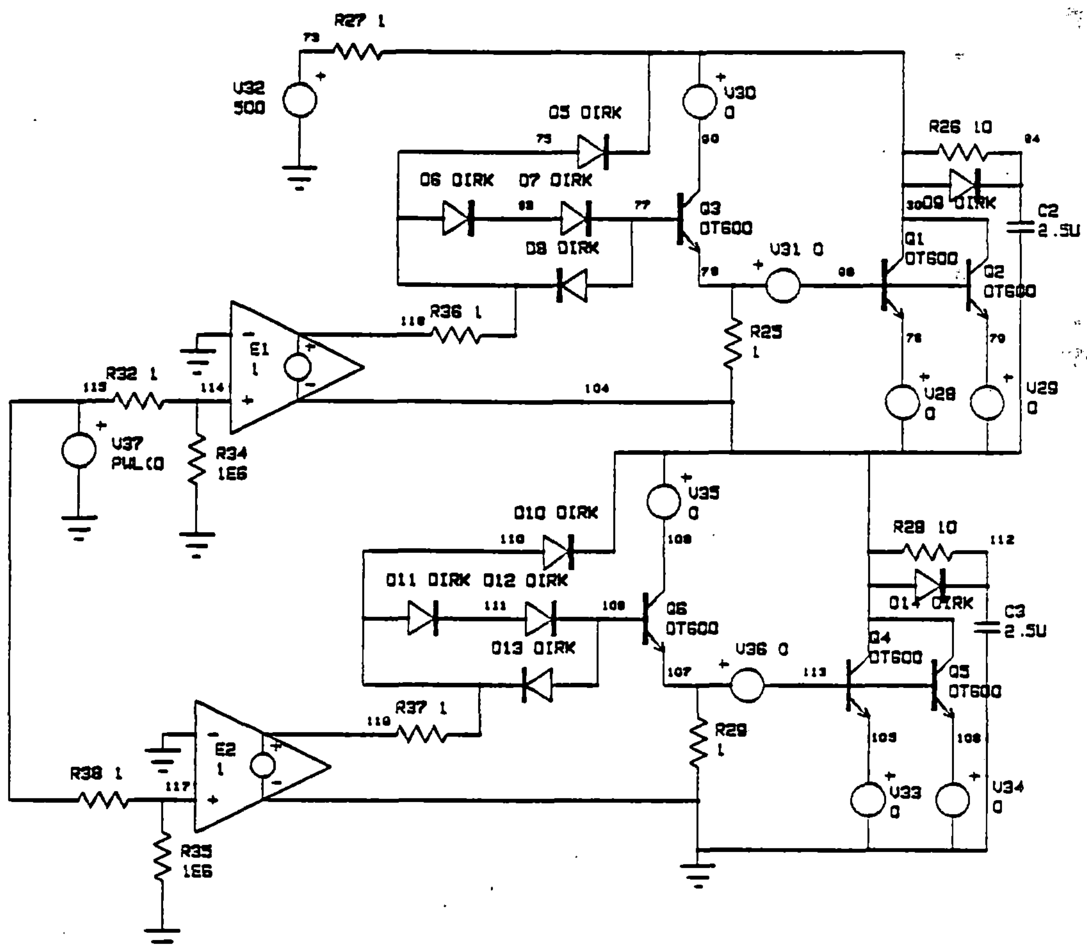


Figure 4-4. Model for two BJT cells in series.

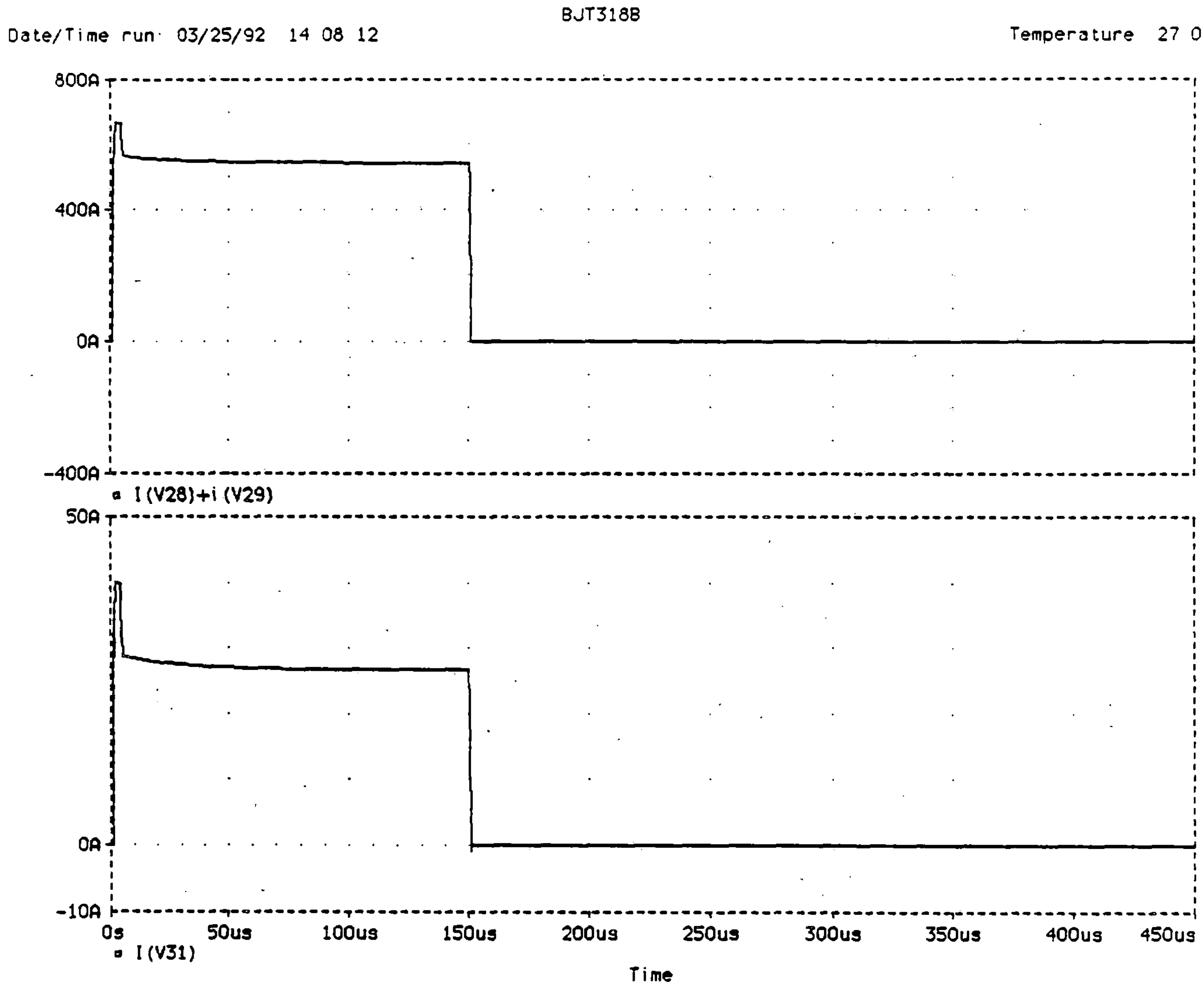


Figure 4-5. Parallel BJT collector current (top) and base current (bottom).

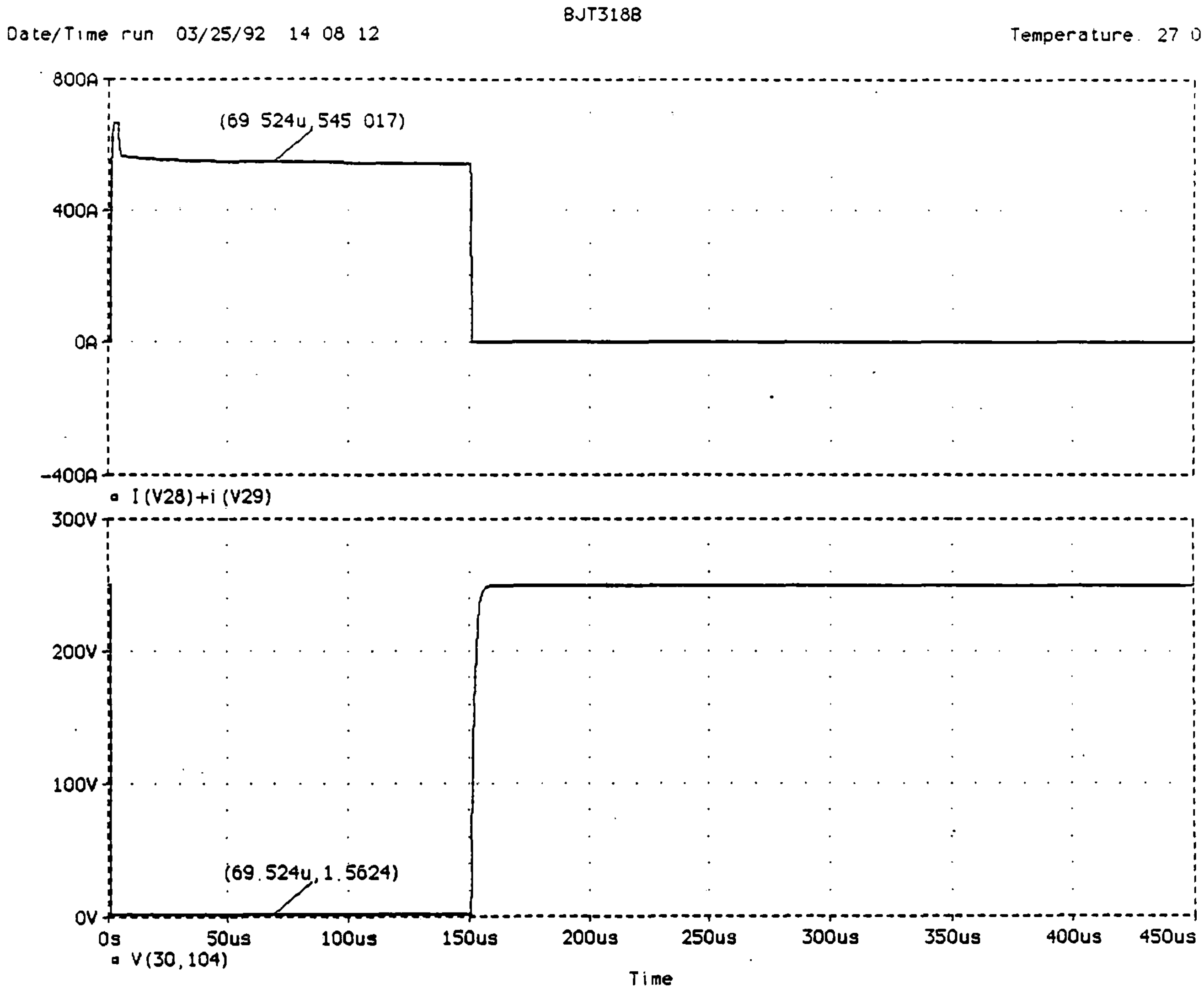


Figure 4-6. Collector current waveform (top) and collector-emitter voltage (bottom) of BJT cell.

Once the cell was working, the simulation was expanded until each power switch consisted of 23 cells in series. The subcircuit BJTSW1 contains the 23 cells. Two of these 23 x 2 power switches were then inserted into a half-bridge arrangement and loaded by an arbitrary induction motor load. Figure 4-7 is the half-bridge schematic as modelled and Figure 4-8 shows some of the pertinent waveforms of the circuit.

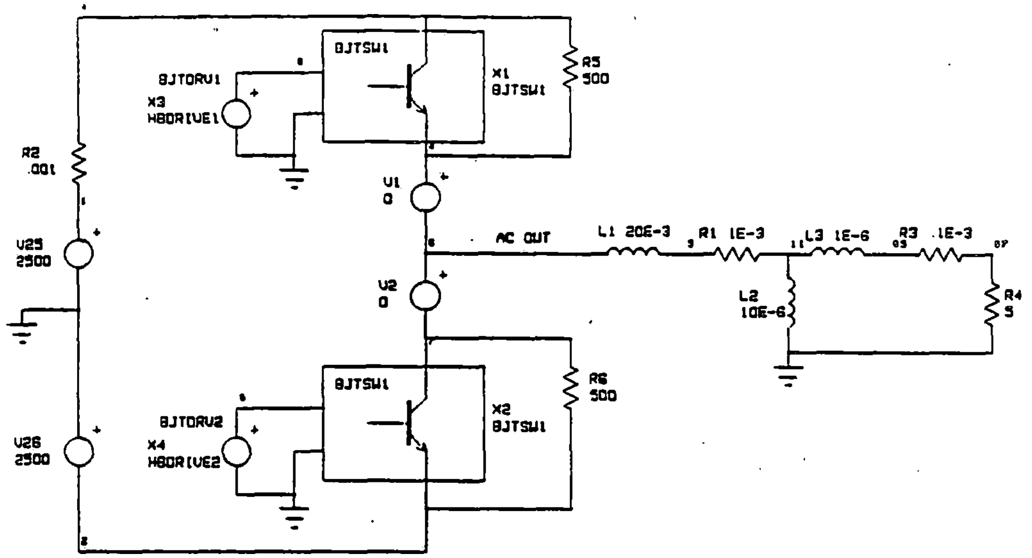


Figure 4-7. Computer model of BJT inverter leg with a motor load.

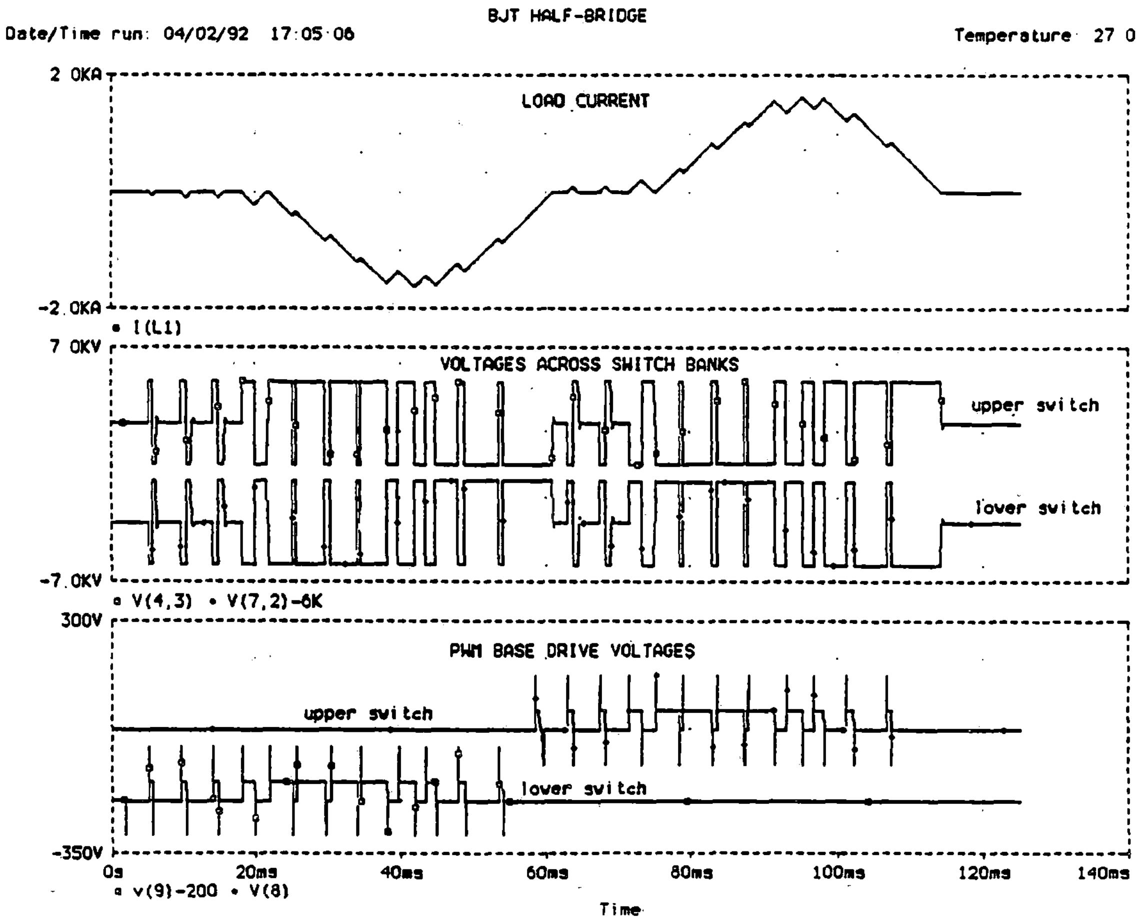


Figure 4-8. PWM voltage (top) and current (bottom) in the BJT half-bridge.

4.1.3 PSpice Inverter Simulation with BJT Switches

The three phase inverter simulation using BJT switches is pictured in Figure 4-9. The derated input voltage for this single device simulation using the Marconi DT600 is the rated input voltage (500 V) x 0.4 or 200 V. From the manufacturer's data sheet, the peak current rating of each device is 1000 A and the continuous current rating is 750 A.

The switching frequency of this simulation is 2.5 kHz, and the PWM control is set for an output ac frequency of 60 Hz. The pulse width modulation method in this computer model was chosen for its coding simplicity although it is recognized that other methods may have more optimal results in a Maglev system. The PWM drive signals are determined by comparison of a triangle wave with a 60 Hz sine wave and then each phase is staggered by 120°.

The line-to-line voltage and load current waveforms are shown in Figure 4-10. Figure 4-11 shows the switch current and switch power waveforms of an upper BJT switch. The waveforms of Figure 4-12 take a closer look within a switch cell to determine the peak collector-emitter voltage and snubber capacitor voltage and current.

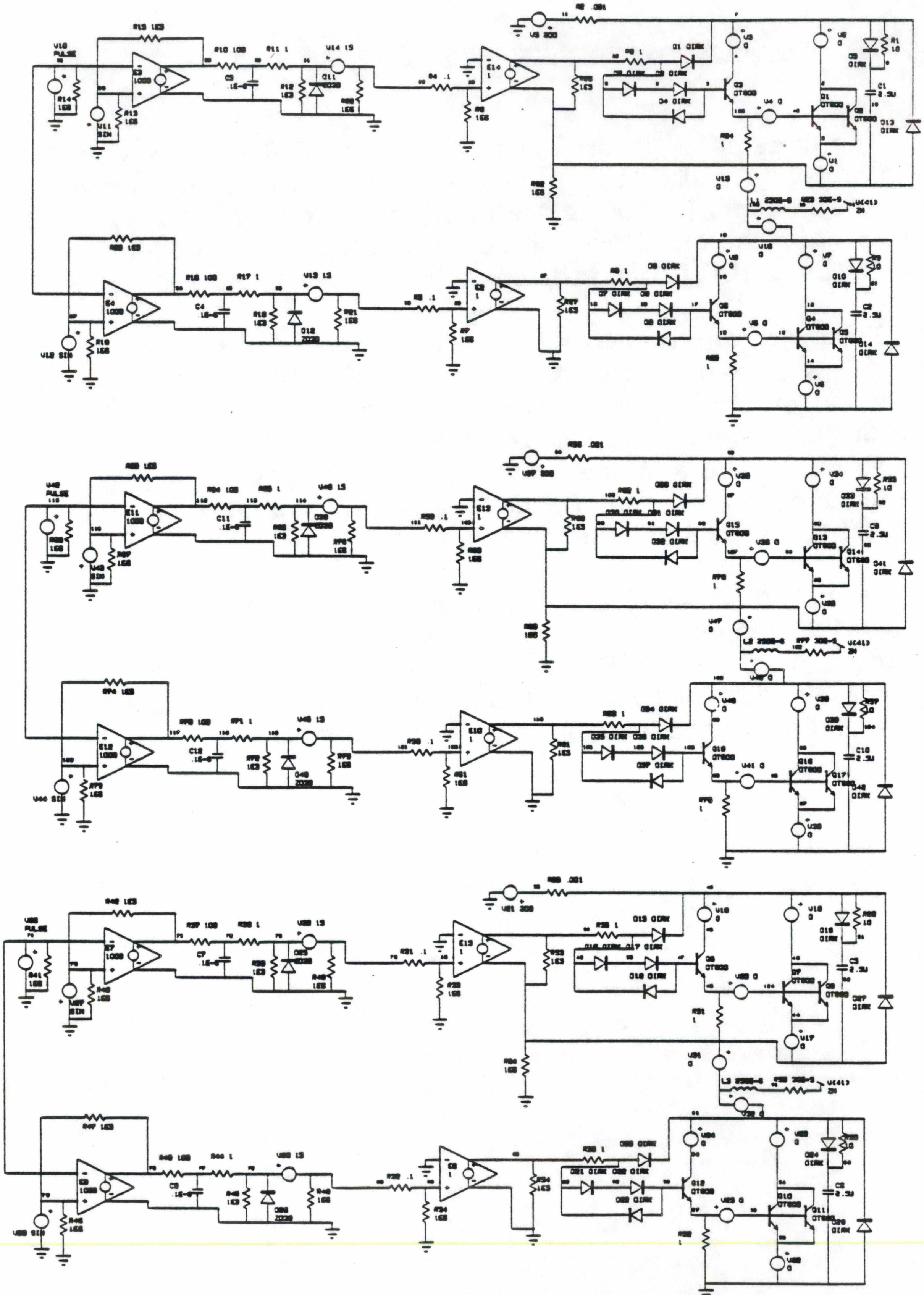


Figure 4-9. Three-phase inverter with BJT switches.

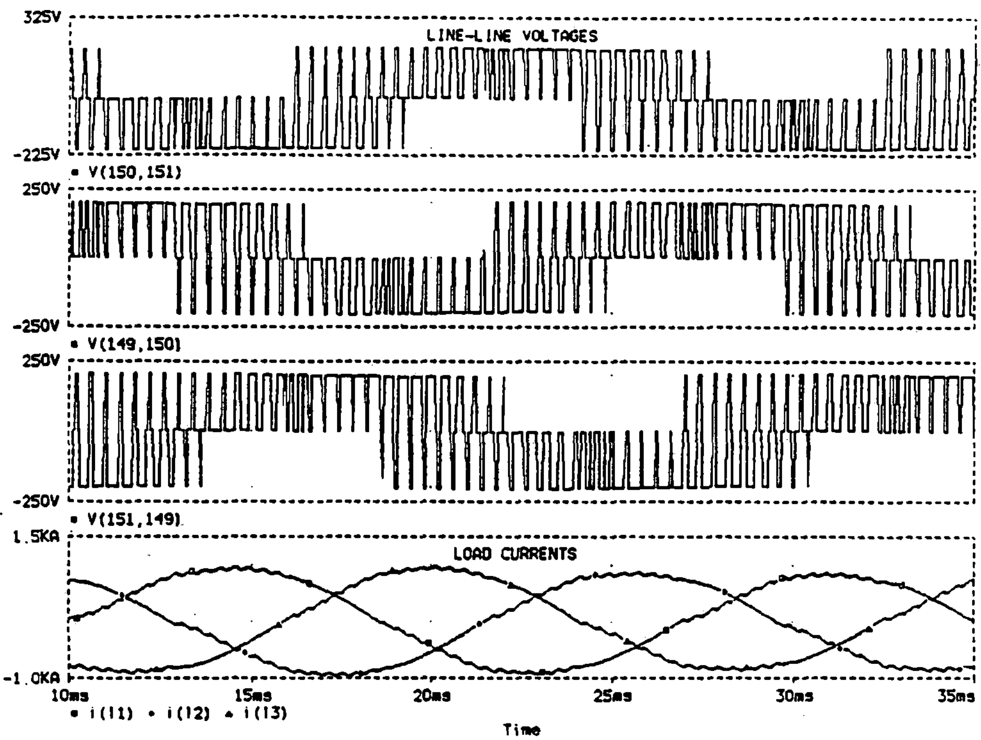


Figure 4-10. Line-line voltages and load currents of BJT inverter.

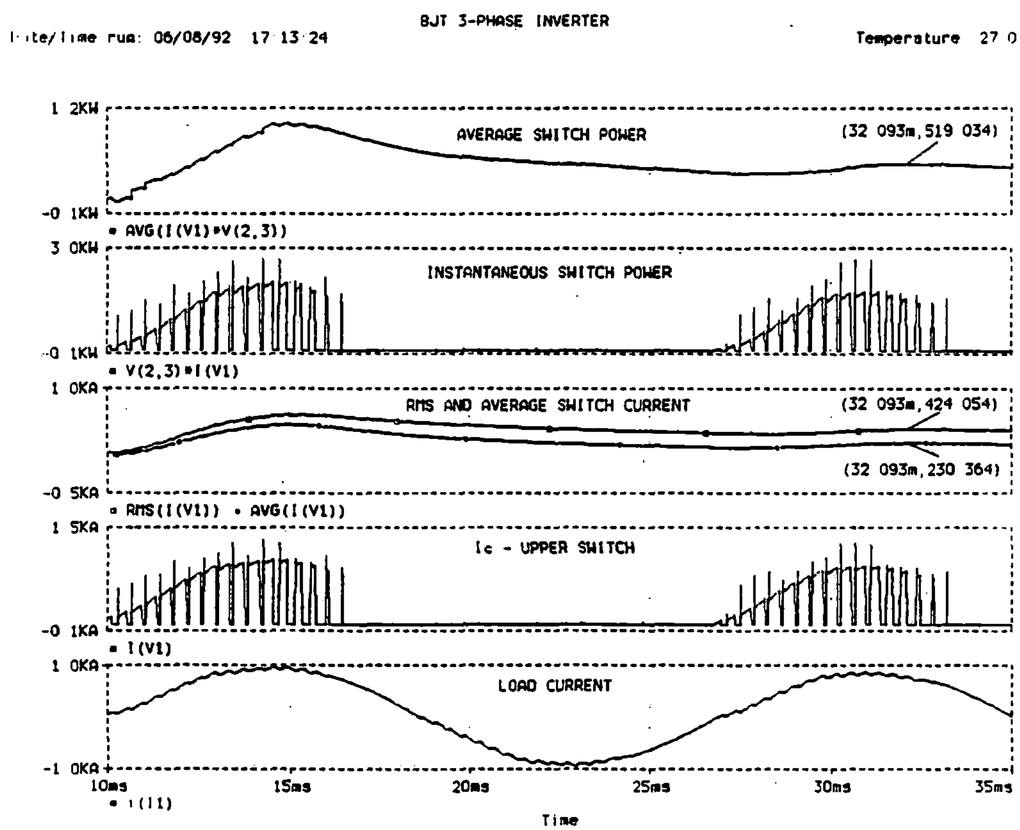


Figure 4-11. BJT switch currents and power.

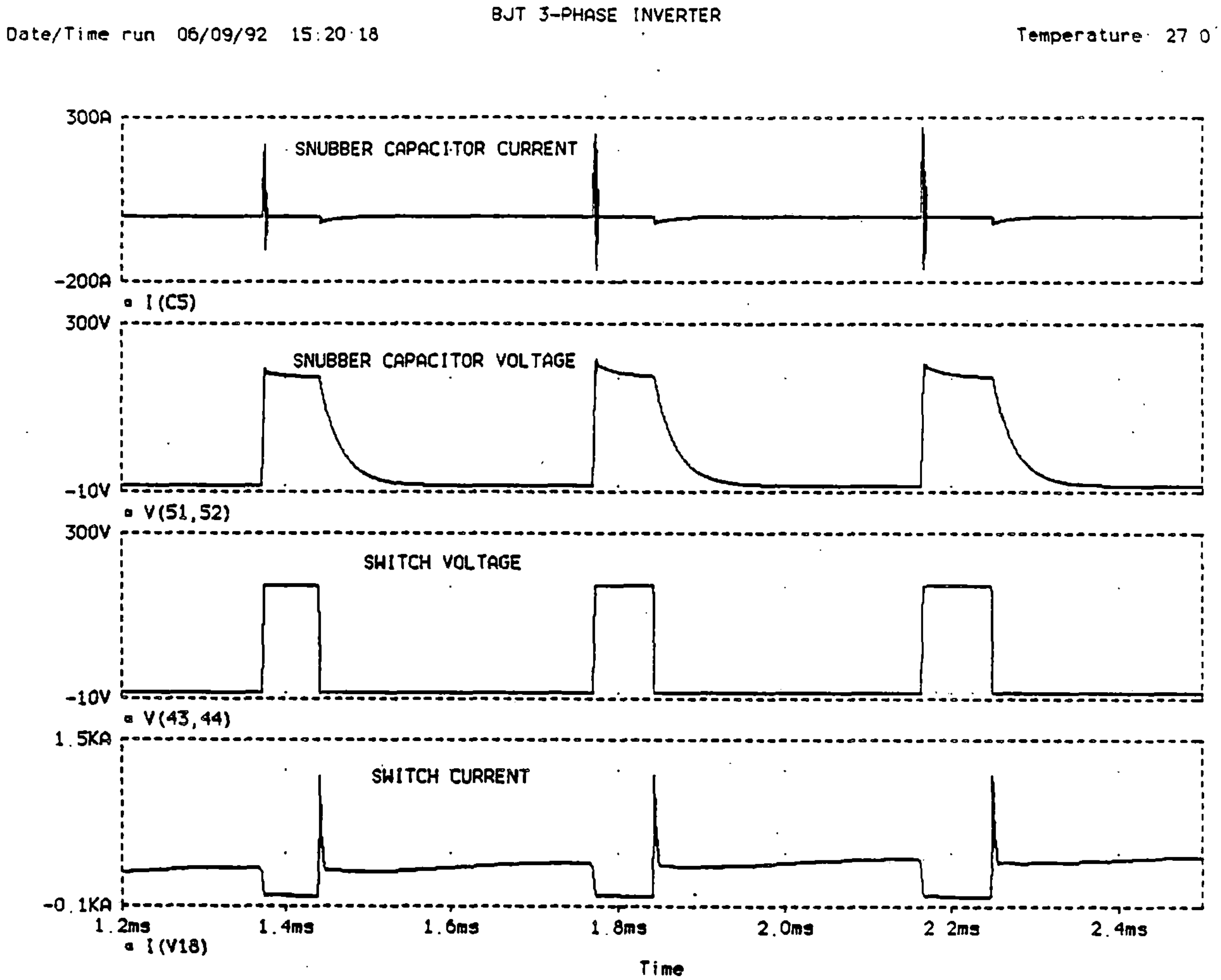


Figure 4-12. Detailed switch waveforms in BJT cell.

4.2 GATE TURN-OFF THYRISTOR (GTO) COMPUTER MODELS

4.2.1 PSpice Semiconductor Model

The computer model of the GTO is given in Figure 4-13 along with a schematic of the detailed model. This particular model is based on the J3 SCR model developed by Avant and Lee [1], with the appropriate changes to the gain of the device to allow gating control.

```
.SUBCKT GTO1 A G C
* 2/21/92
*REVISED J3 THYRISTOR MODEL OF THE
*TOSHIBA SG3000JX24,  ITGQ=3000A, ITRMS=1200A AND VDRM=6000V
.MODEL DA D(IS=1.19E-11,CJO=1E-6,M=0.33,TT=8E-6,BV=16)
.MODEL DC D(IS=1E-5,CJO=1E-6,M=0.33,TT=8E-6,BV=6000)
.MODEL DK D(IS=1.1E-4,CJO=0.5E-6,M=0.33,TT=0.1E-6,BV=18,IBV=1E-3)
.MODEL DA1 D(IS=1.19E-11)
.MODEL DKI D(IS=1.1E-4)
R1 A 3 1.15E-3
RA 3 4 1600
RC 4 G 25E3
RK G C 1600
DA 3 4 DA
DC G 4 DC
DK G C DK
VK 13 C 0
EA 12 C 3 4 1.0
FC 4 G POLY(2) VA VK 0. 1.0 1.0
DA1 12 6 DA1 0.2
VA 6 C 0
DKI 8 13 DKI 0.95
EK 8 C G C 1.0
.ENDS
```

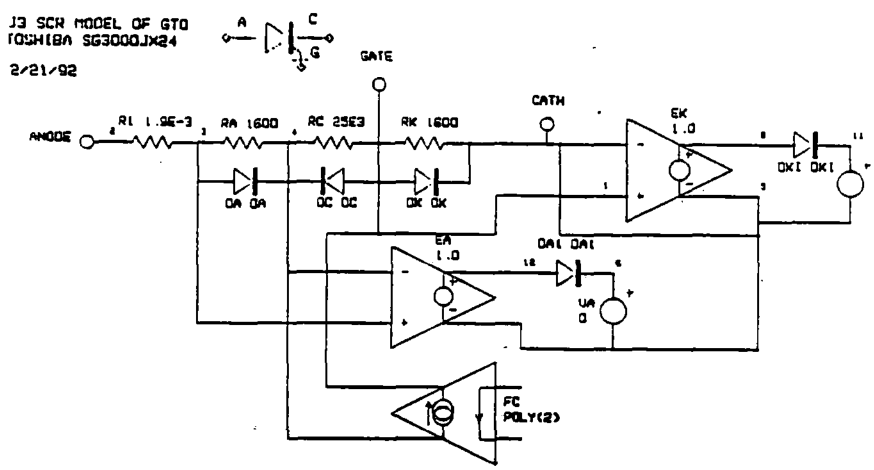


Figure 4-13. PSpice model and schematic of a GTO thyristor.

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1 Roger L. Avant and Fred C. Lee, "A Unified SCR Model for Continuous Topology CADA," *IEEE Transactions on Industrial Electronics*, Vol. IE-31, No. 4, November 1984.

4.2.2 PSpice Circuit Simulation with GTO Thyristor Switches

Just as was done with the bipolar transistor simulation, first the GTO device model was placed into a simple circuit to verify proper operation. Figure 4-14 shows this simple circuit and the resulting waveforms.

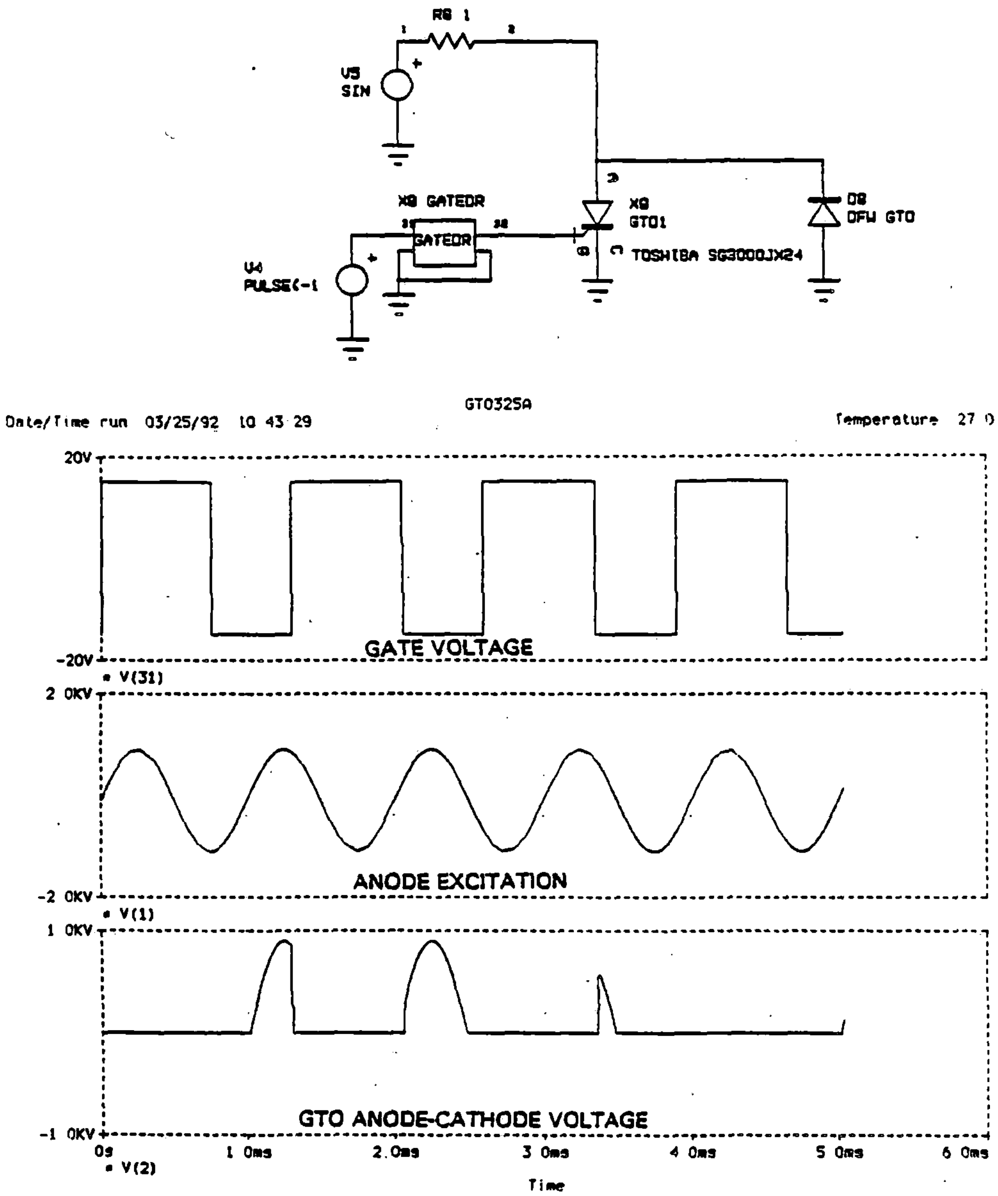


Figure 4-14. GTO test circuit and waveforms.

The inverter circuit to be modelled is shown in Figure 4-15. This circuit includes turn-on and turn-off snubbers for each device. In order to verify the operation of a switch in one leg, the circuit shown in

Figure 4-16 is simulated. This circuit also includes the pulse width modulation driver models. The circuit simulation waveforms are shown in Figure 4-17. Notice that this model includes estimated lead inductances in order to fully check the operation of the GTO cell.

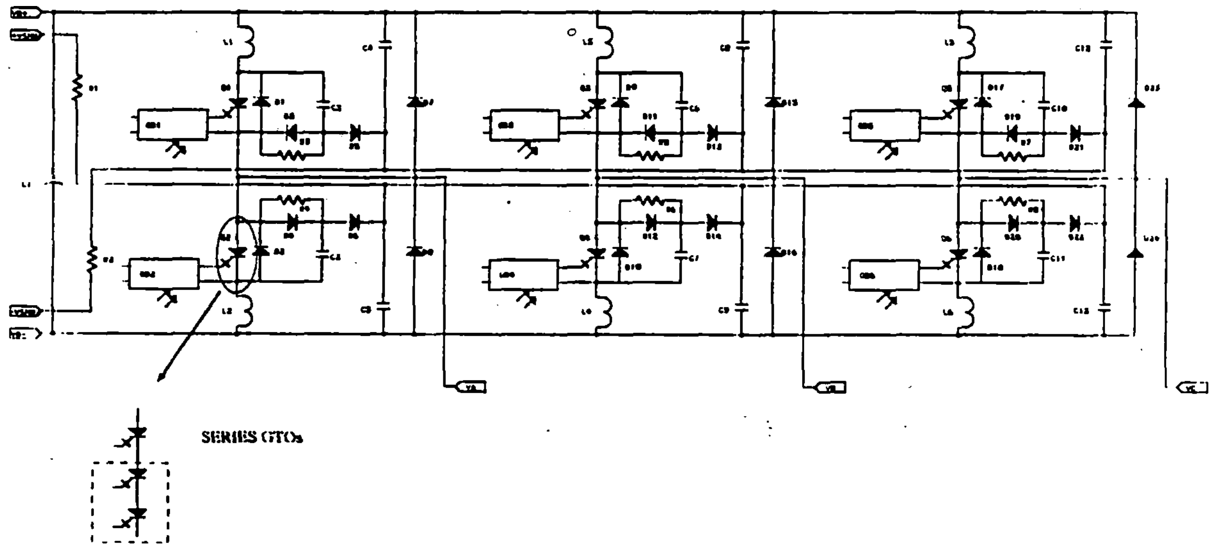


Figure 4-15. GTO-based, three phase motor drive inverter.

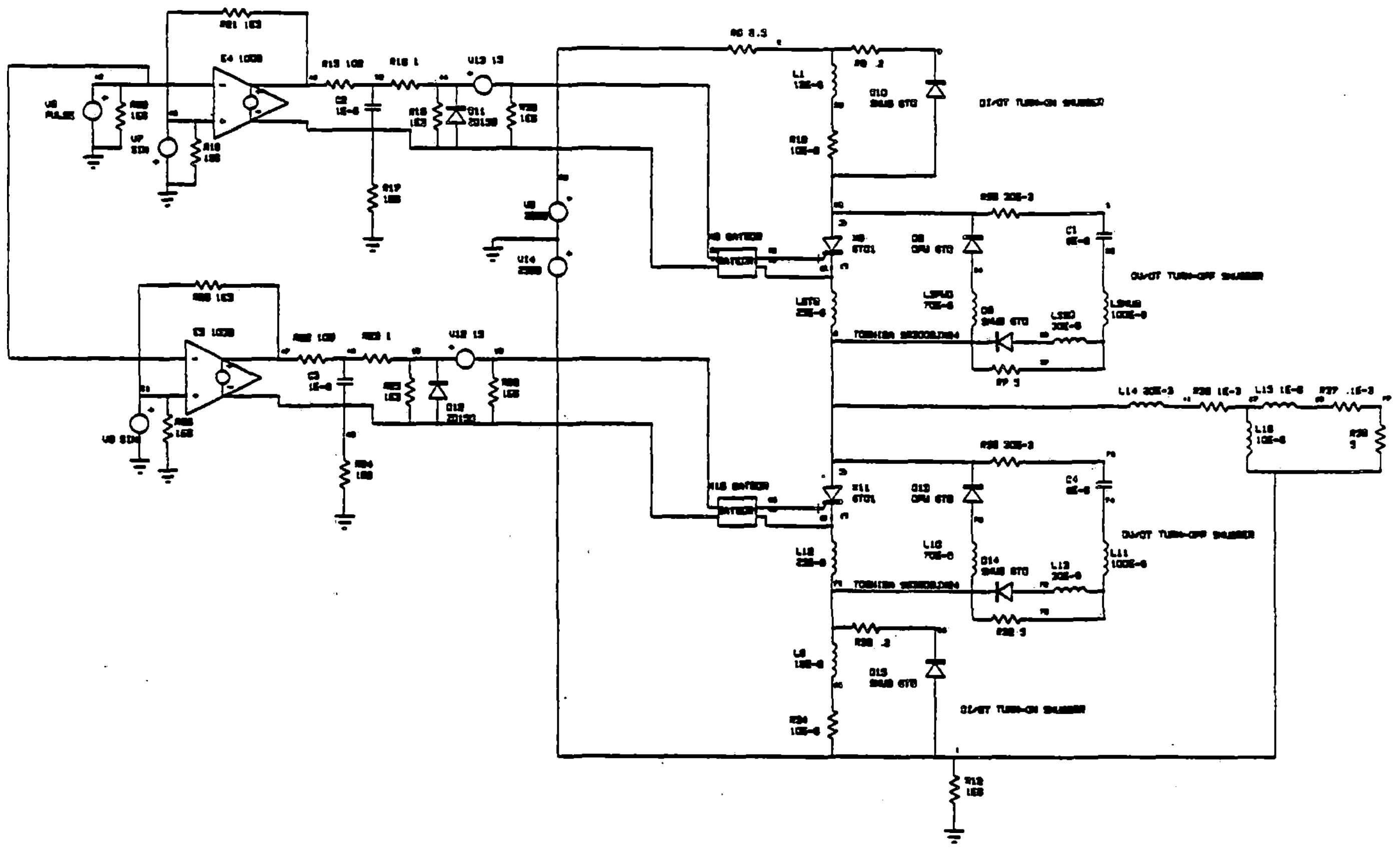


Figure 4-16. GTO inverter leg computer model.

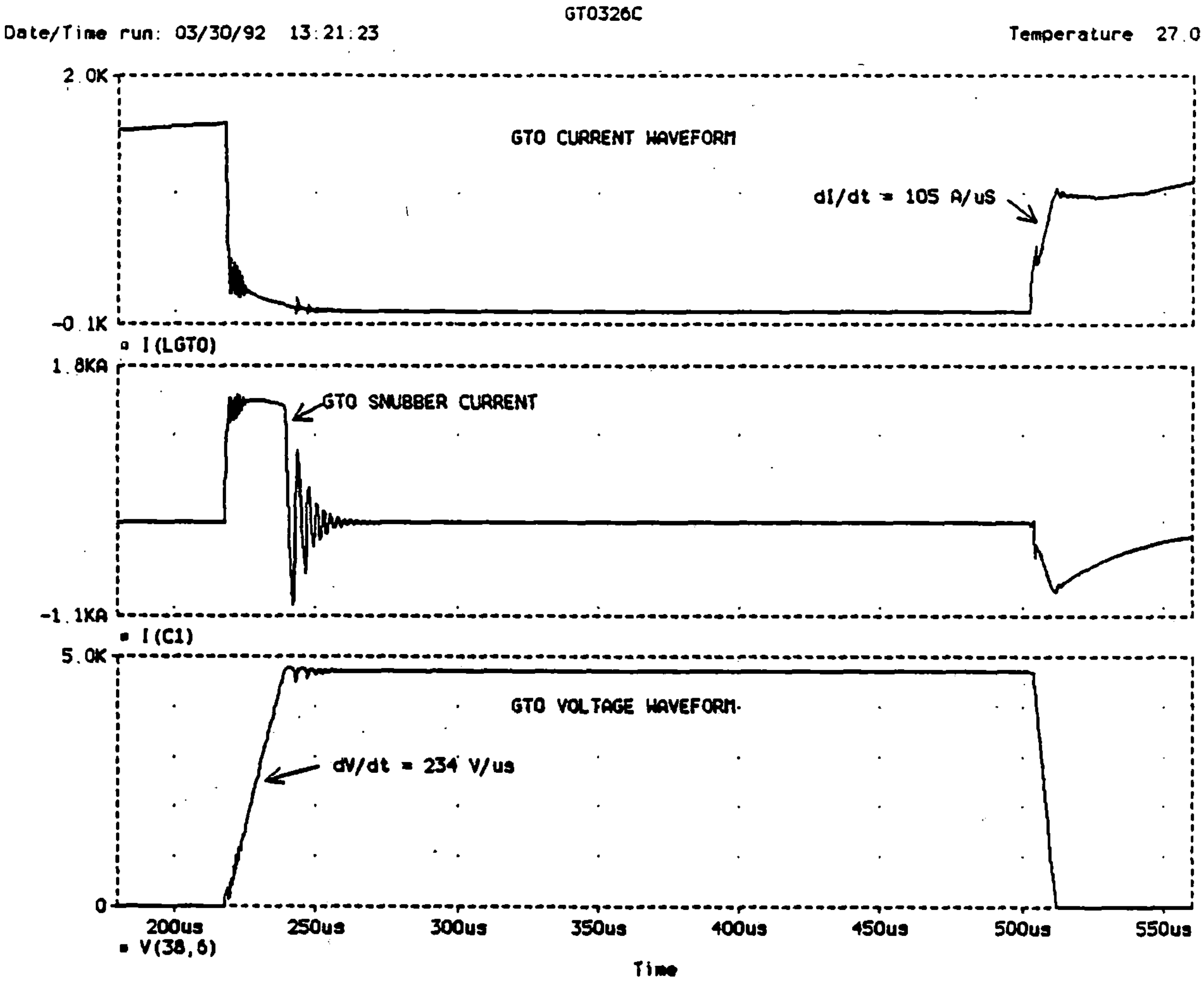


Figure 4-17. Simulated GTO switching waveforms.

4.2.3 PSpice Inverter Simulation with GTO Thyristor Switches

The three phase inverter model using GTO switches is shown in Figure 4-18. The derated input voltage for this single device simulation using the Toshiba SG3000JX24 GTO is the rated input voltage (6000 V) x 0.4 or 2400 V. According to the manufacturer's specifications, the peak turn-off current rating of the device, I_{TGQ}, is 3000 A and the rms on-state current rating is 1200 A. The method of pulse width modulation is the same as for the inverters previously described except the PWM switching frequency has been decreased to 1.25 kHz. This switching frequency is probably the upper end of the useable range because at higher frequencies the GTO switching losses for a single device are greater and the operating current must be dropped to maintain the junction temperature within safe limits.

The line-to-line voltage and load current waveforms are shown in Figure 4-19, and Figure 4-20 shows the voltage and current waveforms of an upper and lower GTO switch. The waveforms of Figure 4-21 take a closer look within a switch cell to determine the peak anode-cathode voltage and peak snubber capacitor voltage as well as the peak currents.

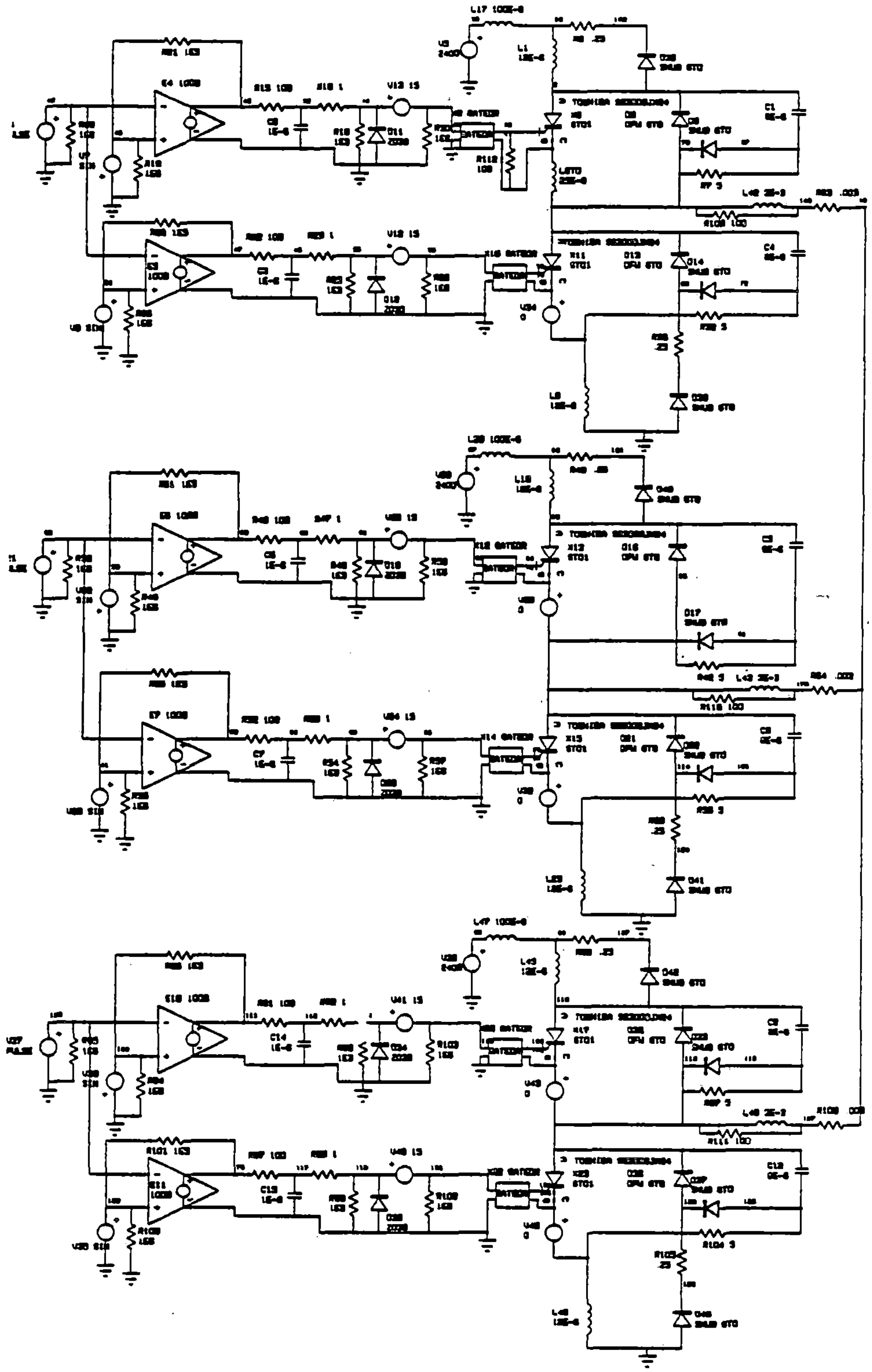


Figure 4-18. Three-phase inverter with GTO switches.

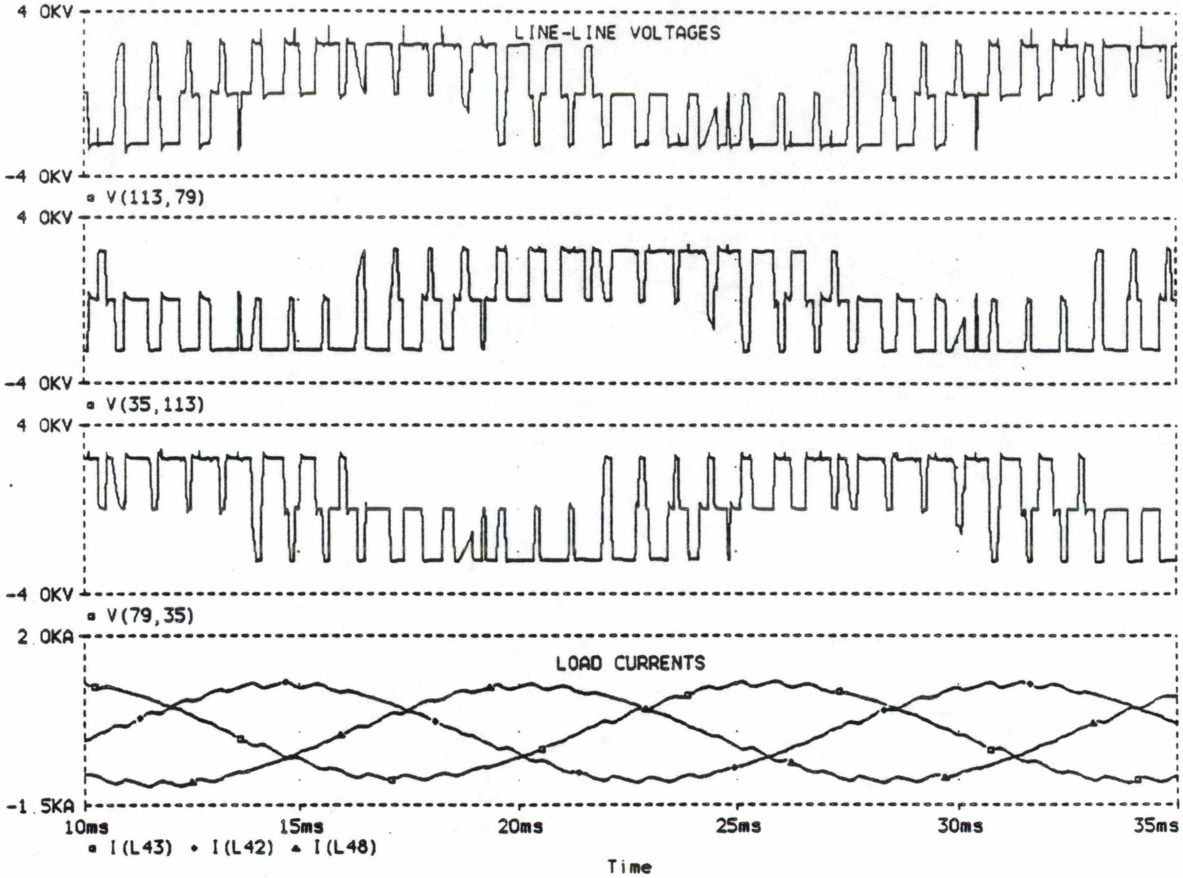


Figure 4-19. Line-line voltages and load currents of GTO inverter.

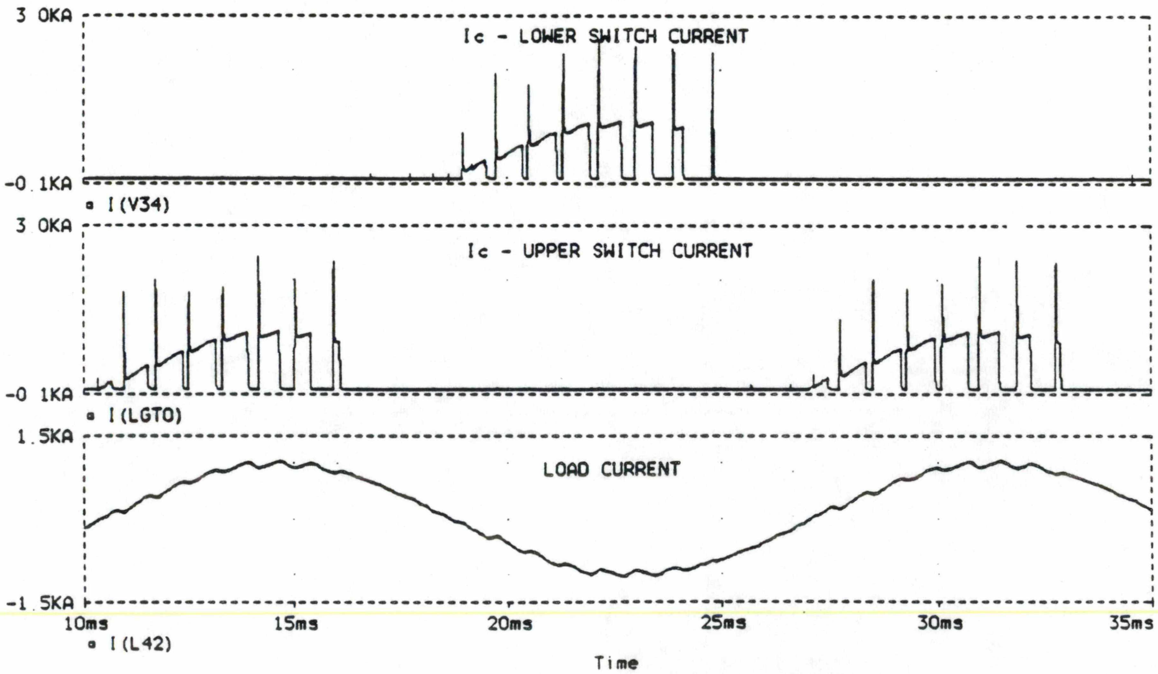


Figure 4-20. GTO switch currents.

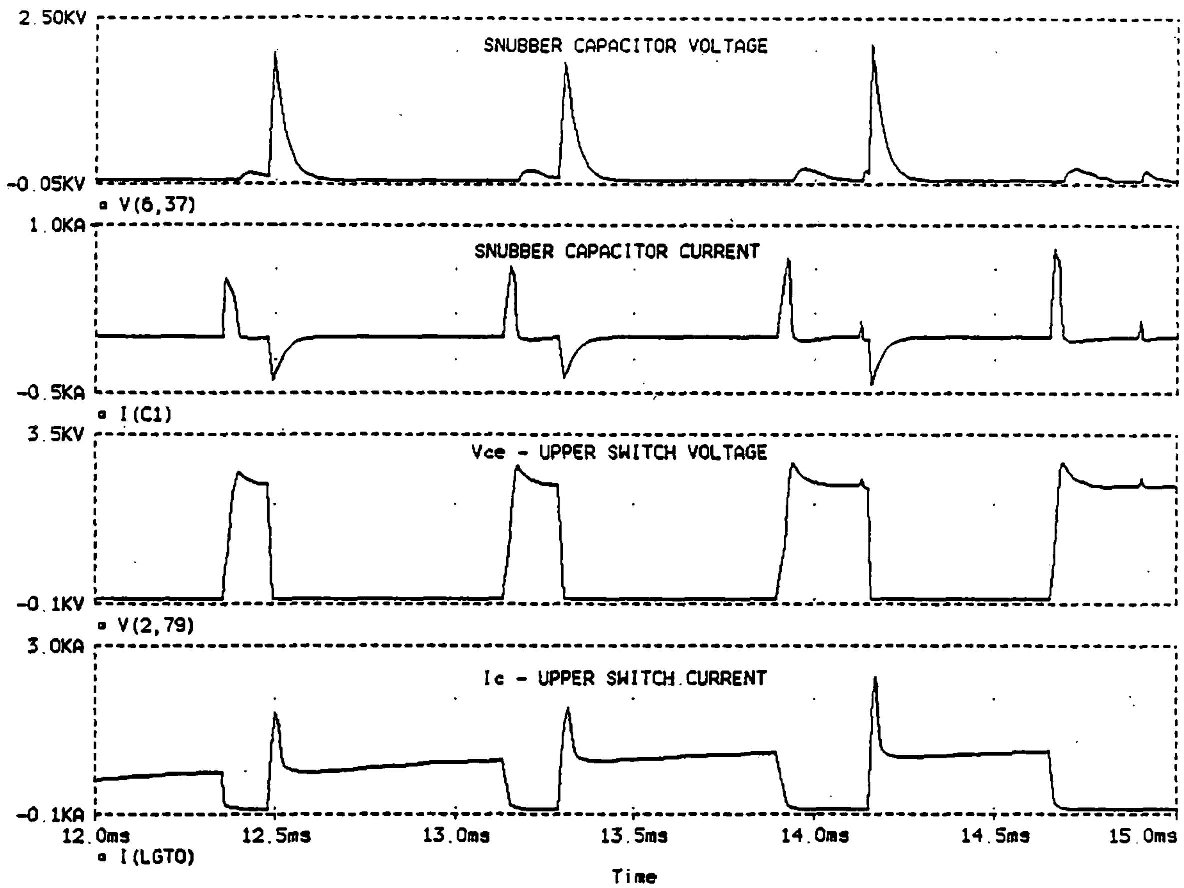


Figure 4-21. Detailed switch waveforms in GTO cell.

4.3 INSULATED GATE BIPOLAR TRANSISTOR (IGBT) COMPUTER MODELS

4.3.1 PSpice Semiconductor Model

The PSpice computer model of the third power semiconductor device type, an IGBT, was refined and tested. The simulated device was the Advanced Power Technology APT200G100BFN. Figure 4-22 is the subcircuit computer code developed to simulate the APT device.

```
.SUBCKT IGBT1 C G E
*
* THIS IS THE BIPOLAR TRANSISTOR OUTPUT SECTION
* OF THE IGBT:
*
* IGBT_PNP model created using Parts version 5.1
*        on 04/23/92 at 13:11
*
.MODEL IGBT_PNP PNP(Is=921.9n Xti=3 Eg=1.11 Vaf=100
+        Bf=1.092 Ise=2.777m Ne=1.821 Ikf=.804
+        Nk=.5062 Xtb=1.5 Br=2 Isc=9.219u Nc=1.5
+        Ikr=1 Rc=10m Cjc=3.208p Mjc=.3333 Vjc=.75
+        Fc=.5 Cje=1.326p Mje=.3333 Vje=.75 Tr=10n
+        Tf=8.011u Itf=4.134 Xtf=1m Vtf=10)
*
* THIS IS THE MOSFET INPUT STRUCTURE OF THE IGBT:
*
* IGBT_APT model created using Parts version 5.1
*        on 04/23/92 at 15:16
*
.MODEL IGBT_APT NMOS(Level=3 Gamma=0 Delta=0 Eta=0
+        Theta=0 Kappa=0 Vmax=0 Xj=0 Tox=100n Uo=600
+        Phi=.6 Kp=20.76u W=1.4 L=2u Rs=86.27u
+        Vto=3.626 Rd=9m Rds=5K Cbd=8.589n Pb=.8
+        Mj=.5 Fc=.5 Cgso=4n Cgdo=1n Rg=0 Is=10f
+        N=1 Rb=1m)
*
C1 1 E 1E-12
R1 C 1 .1
M1 1 G E E IGBT_APT
Q1 E 1 C IGBT_PNP
.ENDS
```

Figure 4-22. PSpice Model of the Advanced Power Technology Insulated Gate Bipolar Transistor, the APT200G100BFN.

The device model for an IGBT is a MOSFET device driving a PNP output transistor. The test circuit for this IGBT is shown in Figure 4-23. The parameters of these two transistors required careful manipulation in order to keep a parasitic SCR (made up of the BJT and the MOSFET source) from latching up.

4.3 INSULATED GATE BIPOLAR TRANSISTOR (IGBT) COMPUTER MODELS

4.3.1 PSpice Semiconductor Model

The PSpice computer model of the third power semiconductor device type, an IGBT, was refined and tested. The simulated device was the Advanced Power Technology APT200G100BFN. Figure 4-22 is the subcircuit computer code developed to simulate the APT device.

```
.SUBCKT IGBT1 C G E
*
* THIS IS THE BIPOLAR TRANSISTOR OUTPUT SECTION
* OF THE IGBT:
*
* IGBT_PNP model created using Parts version 5.1
*         on 04/23/92 at 13:11
*
.MODEL IGBT_PNP PNP(Is=921.9n Xti=3 Eg=1.11 Vaf=100
+         Bf=1.092 Ise=2.777m Ne=1.821 Ikf=.804
+         Nk=.5062 Xtb=1.5 Br=2 Isc=9.219u Nc=1.5
+         Ikr=1 Rc=10m Cjc=3.208p Mjc=.3333 Vjc=.75
+         Fc=.5 Cje=1.326p Mje=.3333 Vje=.75 Tr=10n
+         Tf=8.011u Itf=4.134 Xtf=1m Vtf=10)
*
* THIS IS THE MOSFET INPUT STRUCTURE OF THE IGBT:
*
* IGBT_APT model created using Parts version 5.1
*         on 04/23/92 at 15:16
*
.MODEL IGBT_APT NMOS(Level=3 Gamma=0 Delta=0 Eta=0
+         Theta=0 Kappa=0 Vmax=0 Xj=0 Tox=100n Uo=600
+         Phi=.6 Kp=20.76u W=1.4 L=2u Rs=86.27u
+         Vto=3.626 Rd=9m Rds=5K Cbd=8.589n Pb=.8
+         Mj=.5 Fc=.5 Cgso=4n Cgdo=1n Rg=0 Is=10f
+         N=1 Rb=1m)
*
C1 1 E 1E-12
R1 C 1 .1
M1 1 G E E IGBT_APT
Q1 E 1 C IGBT_PNP
.ENDS
```

Figure 4-22. PSpice Model of the Advanced Power Technology Insulated Gate Bipolar Transistor, the APT200G100BFN.

The device model for an IGBT is a MOSFET device driving a PNP output transistor. The test circuit for this IGBT is shown in Figure 4-23. The parameters of these two transistors required careful manipulation in order to keep a parasitic SCR (made up of the BJT and the MOSFET source) from latching up.

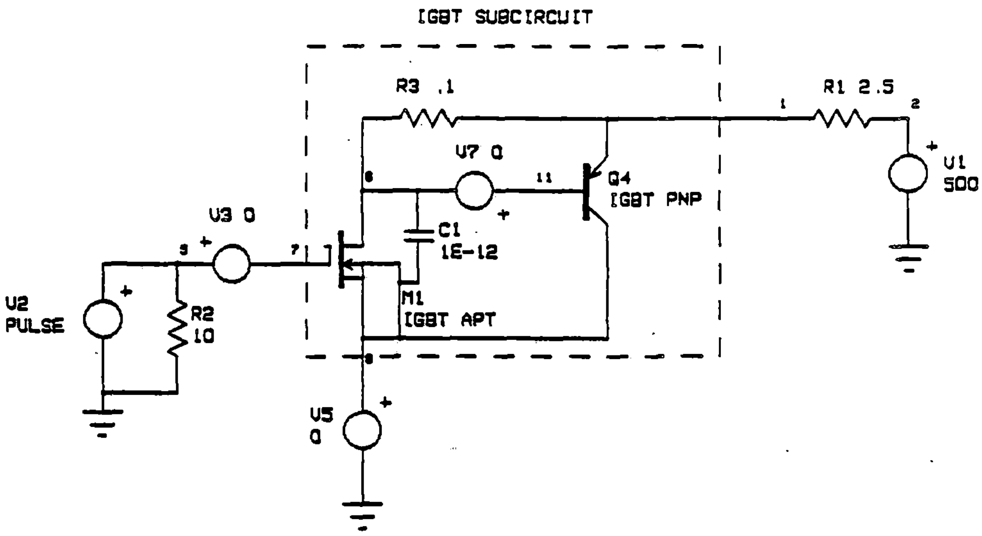


Figure 4-23. IGBT model test circuit.

Figure 4-24 shows a plot of collector current and the collector-to-emitter voltage which closely resemble the data sheet specifications. Notice that $V_{CE}(sat) = 3.4$ V at 198 A whereas the data sheet specifies $V_{CE}(sat)$ as 4.0 V maximum and 3.2 V typical at that current. Also, the IGBT has a tail current during turn-off which this model estimates to be 5-7 μs in duration. We think this value is a good approximation of what the device will exhibit based on test data supplied by the manufacturer. The transconductance of the IGBT subcircuit is shown in Figure 4-25. The data sheet specifies a g_{fe} of 25 S (℧) minimum and 45 S typical, whereas Figure 4-25 shows a value of approximately 31 S.

4.3.2 PSpice Circuit Simulation with IGBT Switches

A computer model of a half bridge circuit using two IGBT switch cells is developed. Figure 4-26 is the half-bridge schematic as modelled and Figure 4-27 shows some of the pertinent waveforms of the circuit. The devices D3, R24, C3 and R25 comprise a snubber to provide static and dynamic voltage equalization when the IGBTs are stacked in series. The values of R24 and C3 were determined by the expected variance in turn-off time between IGBTs to provide dynamic voltage equalization. The value of R25 was determined by the expected variance in IGBT leakage current to provide static voltage equalization.

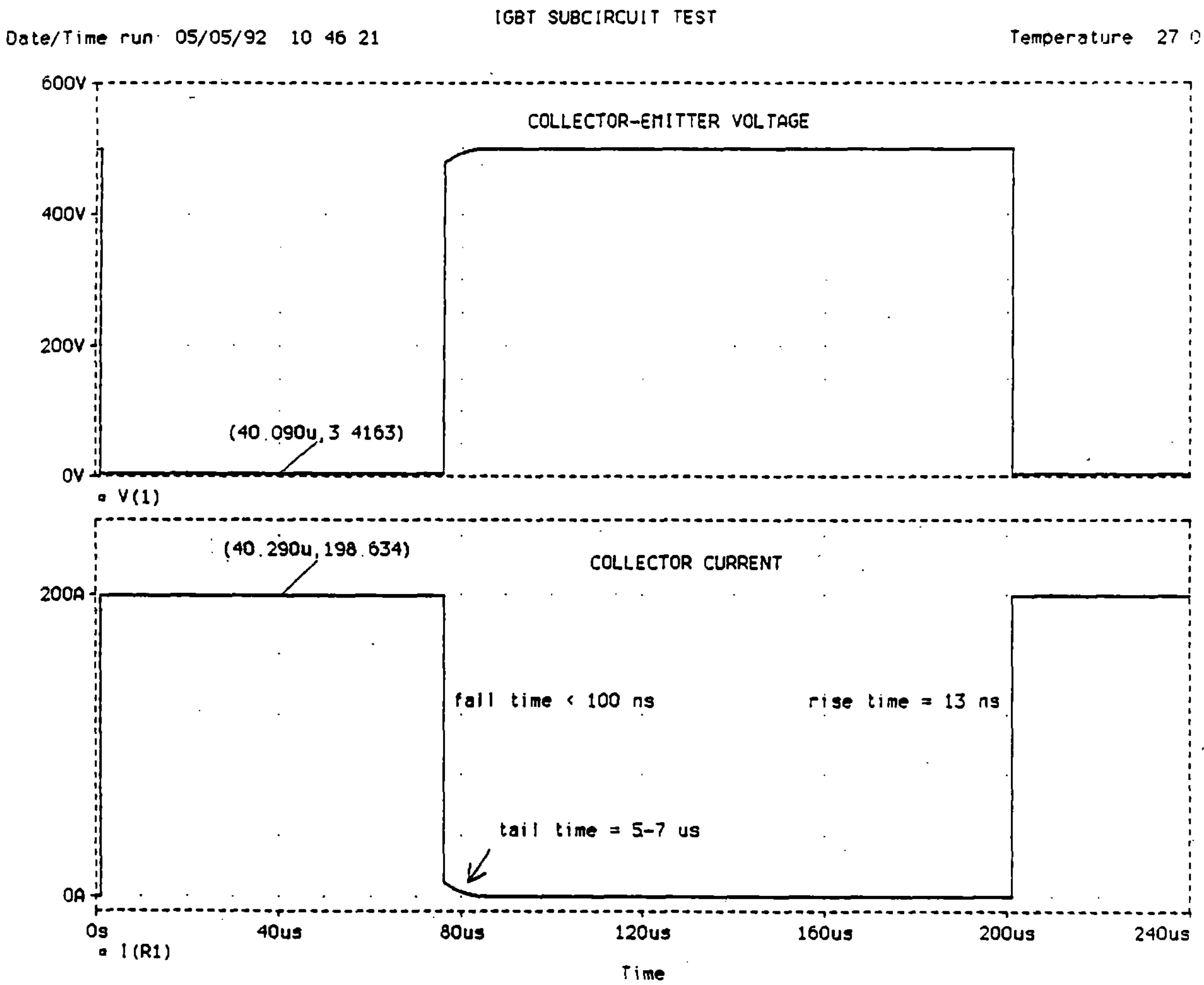


Figure 4-24. V_{CE} and I_C of the IGBT subcircuit.

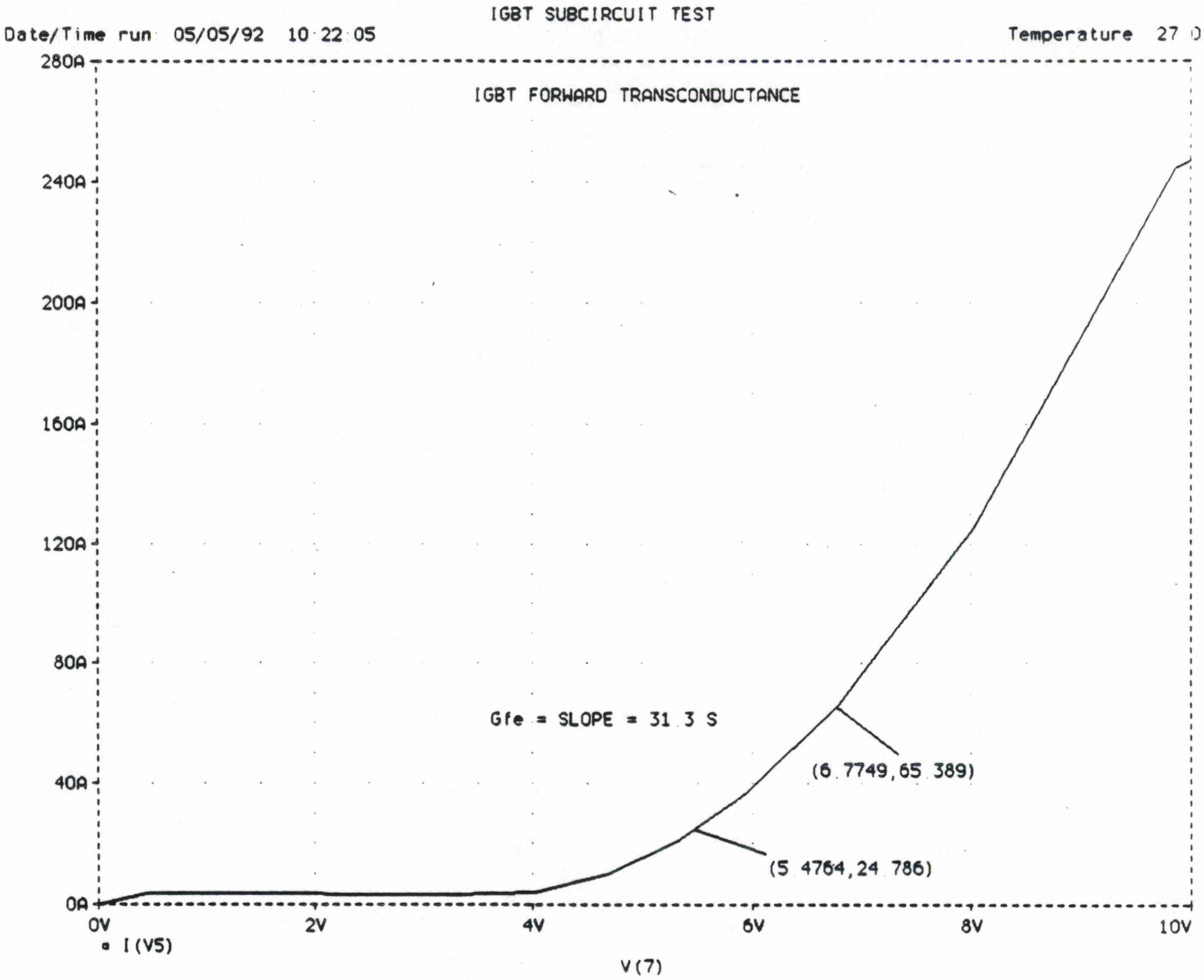


Figure 4-25. Forward transconductance of the IGBT subcircuit.

Notice that inductors have been added to the connection between switches to simulate the anticipated interconnect inductances that will exist in a typical application. Without some series inductance the model

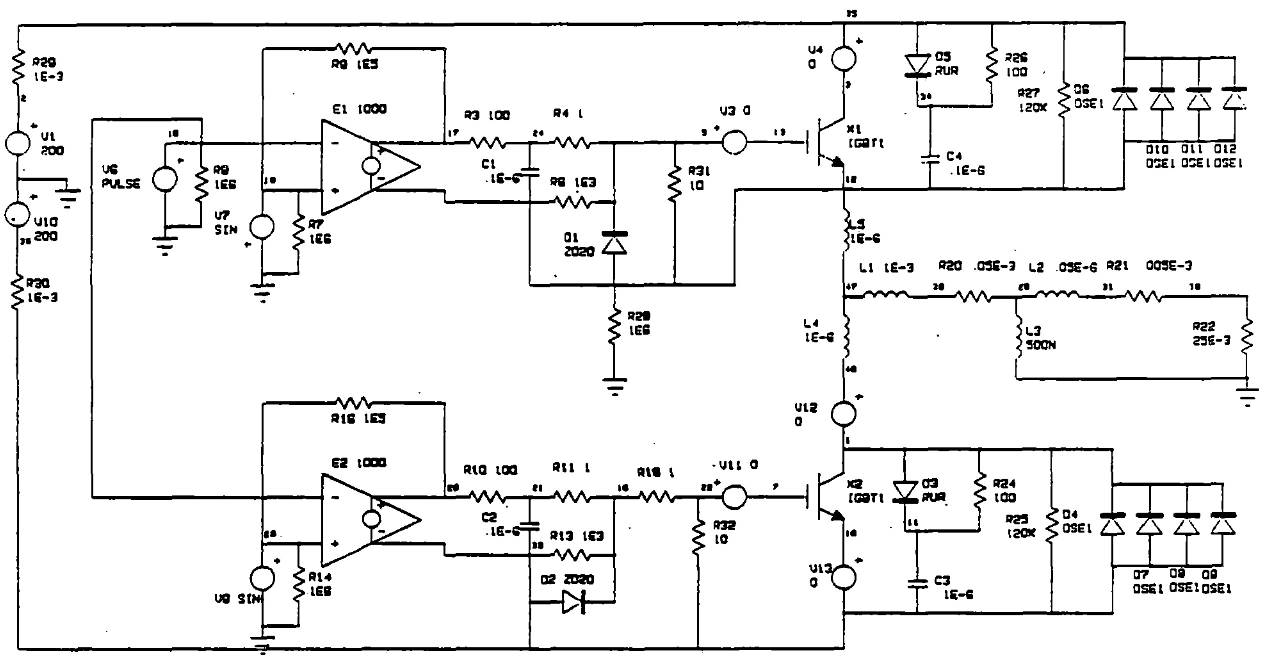


Figure 4-26. I3BT half-bridge model schematic.

correctly predicts a large current spike (~ 200 A) each time a switch turns on. The source of this spike is the charging current of the snubber capacitor in the opposite switch cell. This is because that cell was the freewheeling path for the current but when the other switch turns on, voltage begins to reverse across the freewheeling diode and the snubber capacitor charges. Without the inductor, the snubber capacitor current is limited only by the rate of rise of voltage. Other stray and interconnect impedances will be present in an actual circuit but they are best addressed once a layout is determined.

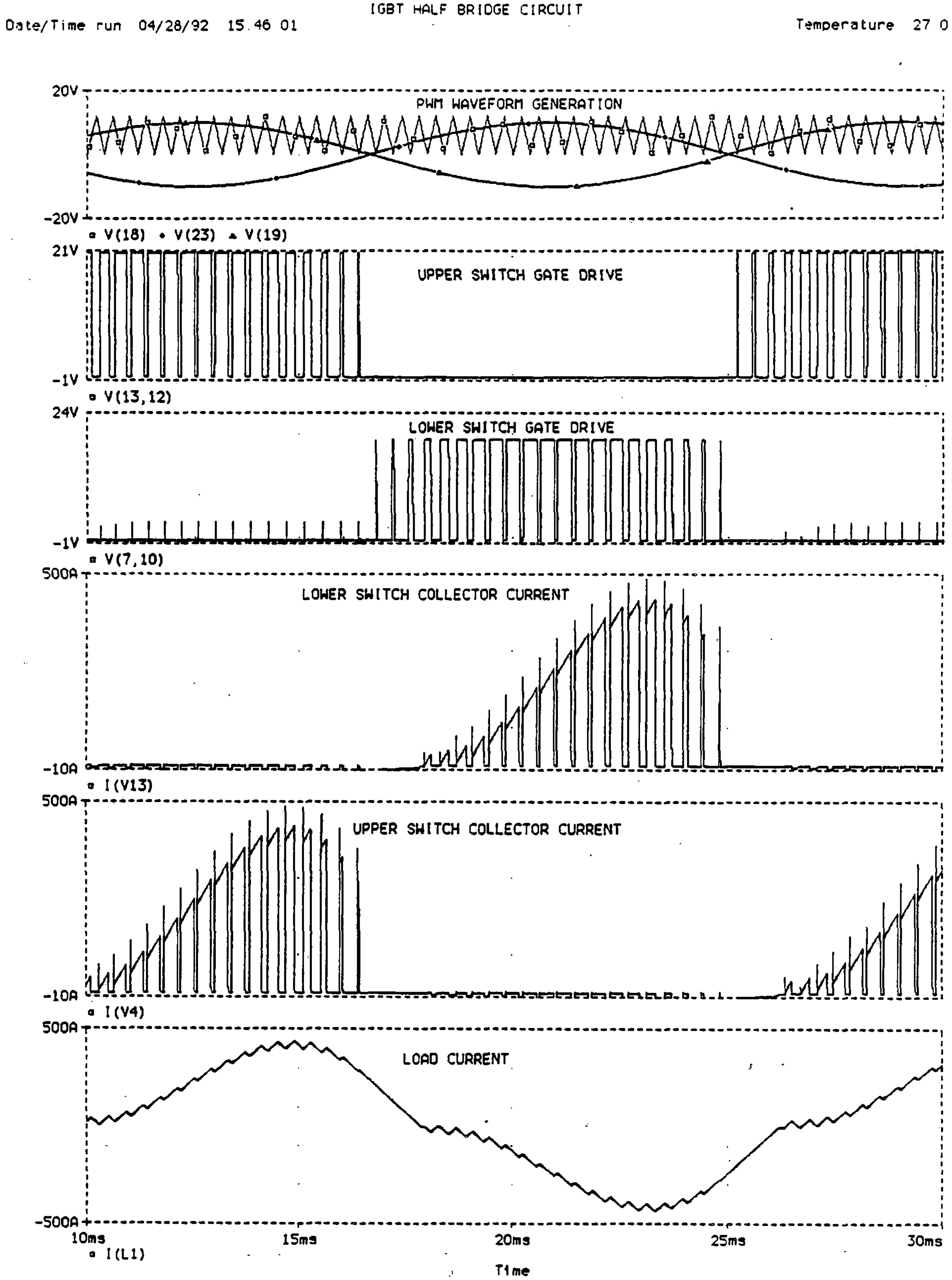


Figure 4-27. IGBT half-bridge model waveforms

4.3.3 PSpice Inverter Simulation with IGBT Switches

The three phase inverter simulation using IGBT switches is pictured in Figure 4-28. The derated input voltage for this single device simulation using the APT IGBT is the rated input voltage (1000 V) x 0.4 or 400 V. The peak current rating of the device is 400 A and the arbitrary load was adjusted accordingly. The pulse width modulation method for this model is again the classic method although it is recognized that other methods may have more optimal results in a Maglev system. The PWM drive signals are determined by comparison of a triangle wave with a 60 Hz sine wave and then each phase was staggered by 120°. The line-to-line voltage and load current waveforms are shown in Figure 4-29, and Figure 4-30 shows the voltage and current waveforms of an upper and lower IGBT switch. The waveforms of Figure 4-31 take a closer look within a switch cell to determine the peak collector-emitter voltage and peak snubber capacitor voltage as well as the peak currents.

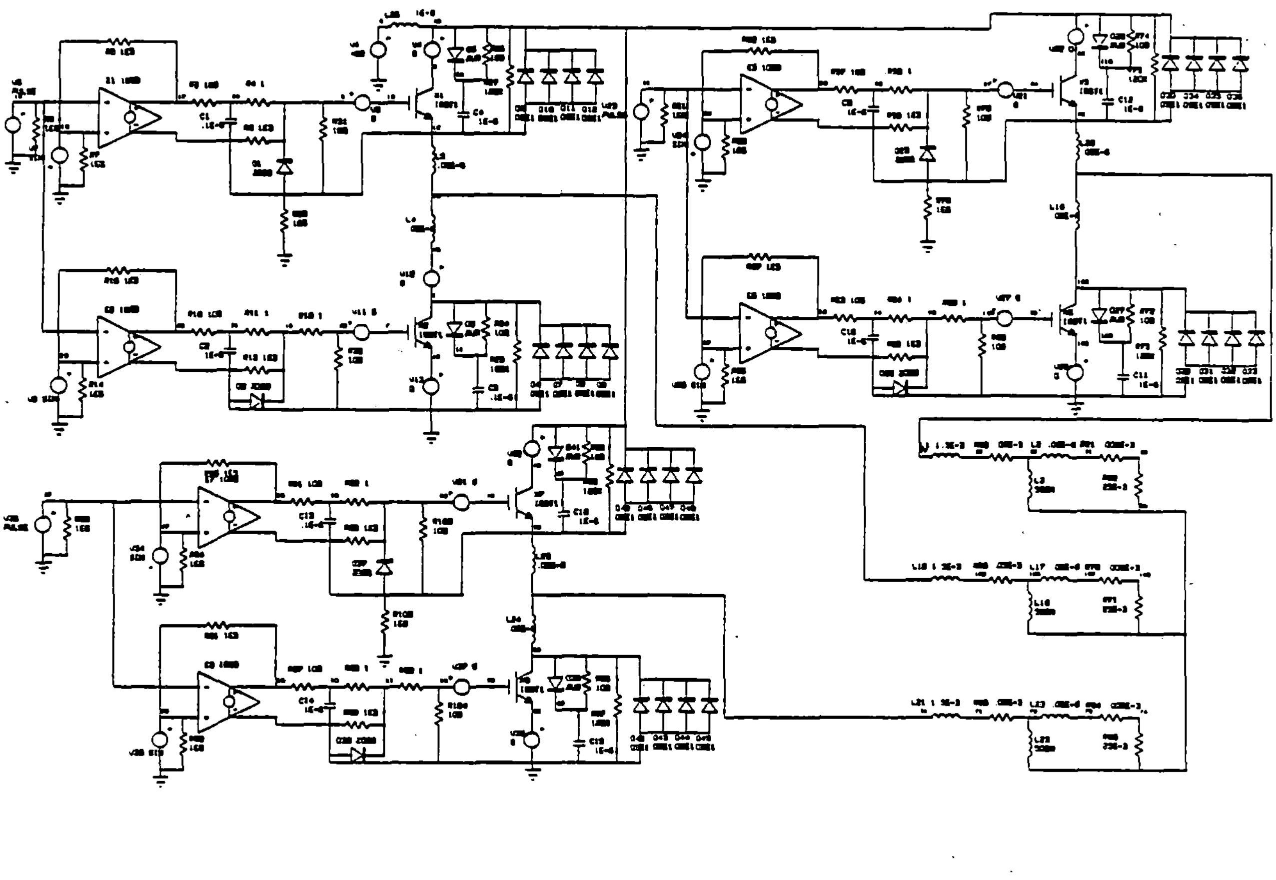


Figure 4-28. IGBT 3-phase inverter model schematic.

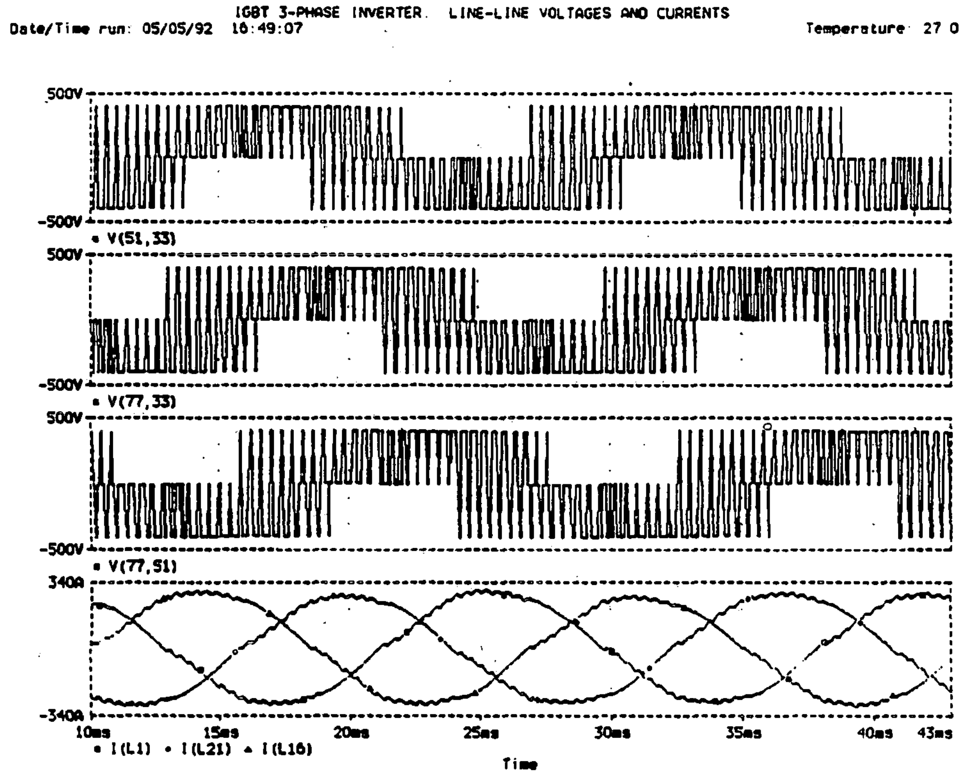


Figure 4-29. IGBT inverter line-line voltage and load current waveforms.

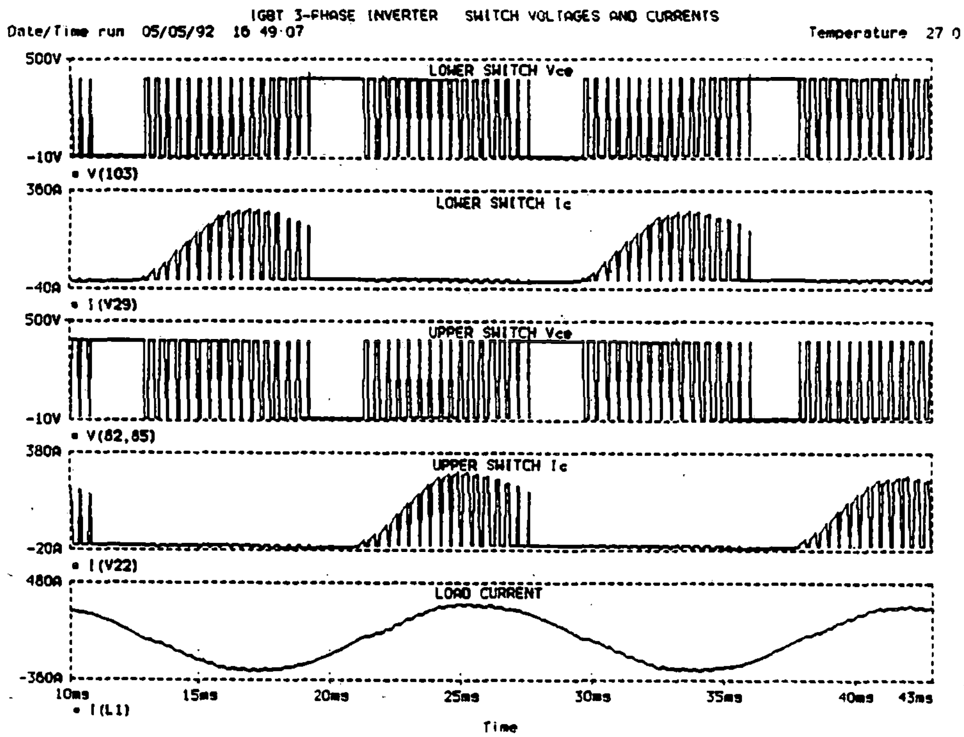


Figure 4-30. Switch voltages and currents in 3-phase IGBT inverter.

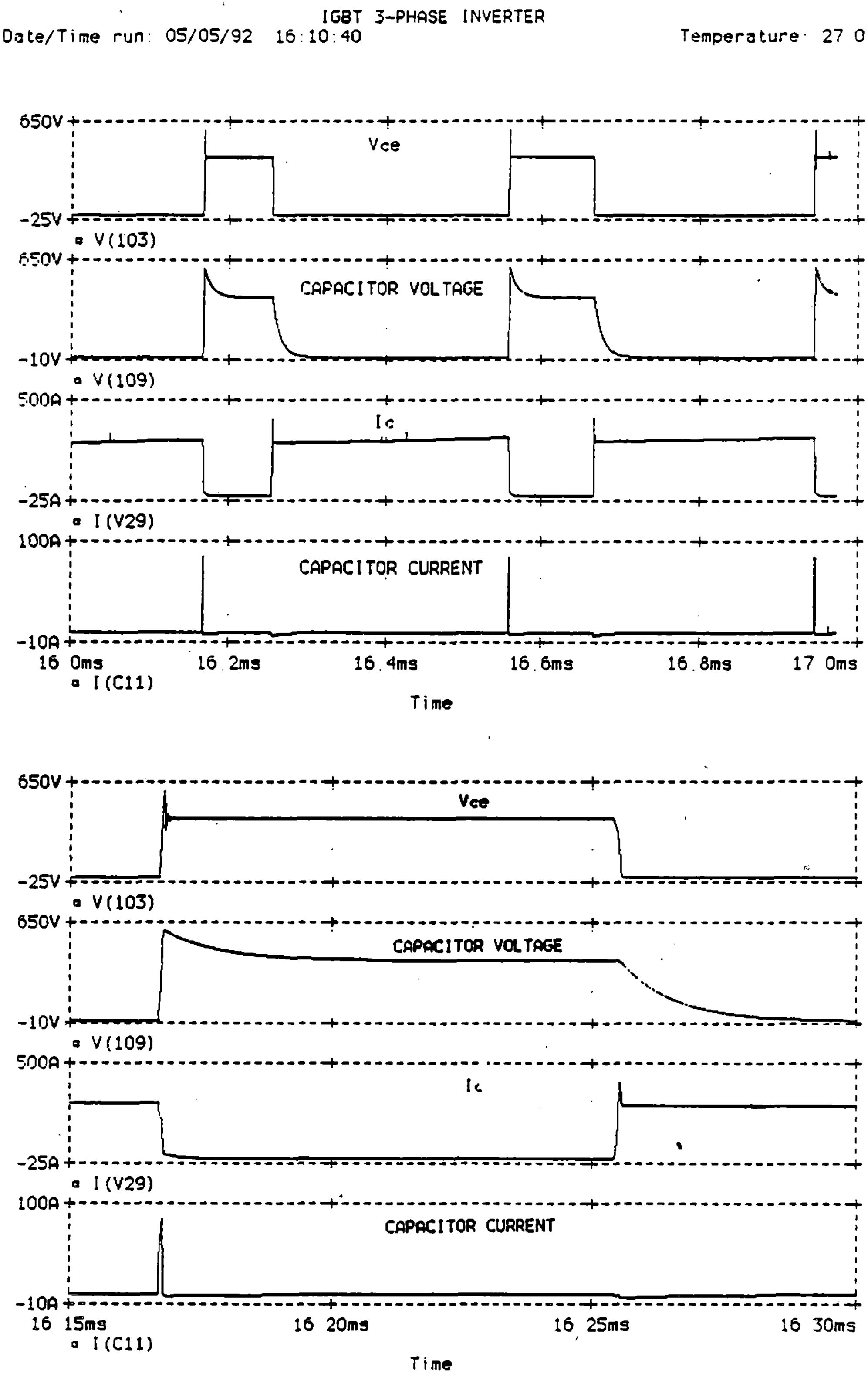
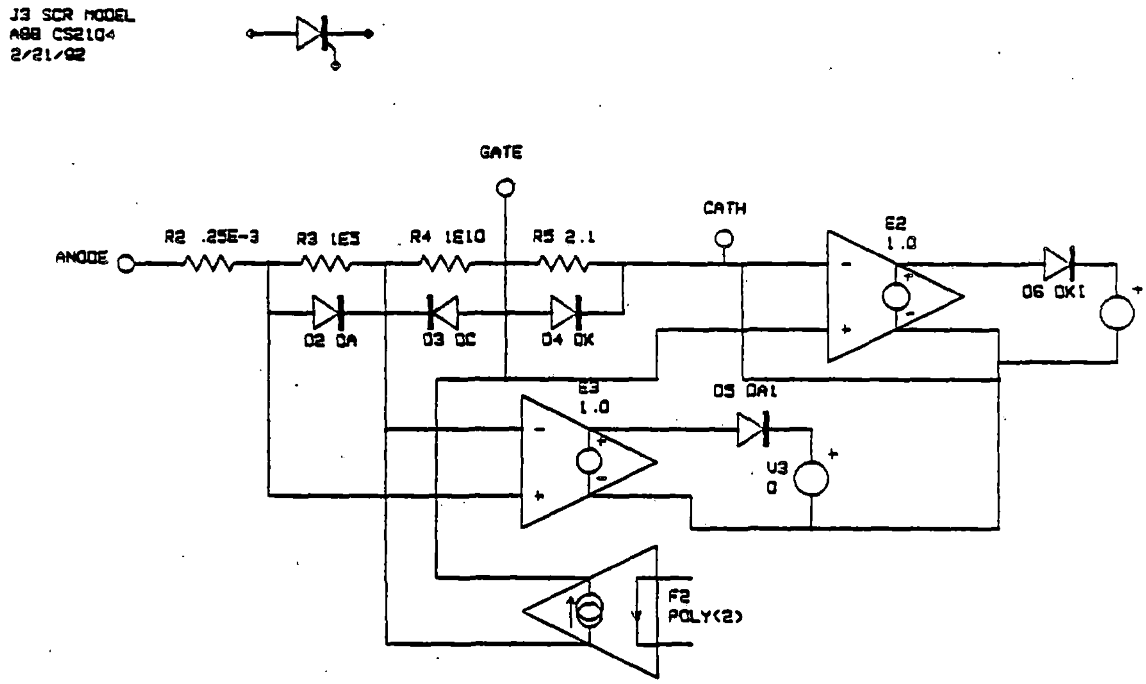


Figure 4-31. Detailed switch cell waveforms in an IGBT inverter at two different time scales.

4.4 SILICON-CONTROLLED RECTIFIER (SCR) COMPUTER MODEL

The computer model of the Asea Brown Boveri CS2104 SCR thyristor is shown in Figure 4-32.




```
.SUBCKT SCR 1 9 7
*THIS IS THE J3 SCR MODEL FOR THE ABB CS2104 THYRISTOR
*
.MODEL DA D(IS=74E-15,CJO=3.4E-6,TT=10.4E-8,BV=5000)
.MODEL DC D(IS=667E-12,CJO=34.0E-9,TT=80E-6,BV=5300)
.MODEL DK D(IS=30E-15,BV=15)
.MODEL DAI D(IS=74E-15)
.MODEL DKI D(IS=30E-15)
D4 9 7 DK
F2 5 9 POLY(2) V3 V2 0. .95 1.0
D3 9 5 DC
D2 4 5 DA
R3 4 5 1E5
R4 5 9 1E10
R5 9 7 2.1
D5 4 6 DAI
R2 1 4 .25E-3
E3 4 7 4 5 1.0
E2 2 7 9 7 1.0
V3 6 7 0
V2 8 7 0
D6 2 8 DKI
.ENDS
```

Figure 4-32. Model and schematic of the CS2104 SCR thyristor.

5. SUPPORTING MATERIAL

5.1 TYPICAL TRANSIT VEHICLE PARAMETERS

Draft maglev system parameters have been prepared by a Federal interagency working group. These parameters provide the framework for the conceptual system design. A list of known transit system vehicles with electric propulsion was prepared from the data obtained from the references in Appendix B. This was done in order to understand the existing parameter space relating to the power converters. The list of typical transit vehicle parameters is included in Table 5-1. This list also includes vehicle power feed voltages and motor voltages used in several different transit applications.

Table 5-1. Typical vehicle parameters.

Vehicle/System	Year	Vehicle Mass tons	Payload tons	Max. Spd. km/h	Motor Thrust kN	Max. Pwr. MW	Pwr. Feed	Hotel Power kW	Motor Voltage	Motor Type	Freq. Hz	Ref. #
InterCity	1991	454		225		9.4				S.Wheel		25
X-2000	1990	343		225		3.3	15kV,16.7Hz			S.Wheel		25
Pendolino	1990	483		250		7	3kVdc			S.Wheel		25
ICE	1990	980		280		9.6	15kV,16.7Hz			S.Wheel		25
Locomotive	1989	138		100	355	4.8	25kV,50Hz		0.9kV	S.Wheel		6
TGV (Paris-Le Mans-Tours)	1989	489		300		8.8	2x25kV,50Hz			S.Wheel		25
TGV (Paris-Lyon)	1981	443		270		6.5	2x25kV,50Hz			S.Wheel		25
Japanese Development METRO	1987	16	5	70	10.9	0.12	1.5kVdc		1.1kV	S. Wheel	0-50	3
Transrapid 05	1983	36	5	75						EMS/LSM		4,5
Transrapid 06	1983	102	20	400	85	11.5		480	4.2kV	EMS/LSM	0-215	4,5
Transrapid 06 II	1988	97	20	450	85	11.5			4.2kV	EMS/LSM		4,5
Transrapid 07		90	16	500	100	35	110kV3p60H		7.8kV	EMS/LSM	0-215	TSC
Shinkansen	1982	733		240		11	25kV,60Hz			S.Wheel		25
MLU 001	1979	17	3	400	79	5.2	66kV,60Hz		5.8kV	EDS/LSM		8
ML500	1979			517	43	12	11kV,120Hz		3kV	EDS/LSM	0-34	20
EET 02	1977	14	3	230						R. Wheel		4
EET 01	1974	17	5	140						EDS		4
Prinzipfahrzeug		130	20	90		7.7				EMS/LIM		17
MLU 002		10	10	420	79.4	5.2					0-28	2
Erlangen		18		200	22						0-105	19

5.2 PARAMETER SPACE FOR MAGLEV POWER CONDITIONING

The requirements list presented in Section 2 was prepared based on the available data from similar mass vehicle systems and calculated power requirements. The design parameter space for primary feed voltages and motor voltages was tentatively determined to range from 12 kVac to 50 kVac (most likely three phase) for the power pickup, and 7 kVac as an upper bound on motor voltages in transit environments.

The calculation of power requirements was made for two different mass vehicle systems, 40 metric ton and 100 metric ton, operating at top speeds of 83 m/s and 135 m/s on level tracks. The effort was aimed at determining the boundaries on parameter space associated with power converters useful in Maglev systems. Vehicle masses of 40 metric ton and 100 metric ton were selected for this purpose with the rationale that these two numbers represent aggressive and pessimistic design goals respectively for the Maglev system designer. The basis for selecting these masses was derived from the table of typical transit vehicle parameters (Table 5-1). It should be noted that the selected vehicle mass systems were not intended to project the design value for mass of any of the vehicle subsystems at this point, but were instead arbitrarily assigned values intended to cover a broad range of vehicle topologies and passenger capacities.

In the analysis done using these vehicle parameters, and EDS maglev system was assumed because this type of system is somewhat less efficient with respect to power consumption than the EMS type system, and thus provides a more conservative upper bound on power rating for the maglev power conditioning hardware. Also, the focus was not on an active or a passive vehicle with respect to power conditioning but rather the determination of a probable range of power system requirements. In all calculations, 100 passengers per vehicle with baggage were assumes. The calculations were made using simple codes which are included in Appendix E. In calculating the magnetic drag, an approximation to the method described in Reference 19 was used. The actual magnetic drag is very dependent upon the specific vehicle and guideway design, and may differ from the result shown in this report. Nevertheless, these calculations are useful in determining rough estimates of power requirements. The results of the calculated power requirements are included in Appendices F and G.

Referring to Appendix F, Figure F-1 shows vehicle speed versus time for a model trip consisting of 0.1 g acceleration to 83 m/s (300 kph), cruising at 83 m/s, and deceleration at 0.2 g to stop. This graph defines the simulated mission performance requirements, and all parameters are calculated from this performance criteria. Figure F-2 shows the normalized magnetic lift and drag forces. Figure F-3 shows the air drag for the vehicle based on the assumption that the frontal area is 9 m^2. These first three figures are applicable to both the 40 metric ton and the 100 metric ton vehicle data that follows. Figure F-4 shows the total drag force for a 40 metric ton vehicle. Note that the total drag (sum of magnetic drag and air resistance) decreases until cruising speed is reached. This is because the magnetic drag of an EDS maglev system is quite high at low speeds. Figure F-5 shows the total thrust force required for a 40 metric ton vehicle. The remaining figures in this appendix show the resulting forces and power requirements for a 100 metric ton vehicle. Appendix G shows similar data for a simulated trip with top speed of 135 m/s (485 kph).

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 TRACTION DRIVES AND INPUT POWER CONDITIONING

The results of our analysis of selected components and topologies show the GTO to be the favored device for the traction power inverters and input power conditioners operating at low unipolar PWM carrier frequencies in the tens of MVAs. The converters based on GTOs are the least costly per MVA and are lighter, smaller and more efficient than the BJT or IGBT converters. Furthermore, the high voltage rating of the GTOs affords a minimum component count which improves reliability.

The IGBT-based inverter begins to look attractive at carrier frequencies above about 700 Hz, as the GTO loses its performance advantage due to increased switching and dv/dt snubber loss. However, the IGBT approach requires a large number of hybrid modules containing several IGBT chips with many bond wires. The reliability of this system would have to be carefully assessed.

The BJT-based traction drive and input converter is clearly inferior to the IGBT approach with respect to cost, mass and volume. Our conclusion is that the BJT is not a good candidate for the traction drive or the input power converter in the tens of MVAs.

The recommended device for the traction drive and input power conditioner is the GTO, provided that the PWM carrier frequency can be kept relatively low. In addition, the lowest cost, mass and volume and the best efficiency are achieved at the lowest carrier frequency that is acceptable in terms of performance of the drive motor. IGBTs can be used if higher carrier frequencies are required.

6.2 AUXILIARY POWER

At the low hundreds of kVA required for auxiliary power, the analysis results indicate that the IGBT is the favored device to use in inverters using unipolar PWM. At this low power level, the BJT-based inverters are a close second. The BJT has poorer efficiency at higher carrier frequencies and costs slightly more. In our view, the BJT will eventually be replaced by the IGBT at this power level due to the IGBT's higher device current density, higher operating frequency, easier circuit paralleling, and simpler drive.

In this power range, the GTO-based auxiliary power inverter was clearly inferior to the IGBT and BJT approaches with respect to cost, mass and volume. The power level and operating voltages are below the optimum operating range of the GTO. Therefore, our conclusion is that the GTO is not a good candidate for the auxiliary power inverter operating in the low hundreds of KVA. The recommended device for the auxiliary power inverter operating in the low hundreds of kVA is the IGBT because of its cost and efficiency advantages.

6.3 BRAKING CHOPPER

The GTO is the recommended device for use with the braking chopper at power levels in the megawatt range. The unique operating parameters of the braking chopper, such as the low operating frequency and high volt-ampere requirement, make the GTO the clear choice for this application.

6.4 SUPERCONDUCTING COIL POWER CONDITIONER

The IGBT is the recommended device for this application based on the results of auxiliary power inverter evaluations. The power level is in the same low range as that of the auxiliary power applications.

APPENDIX A

STATEMENT OF WORK

STATEMENT OF WORK

Advanced Power Conditioning for Maglev Systems

May 28, 1991

1.0 INTRODUCTION AND BACKGROUND

Recent advances in power and semiconductor technology promise substantial improvements in mass, volume, cost and efficiency of power systems suitable for MAGLEV use. The type of system chosen impacts the design of the other MAGLEV system elements, and even the total system architecture. One of the major needs of MAGLEV development is technology with a favorable economic impact. This impact is not limited to the power system alone but impacts the design and cost of other system elements as well. Thorough evaluation of the impact of advances in power technology/systems is important to the MAGLEV program.

2.0 OBJECTIVE

The objective is to quantify the performance and economic advantages of power systems and power system technology currently available for use in a MAGLEV system. This contract shall result in a determination of relative costs of at least three types of power system configurations, when operating in a system consistent with full scale MAGLEV system requirements. An assessment of each power system configuration on the overall system design and cost shall be made.

3.0 SCOPE OF WORK

The work to be performed shall analyze all of the requirements and establish the performance criteria for power systems suitable for Maglev use. This shall be done by developing several computer models to represent various circuits (traction, levitation, and auxiliary) based on various semiconductor technologies. Preliminary and final analyses shall be performed on several circuit configurations resulting in design parameters being developed for each configuration. Final recommendations shall include a comparison of the economics for each configuration.

4.0 TASKS TO BE PERFORMED

4.1 Requirements Definition

The contractor shall conduct a thorough search of all available MAGLEV literature to establish critical requirements for MAGLEV power systems. This will result in a determination of the allowable ranges of performance parameters such as wayside power, voltage, frequency and harmonic content. Other limitations such as power system volumes and masses for on board power systems shall also be determined. This section shall determine the power system space and parameter requirements. It is anticipated that the MAGLEV vehicle will require between 40 and 50 MVA of power.

4.2 Analysis Model

The contractor shall produce traction, levitation, and auxiliary power circuit analysis software models of at least three candidate power system configurations which shall be based on bipolar transistor (BJT), insulated gate bipolar transistor (IGBT), and gate turn-off (GTO) semiconductor technologies. The models shall simulate the electric circuit performance with the use of computer codes. The performance shall be characterized by predicting output performance (traction, levitation, and auxiliary power) parameters, given a set of electrical parameters to the MAGLEV system, or vise-versa.

4.3 Preliminary Analysis

The contractor shall perform preliminary analysis of the candidate power systems' configurations using a computer analysis model(s). This will determine the values of the circuit elements, in each configuration, that perform within the parameters identified in Section 4.1. The results of this effort shall be conceptual designs of candidate power system configurations, which shall be described as circuit models containing the major circuit elements and their values, or ranges of values.

4.4 Final Analysis

The contractor shall determine an estimate of the masses, volumes, efficiencies, and costs of the candidate power system configurations. For each of the configurations the estimates shall account for traction, levitation, and auxiliary (hotel) power requirements of a full scale MAGLEV system. For each of the candidate configurations, scaling data shall be prepared in the form of graphs describing mass, volume, and cost versus the required power rating consistent with that of a full scale MAGLEV system. The analysis shall conclude with design parameters for each of the candidate configurations. Final recommendations shall be based primarily on economic impact consistent with acceptable operational restrictions.

4.5 Final Recommendations

The contractor shall present final recommendations based primarily on economic impacts. An assessment of the relative costs of the various approaches which take into account their impact of the vehicle and guideway designs shall be included.

5.0 Reports, Documentation and Other Deliverable End Items

5.1 Interim Report

The contractor shall prepare and submit a draft Interim Report, including but not limited to, a synopsis of the power system(s) design, and conceptual sketches of the interim system configuration(s). This shall be followed by a description of all efforts conducted during the first half of the contract, especially all efforts performed under Section 4.0. The contractor shall submit said draft Interim Report **not later than one-hundred and seventy (170) days after contract award.**

5.2 Interim Program Review

The contractor shall conduct an Interim Program Review at the contractor's facilities, during which, the Government shall present it's comments relative to the draft Interim Report, referenced in 5.1 above. Said Interim Program Review shall be held **not later than two-hundred (200) days after contract award.** The contractor shall provide hard copies of all viewgraphs and other graphic/visual aid materials used during the meeting, to those in attendance. The COTR shall inform the contractor of the date and those Government personnel to be in attendance.

5.3 Final Interim Report

The contractor shall prepare and submit a Final Interim Report, inclusive of all Government review comments resulting from 5.2 above. Said Final Interim Report shall be submitted **not later than thirty (30) days after the date of the Interim Program Review in 5.2 above.**

5.4 Draft Final Report

The contractor shall prepare and submit a draft final report describing all results and findings, inclusive of the actual computer models of the various circuit configurations, as appendixes. The final technical report shall also include a performance and cost report describing the project cost as compared to the amounts budgeted. Said draft Final Report shall be submitted **not later than three-hundred (300) days after contract award.**

5.5 Final Program Review

The contractor shall deliver a final program review to discuss the project, during which, the Government shall present it's comments relative to the draft Final Report, referenced in 5.4 above. This Final Program Review shall be held at VNTSC. The contractor shall provide hard copies of all viewgraphs and other graphic/visual aid materials used during the meeting, to those in attendance. The COTR shall inform the contractor of the date and those Government personnel to be in attendance. Said Final Program Review shall take place **not later than three-hundred and thirty (330) days after contract award.**

5.6 Final Report

The contractor shall prepare and submit a Final Report, inclusive of all Government review comments in 5.5 above. Said Final Report shall be submitted **not later than thirty (30) days after the date of the Final Program Review.**

5.7 Post Award Meeting

In addition to the interim and final program reviews, there will be a Post Award meeting, to be held at VNTSC, to discuss the work to be performed. Said Post Award meeting shall take place **not later than ten (10) days after contract award.**s the scope of the project.

APPENDIX B

LITERATURE SEARCH - SELECTED REFERENCES

SELECTED REFERENCES

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APPENDIX C

POWER SEMICONDUCTOR DATA SHEETS

BIPOLAR JUNCTION TRANSISTORS (BJTs)

Marconi
Electronic Devices

'POWERLINE' NPN TRANSISTOR RANGE

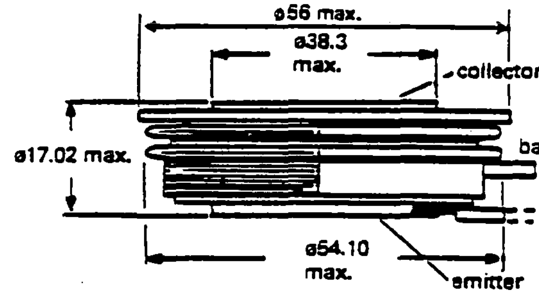
DT600 SERIES

$V_{CER(SUS)}$	=	500/450/400V
V_{CEX}	=	550/500/450V
$I_{C(CONT)}$	=	750A
$I_{C(PK)}$	=	1000A
t_f (125°C)	<	1.5 μs

APPLICATIONS
- Choppers
- Inverters
- Speed Regulation of AC Machines
- Aircraft Electrical Drives

FEATURES
- Triple Diffused
- Pressure Contact Construction
- Wide FBSOA and RBSOA
- Very High Power Capability
- Low Saturation Voltages
- High Sustaining Voltages

S CAPSULE OUTLINE



Dimensions in mm.
Finish: Nickel Plate
Recommended Clamping Force: 10kN ± 10%
Transistor must only be tested when clamped to correct pressure.
Base Wire: Uninsulated multi strand flexible cable. 100mm long.

		TEST CONDITIONS	DT600 −550	DT600 −500	DT600 −450	Units
RATINGS						
V_{CEX}	Collector-emitter voltage	V_{BE} = −1.5V	550	500	450	V
V_{EBO}	Emitter-base voltage		8	8	8	V
$I_{C(CONT)}$	Continuous collector current		750	750	750	A
$I_{B(CONT)}$	Continuous base current		150	150	150	A
$I_{C(PK)}$	Peak collector current		1000	1000	1000	A
P_{TOT}	Power dissipation		3000	3000	3000	W
$R_{th(j-c)}$	Thermal resistance junction to case (double side cooled)		0.05	0.05	0.05	°C/W
T_{vj}	Virtual junction temperature		175	175	175	°C
	Operating and storage temperature range		−55 to 175	−55 to 175	−55 to 175	°C

OFF-STATE CHARACTERISTICS T_C = 125°C unless otherwise stated

		TEST CONDITIONS	DT600 −550	DT600 −500	DT600 −450	Units
$V_{CER(SUS)(min)}$	Collector-emitter sustaining voltage	I_C = 0.5A	500	150	400	V
$V_{EBO(min)}$	Emitter-base voltage	R_{BE} = 10Ω				V
$I_{CEX(max)}$	Collector cut-off current	At rated V_{CEX}, V_{BEO} = −1.5V	20	20	20	mA
$I_{EBO(max)}$	Emitter cut-off current	V_{EB} = 8V	100	100	100	mA

ON-STATE CHARACTERISTICS Measured under pulse conditions T_C = 125°C

		TEST CONDITIONS	−550 max	−550 typ	−500 max	−500 typ	−450 max	−450 typ	Units
$V_{CE(sat)}$	Collector-emitter saturation voltage	I_C = 400A, I_B = 60A	1.5	0.6	1.5	0.6	1.5	0.6	V
$V_{BE(sat)}$	Emitter-base saturation voltage	I_C = 400A, I_B = 60A	1.75	1.3	1.75	1.3	1.75	1.3	V
$h_{FE(min)}$	DC current gain	I_C = 400A, V_{CE} = 2V		7		9		11	

NOTE: $V_{CER(sus)}$ must not be measured on a curve tracer.

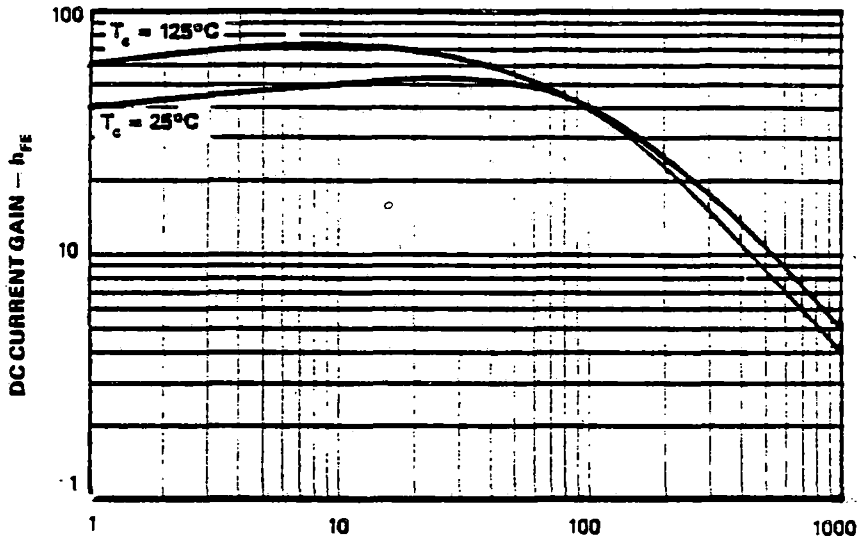
Power Division
Carholme Road.

Issue 2
June 1986

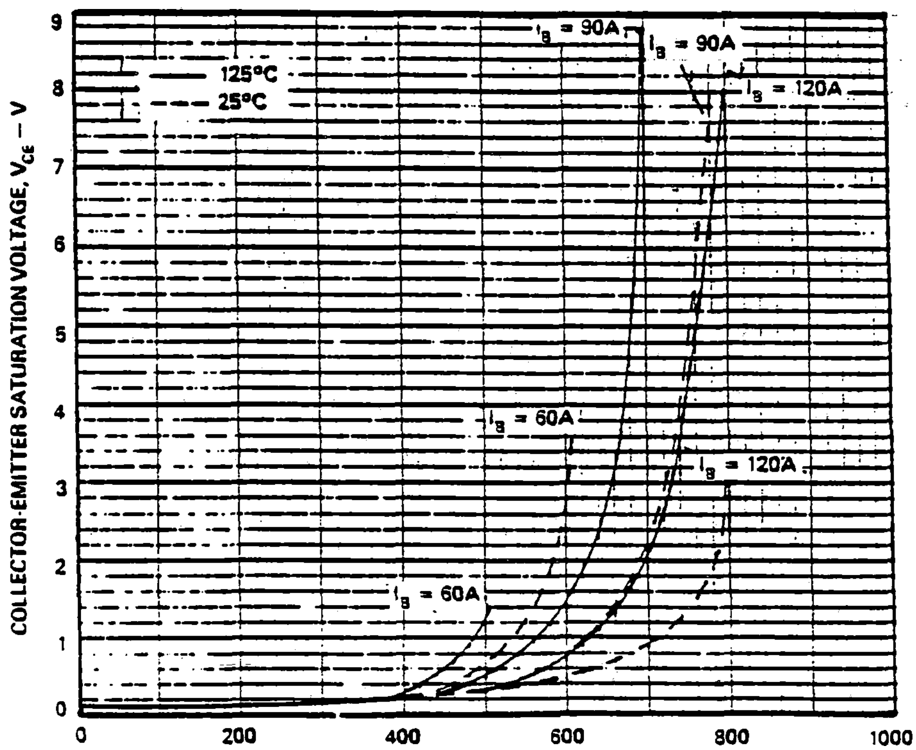
DT600 SERIES

$V_{CER(SUS)}$ = 500/450/400V
V_{CEX} = 550/500/450V
$I_{C(CONT)}$ = 750A
$I_{C(PK)}$ = 1000A
t_f (125°C) < 1.5μs

Marconi
Electronic Devices



TYPICAL DC FORWARD CURRENT TRANSFER RATIO



TYPICAL $V_{CE(SAT)}$ versus COLLECTOR CURRENT

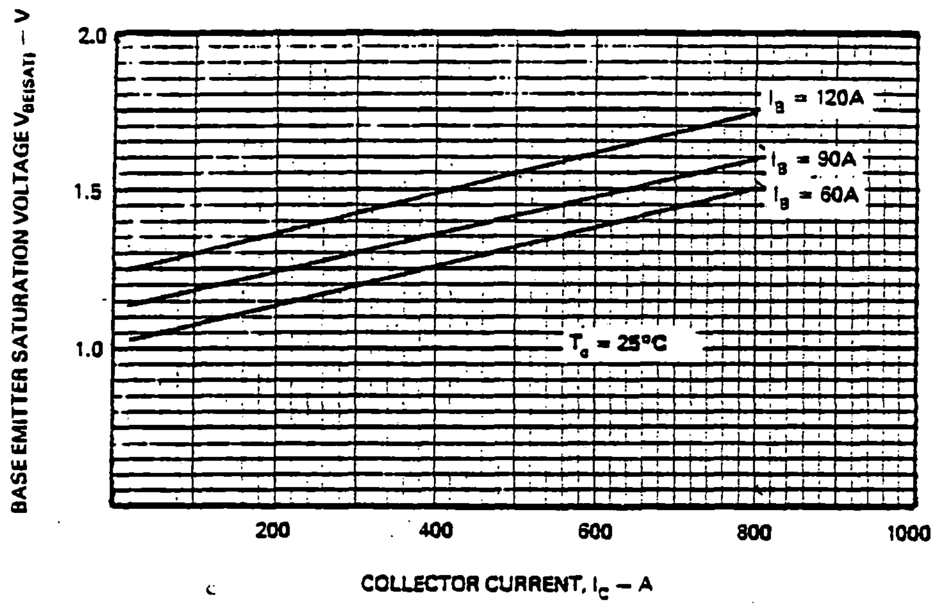
Marconi
Electronic Devices

'POWERLINE' NPN TRANSISTOR RANGE

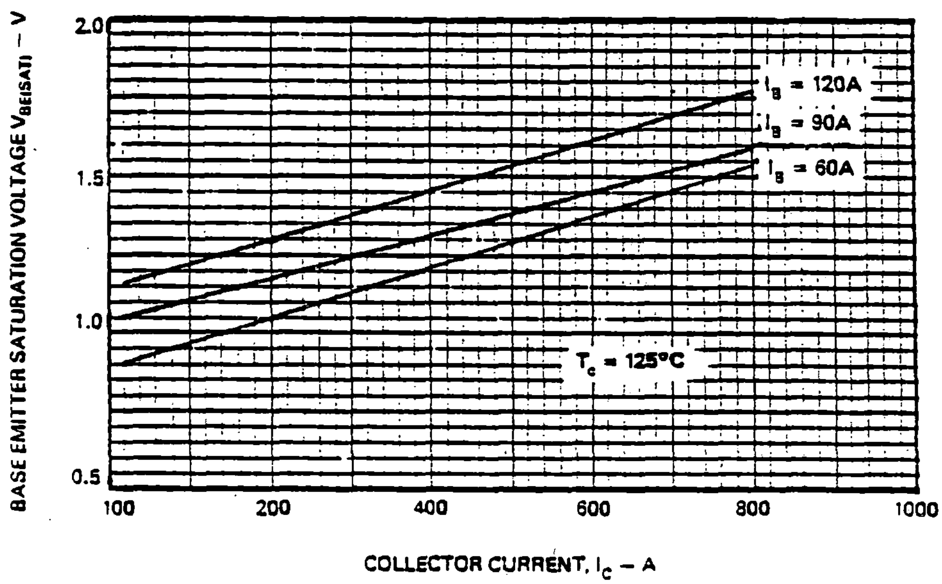
DT600 SERIES

$V_{CER(SUS)}$ = 500/450/400V
V_{CEX} = 550/500/450V
$I_{C(CONT)}$ = 750A
$I_{C(PK)}$ = 1000A
t_f (125°C) < 1.5μs

VARIATION OF $V_{BE(SAT)}$ WITH I_C FOR VARIOUS I_B VALUES FOR DT600-450



TYPICAL $V_{BE(SAT)}$ versus COLLECTOR CURRENT



TYPICAL $V_{BE(SAT)}$ versus COLLECTOR CURRENT

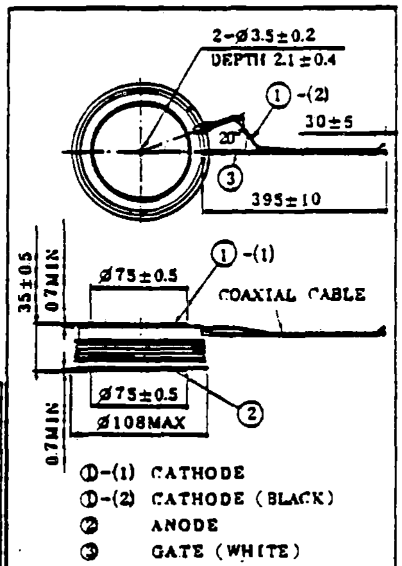
GATE TURN-OFF THYRISTORS (GTOs)

SG3000JX24

INVERTER APPLICATION

- Repetitive Peak Off-State Voltage : V_{DRM}=6000V
- R.M.S On-State Current : $I_{T(RMS)}$=1200A
- Peak Turn-Off Current : I_{TGQM}=3000A
- Critical Rate of Rise of On-State Current : di/dt=400A/μs
- Critical Rate of Rise of Off-State Voltage : dv/dt=1350V/μs

Unit in mm



JEDEC	
EIAJ	
TOSHIBA	

Weight : 1700g

MAXIMUM RATINGS

CHARACTERISTIC	SYMBOL	RATING	UNIT
Repetitive Peak Off-State Voltage (Note 1)	V_{DRM}	6000	V
Repetitive Peak Reverse Voltage	V_{RRM}	16	V
Peak Turn-Off Current (Note 2)	I_{TGQM}	3000	A
R.M.S On-State Current (Note 3)	$I_{T(RMS)}$	1200	A
Peak One Cycle Surge On-State Current (Non-Repetitive, 10ms Width Half Sine Waveform)	I_{TSM}	16000	A
Critical Rate of Rise of On-State Current (Note 4)	di/dt	400	A/μs
Peak Forward Gate Current	I_{FGM}	100	A
Average Forward Gate Power Dissipation	$P_{FG(AV)}$	50	W
Average Reverse Gate Power Dissipation	$P_{RG(AV)}$	150	W
R.M.S Gate Current (Note 5)	$I_{G(RMS)}$	50	A
Peak Reverse Gate Voltage (at Static)	V_{RGM}	16	V
Operating Junction Temperature Range	T_j	−40~125	°C
Storage Temperature Range	T_{stg}	−40~150	°C
Mounting Force	-	3400±500	kg

Note 1. V_{GK}=−2V

Note 2. V_{DM}=6000V, C_S=6μF, R_S=5Ω, di_{RG}/dt=50A/μs, $V_{dsp}\leq$850V, $L_S\leq$0.3μH

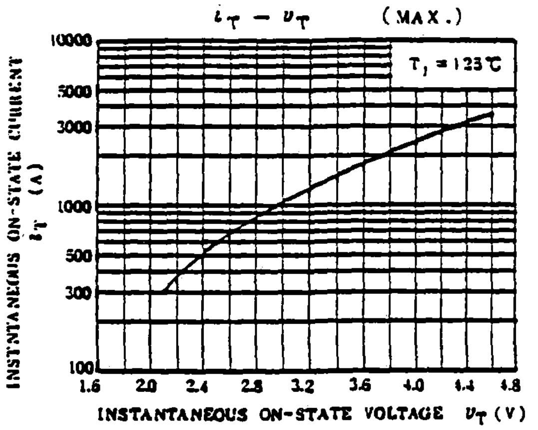
Note 3. 50Hz Half Sine Waveform at T_f=76°C

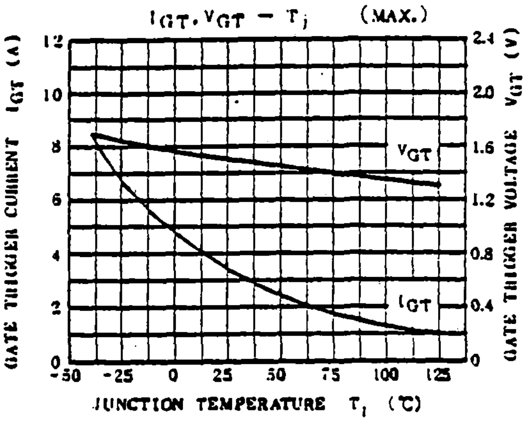
Note 4. V_D=1/2V_{DRM}, I_{GM}=25A

Note 5. Ambient Temperature of coaxial gate-cathode lead=90°C

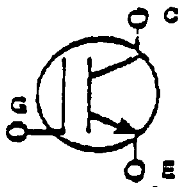
ELECTRICAL CHARACTERISTICS

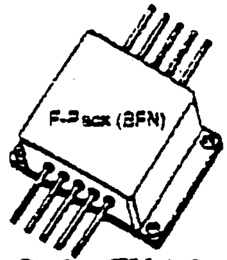
CHARACTERISTIC	SYMBOL	TEST CONDITION		MIN.	TYP.	MAX.	UNIT
Repetitive Peak Off-State Current	I_{DRM}	V_{DRM}=Rated, V_{GK}=-2V, Tj=125°C		-	-	150	mA
Repetitive Peak Reverse Current	I_{RRM}	V_{RRM}=Rated, Tj=125°C		-	-	10	mA
Repetitive Peak Reverse Gate Current	I_{RGM}	V_{RGM}=16V, Tj=125°C		-	-	10	mA
Peak On-State Voltage	V_{TM}	I_{TM}=3000A, Tj=125°C		-	-	4.3	V
Gate Trigger Voltage	V_{GT}	V_D=24V R_L=0.1Ω	Tj=-40°C	-	-	1.7	V
			Tj=25°C	-	-	1.5	
Gate Trigger Current	I_{GT}		Tj=-40°C	-	-	10	A
			Tj=25°C	-	-	3.5	
Turn-on Delay Time	t_d	V_D=1/2 V_{DRM}, I_{TM}=3000A di/dt=400A/µs I_{GM}=25A, Tj=25°C		-	-	3	µs
Turn-on Time	t_{gt}			-	-	10	µs
Critical Rate of Rise of Off-State Voltage	dv/dt	V_D=2/3 V_{DRM} Tj=125°C, V_{GK}=-2V		1350	-	-	V/µs
Storage Time	t_s	I_{TGQ}=3000A, V_{DM}=6000V V_D=1/2 V_{DRM} di_{RG}/dt=50A/µs C_s=6µF, R_s=5Ω Tj=125°C, L_s≤0.3µH		-	-	28	µsec
Gate Turn-off Time	t_{gq}			-	-	30	µsec
Tail Time	t_{tail}			-	-	115	µsec
Turn-off Gate Current	I_{RG}			-	-	800	A
Thermal Resistance	$R_{th(j-f)}$	Junction to Fin		-	-	0.017	°C/W


$i_T - v_T$ (MAX.)
T_j = 125℃
INSTANTANEOUS ON-STATE CURRENT i_T (A)
10000
5000
3000
1000
500
300
100
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
INSTANTANEOUS ON-STATE VOLTAGE v_T (V)


$I_{GT}, V_{GT} - T_j$ (MAX.)
GATE TRIGGER CURRENT I_{GT} (A)
GATE TRIGGER VOLTAGE V_{GT} (V)
12
10
8
6
4
2
0
2.4
2.0
1.6
1.2
0.8
0.4
0
V_{GT}
I_{GT}
-50
-25
0
25
50
75
100
125
JUNCTION TEMPERATURE T_j (℃)

INSULATED GATE BIPOLAR TRANSISTORS (IGBTs)





ADVANCED POWER TECHNOLOGY®

APT200G100BFN 1000V 200A

POWER MOS IV™ IGBT

N-CHANNEL ENHANCEMENT MODE HIGH VOLTAGE POWER INSULATED GATE BIPOLAR TRANSISTOR

MAXIMUM RATINGS All Ratings: $T_C = 25°C$ unless otherwise specified.

Symbol	Parameter	APT200G100BFN	UNIT
V_{CES}	Collector-Emitter Voltage	1000	Volts
V_{GE}	Gate-Emitter Voltage	±20	Volts
I_{C1}	Continuous Collector Current	200	Amps
I_{C2}	Continuous Collector Current @ $T_C = 90°C$	150	Amps
I_{CM}	Pulsed Collector Current ①	400	Amps
I_{LM}	Clamped Inductive Load Current @ $T_J = +125°C$ ②	200	Amps
E_{ARV}	Reverse Voltage Avalanche Energy	200	mJ
P_D	Total Power Dissipation	830	Watts
T_J, T_{STG}	Operating and Storage Junction Temperature Range	-55 to 150	°C
T_L	Max. Lead Temp. for Soldering: 0.063" from Case for 10 Sec.	260	°C

STATIC ELECTRICAL CHARACTERISTICS

Symbol	Characteristic / Test Conditions / Part Number		MIN	TYP	MAX	UNIT
BV_{CES}	Collector-Emitter Breakdown Voltage ($V_{GE} = 0V$, $I_C = 10.0mA$)	APT200G100BFN	1000			Volts
RBV_{CES}	Collector-Emitter Reverse Breakdown Voltage ($V_{GE} = 0V$, $I_C = -1.0A$)		-15	-25		Volts
$V_{GE}(TH)$	Gate Threshold Voltage ($V_{CE} = V_{GE}$, $I_C = 10mA$)		2.5		5	Volts
$V_{CE}(ON)$	Collector-Emitter On Voltage ($V_{GE} = 15V$, $I_C = I_{C1}$)			3.2	4.0	Volts
I_{CES}	Collector Cut-off Current ($V_{CE} = 0.8 V_{CES}$, $V_{GE} = 0V$)				2	mA
I_{CES}	Collector Cut-off Current ($V_{CE} = 0.8 V_{CES}$, $V_{GE} = 0V$, $T_C = 125°C$)				4	mA
I_{GES}	Gate-Emitter Leakage Current ($V_{GE} = ±20V$, $V_{CE} = 0V$)				±100	nA
$V_{GE}/\Delta T_J$	Gate-Emitter Threshold Voltage Temperature Coefficient			-7.2		mV/°C
gfe	Forward Transconductance ($V_{CE} = 10V$, $I_C = 20A$)		25	45		S

405 S.W. COLUMBIA STREET
BEND, OREGON 97702-1035
U.S.A.

PHONE . . . (503) 382-8028

FAX . . . . . . (503) 388-0364

DYNAMIC CHARACTERISTICS

Symbol	Characteristic	Test Conditions	MIN	TYP	MAX	UNIT
C_{ies}	Input Capacitance	Capacitance		18,000	20,000	pF
C_{oes}	Output Capacitance	$V_{GE} = 0V$, $V_{CE} = 25V$		1,400	3,000	
C_{res}	Reverse Transfer Capacitance	$f = 1$ MHz		300	600	
Q_g	Total Gate Charge ③	Gate Charge		800	1,200	nC
Q_{ge}	Gate-Emitter Charge	$V_{GE} = 15V$, $V_{CC} = 0.5\ V_{CES}$		120		
Q_{gc}	Gate-Collector ("Miller") Charge	$I_C = I_{C1}$		680		
$t_d(on)$	Turn-on Delay Time	Resistive Switching (25°C)		50	300	ns
t_r	Rise Time	$V_{GE} = 15V$		100	300	
$t_d(off)$	Turn-off Delay Time	$V_{CC} = 0.5\ V_{CES}$, $I_C = I_{C1}$		450	1,000	
t_f	Fall Time	$R_G = 6\Omega$		500	800	
$t_d(on)$	Turn-on Delay Time				TBD	ns
t_r	Rise Time	Inductive Switching (125°C)			TBD	
$t_d(off)$	Turn-off Delay Time	$V_{CLAMP}(Peak) = 0.8V_{CES}$		600	1,000	
t_f	Fall Time	$V_{GE} = 15V$, $I_C = I_{C1}$		500	800	
E_{on}	Turn-on Switching Energy	$R_G = 5\Omega$			TBD	mJ
E_{off}	Turn-off Switching Energy	$T_J = +125°C$			TBD	
E_{ts}	Total Switching Losses				TBD	

THERMAL CHARACTERISTICS

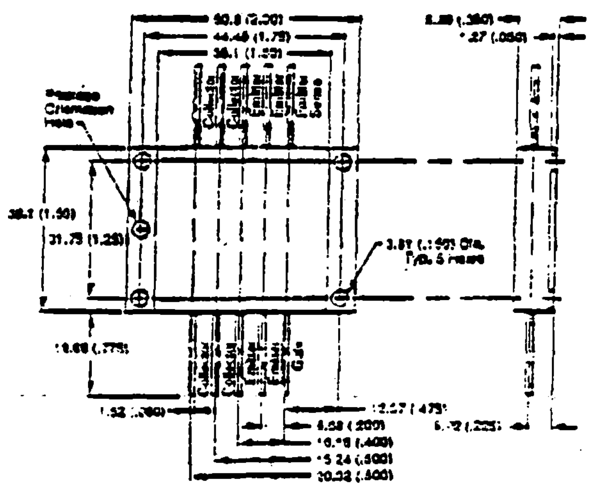
Symbol	Characteristic	MIN	TYP	MAX	UNIT
$R_{\theta JC}$	Junction to Case			0.15	°C/W
$R_{\theta JA}$	Junction to Ambient			20	
Torque	Mounting Torque using a 6-32 or 3mm Binding Head Machine Screw.		10		in-Lbs.

① Repetitive Rating; Pulse width limited by maximum junction temperature.

② $V_{CLAMP} = 0.8V_{CES}$ Volts, $R_G = 6\Omega$.

③ See MIL-STD-750 Method 3471

F-Pack Package Outline (Type BF)



Dimensions in Millimeters and (Inches)

052-1003
Rev A

SILICON CONTROLLED RECTIFIER (SCR)

BBC
BROWN BOVERI

Druckschrift/Publication
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Thyristor
CS 2104

I_{TRMS} = 5000 A
I_{TAVM} = 2020 A
V_{RRM}, V_{DRM} = 4800...5000 V

Merkmale

Höchstleistungsthyristor im Metall-Keramik-Gehäuse.
Volldiffundierte Tablette.
Direkter Druckkontakt.
Integrierte Zündverstärkung mit verteiltem Gate.

Anwendungen

Leistungssteuerung für hohe Spannungen.
Blindstromkompensatoren.
Gleich- und Wechselrichter.
Kurzschluss- und Überspannungsschutz.

Technische Daten

Die Begriffe, Symbole, Daten und Messbedingungen entsprechen den internationalen Normen IEC 147/148 und DIN 41785, 41786, 41787.

Ⓛ kennzeichnet Grenzwerte
(L wie Limit)

Features

High power thyristor in metal ceramic housing.
Fully diffused silicon wafer.
Direct pressure contact.
Interdigitated amplifying gate.

Applications

High voltage power control.
Reactive power compensators.
DC and AC converters.
Short circuit and overvoltage protection.

Technical specifications

Terms, symbols and measuring conditions are according to the international standards IEC 147/148 and DIN 41785, 41786, 41787.

Ⓛ marks limiting ratings
(L like limit)

Particularités

Thyristor de très grande puissance en boîtier métal-céramique.
Pastille entièrement diffusée.
Contact par pression directe.
Gâchette amplificatrice interdigitée.

Applications

Régulation de puissance pour hautes tensions.
Compensateurs de puissance réactive.
Redresseurs et onduleurs.
Protection contre les courts-circuits et les surtensions.

Spécifications techniques

Les définitions et les symboles, les spécifications et les conditions de mesure sont conformes aux normes internationales CEI 147/148 et DIN 41785, 41786, 41787.

Ⓛ marque les valeurs limites
(L comme limite)

Typen **Types** **Types**

V_{RRM}, V_{DRM}	4800 V	5000 V			
	CS 2104-48 Io 1	CS 2104-50 Io 1			

Sperreigenschaften **Blocking characteristics** **Caractéristiques de blocage**

Ⓛ V_{RRM}, V_{DRM}	4800 V	5000 V			t_p = 10 ms
Ⓛ V_{RSM}, V_{DSM}	5100 V	5300 V			t_p = 1 ms
I_{RRM}	≤ 300 mA				V_{RRM}; T_{VJ} = 120 °C
I_{DRM}	≤ 300 mA				V_{DRM}; T_{VJ} = 120 °C

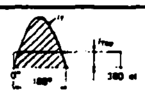
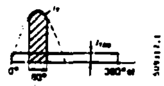
Durchlasseigenschaften	**On-state characteristics**	**Caractéristiques à l'état passant**

V_T	≤ 2.25 V	I_T = 4000 A T_{VJ} = 120 °C	
V_{TO} r_T	1.25 V 0.25 mΩ	T_{VJ} = 120 °C	
Ⓛ I_{TRMS}	5000 A	T_C = 50 °C	50 Hz
Ⓛ I_{TAVM}	2020 A	T_C = 85 °C	50 Hz
Ⓛ I_{TSM}	45.0 kA 49.0 kA 70.0 kA	10 ms 8.3 ms 1 ms	T_C = 85 °C T_{VJ} = 120 °C V_R = 0 V
Ⓛ $\int i^2 \cdot dt$	10.1 × 10.0 × 10^6 A²s 2.45 ×	10 ms 8.3 ms 1 ms	

Dauergrenzstrom
Typische Betriebsfälle:

Mean forward current
Typical operating conditions:

Courant direct moyen
Cas typiques de fonctionnement:

T_A	35	45	°C	
R_{thKA}	0.01	0.08	K/W	
I_{TAV}, δ = 180°el	1905	535	A	
I_{TAV}, δ = 120°el	1770	510	A	
I_{TAV}, δ = 60°el	1400	440	A	

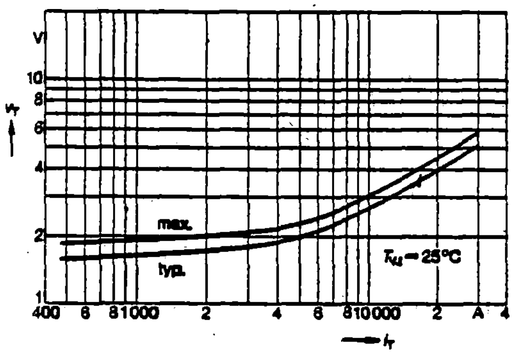


Fig. 1 Durchlasskennlinien
On-state characteristics $v_T = f(i_T)$; T_{VJ} = 25 °C
Caractéristiques directes

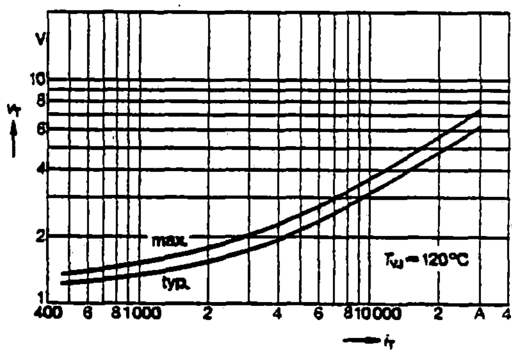


Fig. 2 Durchlasskennlinien
On-state characteristics $v_T = f(i_T)$; T_{VJ} = 120 °C
Caractéristiques directes

Thermische Werte | **Thermal values** | **Valeurs thermiques**

T_{VJM}	120 °C	
T_{stg}	−40...+120 °C	
T_{A}	−40...+120 °C	
R_{thJC}	0.013 K/W 0.015 K/W 0.007 K/W	Anode Cathode Anode + Cathode
R_{thCK}	0.0030 K/W 0.0015 K/W	Anode (Cathode) Anode + Cathode

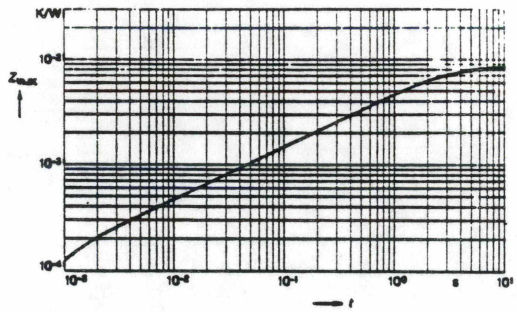


Fig. 3 $Z_{thJK} = f(t)$

Transienter Wärmewiderstand
Sperrschicht – Kühlkörper

Transient thermal impedance
junction – heatsink

Résistance thermique
transitoire jonction – radiateur

Mechanische Werte | **Mechanical values** | **Valeurs mécaniques**

F_m	72–88 kN	Anpresskraft Mounting force Force de serrage
a	50 m/s² [1] 200 m/s²	50-Hz-Rüttelfestigkeit Max. acceleration at 50 Hz Résistance aux vibrations de 50 Hz
m	2.700 kg	Masse Mass Masse
D_s	33 mm	Kriechstrecke Surface creepage distance Distance de fuite en surface
D_a	20 mm	Luftstrecke Air creepage distance Distance de fuite dans l'air

[1] Element eingespannt
Component mounted
Composant monté

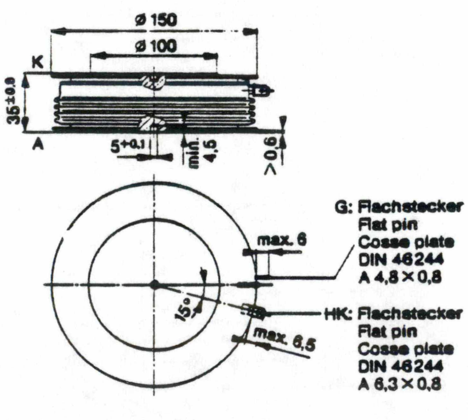


Fig. 4 Masse in:
Dimensions in: mm
Dimensions en:

A = Anode/anode/anode
K = Kathode/cathode/cathode
G = Zündelektrode/gate/gâchette
HK = Hilfskathode/auxiliary cathode/cathode auxiliaire

Steuereigenschaften	Gate trigger characteristics	Caractéristiques de commande

V_{GT}	≤ 3.0 V	V_D = 6.0 V ; T_{VJ} = 25 °C
I_{GT}	≤ 350 mA	
V_{GD}	≥ 0.5 V	$V_D = 0.67 \times V_{DRM}$; T_{VJ} = 120 °C
I_{GD}	≥ 10 mA	
Ⓛ V_{RGM}	15 V	
Ⓛ P_{GAV}	15 W	
Ⓛ P_{GM}	120 W	t_G = 30 µs ; T_{VJ} = 25 °C

Dynamische Eigenschaften und Schaltzeiten	Dynamic characteristics and switching times	Caractéristiques dynamiques et temps de commutation

[1] $t_{q\,typ}$	o: 350 µs	T_{VJ} = 120 °C ; $V_D = 0.67 \times V_{DRM}$; $dv/dt_{(lin.)}$ = 100 V/µs ;	V_R = 100 V; I_T = 1000 A; di/dt = −4 A/µs
t_q	≤ 700 µs		
Ⓛ $(dv/dt)_{c,\,exp}$	l: ≥ 2000 V/µs	T_{VJ} = 120 °C ; $V_D = 0.67 \times V_{DRM}$;	f = 50 Hz; R_{GK} = ∞
t_{gd}	≤ 1.6 µs	T_{VJ} = 25 °C ; $V_D = 0.67 \times V_{DRM}$;	i_G = 1.5 A; di_G/dt = 1.5 A/µs
Q_{rr}	≤ 9.0 mC	T_{VJ} = 120 °C ; $V_R \leq 0.67 \times V_{RRM}$;	I_T = 1000 A; di/dt = −5 A/µs
I_L	≤ 2.0 A	T_{VJ} = 25 °C ; i_G = 1.5 A ;	t_G = 50 µs; di_G/dt = 1.5 A/µs
I_H	≤ 250 mA	T_{VJ} = 25 °C ;	R_{GK} = ∞
I_{TER}	≥ 200 A	T_{VJ} = 120 °C ; i_G = 1.5 A ; di_G/dt = 1.5 A/µs ;	$V_D = 0.8 \times V_{DRM}$; di_T/dt = 100 A/µs
Ⓛ $(di/dt)_c$ (turn-on)	100 A/µs	f = 50 Hz	T_{VJ} = 120 °C; $V_D = 0.67 \times V_{DRM}$; i_G = 1.5 A; $I_T = 3 \times I_{TAVM}$; di_G/dt = 1.5 A/µs
	500 A/µs	Einzelimpuls Non-repetitive pulse Impulsion isolée	

[1] Bei abweichenden Bedingungen: siehe Seite 6, Fig. 13, 14, 15
For other conditions: see page 6, Fig. 13, 14, 15
Pour d'autres conditions: voir page 6, Fig. 13, 14, 15

Belastbarkeitsdiagramme
Current load capacity
Diagrammes de capacité de charge
(Fig. 5)

Dauergrenzstrom
Mean forward current
Courant direct moyen
(Fig. 6)

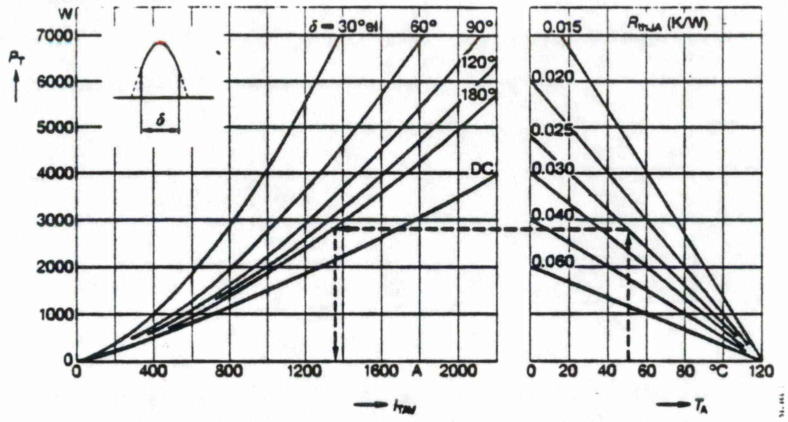


Fig. 5a $P_T = f(I_{TAV})$

Ohne Einschaltverluste
Without turn-on losses
Sans les pertes à l'allumage

Fig. 5b $P_T = f(T_A)$

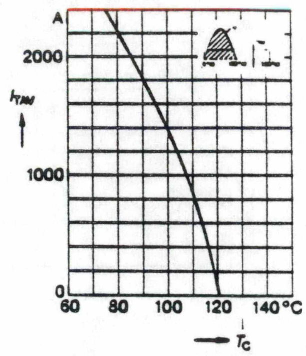


Fig. 6 $I_{TAV} = f(T_C)$

Grenzstromkennlinien und Grenzlastintegral

Diagrams of limiting current and i^2t for fusing

Diagrammes du courant limite et de l'intégrale limite de fusion

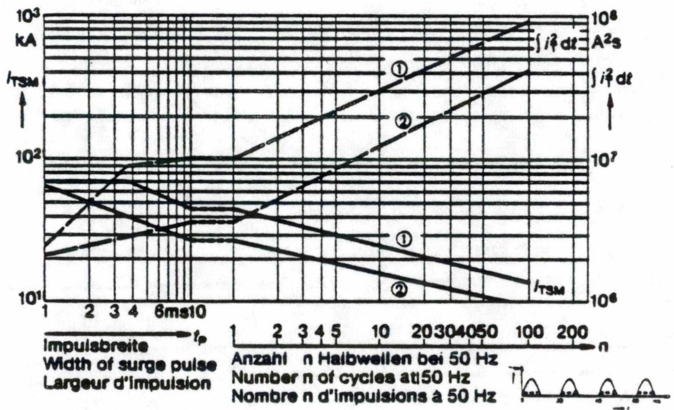
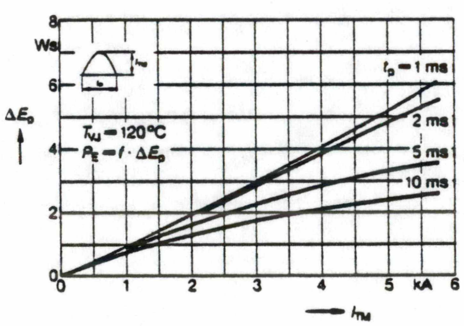


Fig. 7 T_C = 85 °C
T_{VJ} = 120 °C
①: V_R ≈ 0 V
②: V_R = $0.8 \times V_{RRM}$

Einschaltverluste **Turn-on losses** **Pertes à l'allumage**



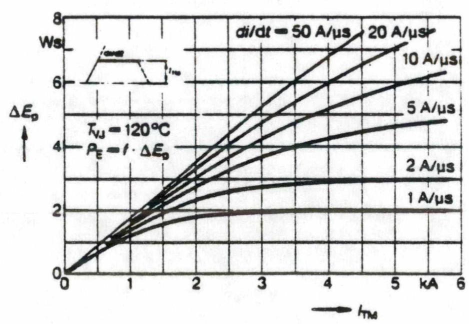


Fig. 8 $\Delta E_p = f(I_{TM}, t_p)$

Fig. 9 $\Delta E_p = f(I_{TM}, di/dt)$

Steuerkennlinien

Gate characteristics

Caractéristiques de gâchette

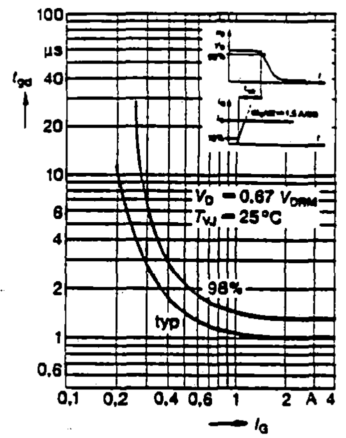


Fig. 10 $t_{gd} = f(I_G)$

t_{gd}
Zündverzugszeit
Turn-on delay time
Retard à la commande d'amorçage

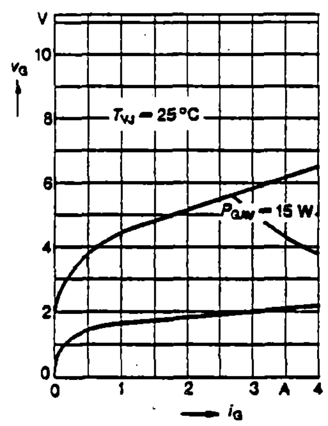


Fig. 11 $v_G = f(i_G)$, P_{GAV}

v_G, i_G
Steuerspannung und Steuerstrom
Gate voltage and gate current
Tension et courant de gâchette

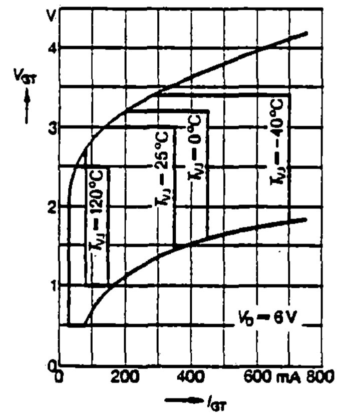


Fig. 12 $V_{GT} = f(I_{GT})$, T_{VJ}

V_{GT}, I_{GT}
Zündspannung und Zündstrom
Turn-on voltage and current
Tension et courant d'amorçage

Änderung der Freiwerdezeit

Typische Änderung der Freiwerdezeit bei Abweichung von den auf Seite 4 angegebenen Bedingungen.

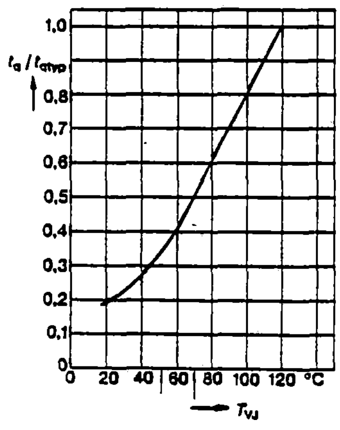


Fig. 13 $t_q/t_{qtyp} = f(T_{VJ})$

Variation of turn-off time

Typical variation of turn-off time at conditions differing from values on page 4.

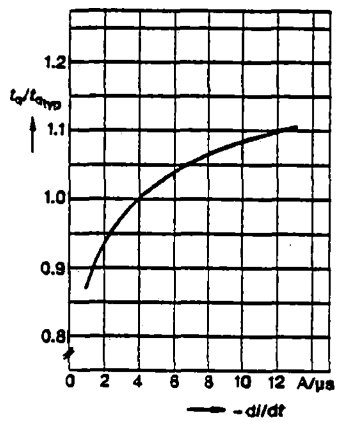


Fig. 14 $t_q/t_{qtyp} = f(-di/dt)$

Variation du temps de désamorçage

Variation typique du temps de désamorçage sous des conditions différant de celles de la page 4.

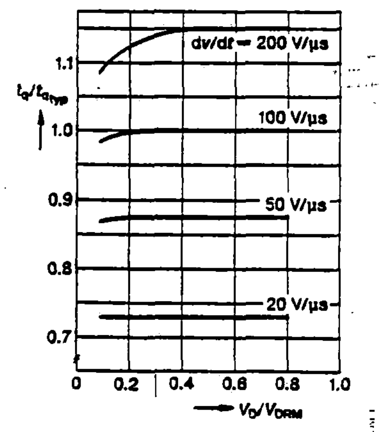


Fig. 15 $t_q/t_{qtyp} = f(V_D/V_{DRM}, dv/dt)$

Berechnung von t_q:

Calculation of t_q:

Calcul de t_q:

$$t_q = t_{qtyp} \cdot t_q/t_{qtyp}\,(T_{VJ}) \cdot t_q/t_{qtyp}\,(-di/dt) \cdot t_q/t_{qtyp}\,(V_D/V_{DRM},\, dv/dt)$$

wobei:
t_{qtyp}: auf Seite 4 ausgewiesene Werte
t_q : Wert bei abweichenden Bedingungen

wherein:
t_{qtyp}: at conditions stated on page 4
t_q : at varying conditions

où:
t_{qtyp}: selon conditions de la page 4
t_q : selon conditions variables

Dynamische Werte / Dynamic values / Valeurs dynamiques

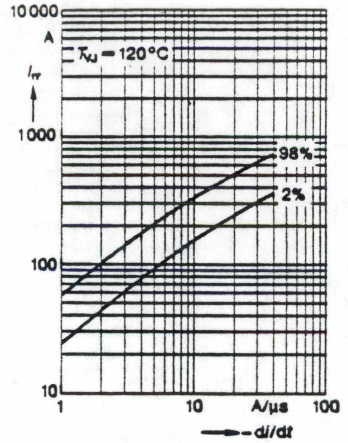


Fig. 16 $I_{rr} = f(-di/dt)$

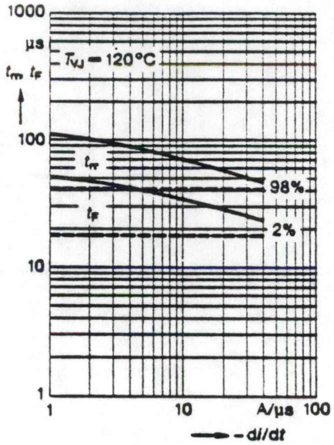


Fig. 17 $t_{rr}, t_F = f(-di/dt)$

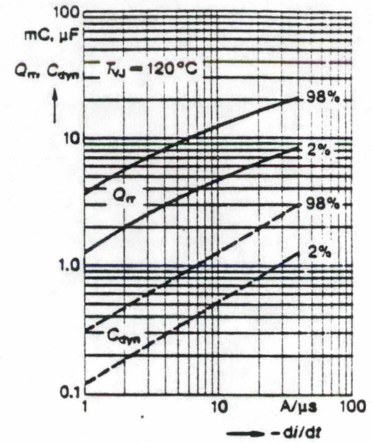


Fig. 18 $Q_{rr}, C_{dyn} = f(-di/dt)$

I_{rr}
Rückstromspitze
Peak reverse recovery current
Pointe de courant de recouvrement

t_{rr}
Sperrverzögerungszeit
Recovery time
Temps de recouvrement

t_F
Fallzeitkonstante
Fall time constant
Constante de temps de décroissance

Q_{rr}
Sperrverzögerungsladung
Recovery charge
Charge de recouvrement

C_{dyn}
Dynamische Sperrschichtkapazität
Dynamic junction capacitance
Capacité dynamique de jonction

Ausschaltverluste

Die Ausschaltverluste P_{RQ} werden anhand der dynamischen Werte aus den Fig. 16, 17, 18 und 19 bestimmt.

Turn-off losses

The turn-off losses P_{RQ} can be calculated using the dynamic values from Fig. 16, 17, 18 and 19.

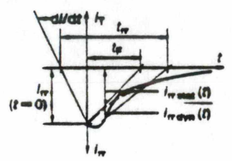
Pertes à l'extinction

On calcule les pertes à l'extinction P_{RQ} en utilisant les diagrammes des valeurs dynamiques selon les Fig. 16, 17, 18 et 19.

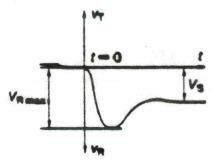
$$E_{RQ} = dv/dt \cdot I_{rr} \cdot t_F^2 \cdot \left(1 - e^{-\frac{V_S}{t_F \cdot dv/dt}}\right) + \tfrac{1}{2} C_{dyn} \cdot V_S^2$$

$$P_{RQ} = f \cdot E_{RQ}$$

Ausschaltvorgang / Turn-off process / Processus d'extinction



a



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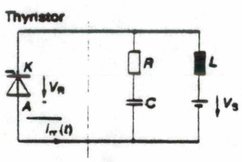

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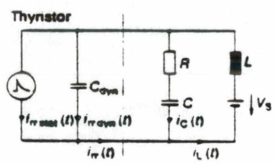


d

Fig. 19a Stromverlauf
Current curve
Allure du courant

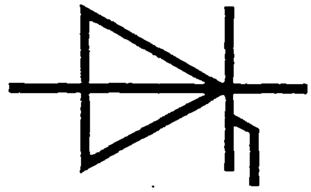
Fig. 19b Spannungsverlauf
Voltage curve
Allure de la tension

Fig. 19c Schaltung
Circuit diagram
Circuit

Fig. 19d Ersatzschaltbild
Equivalent circuit
Schéma équivalent

Thyristor
CS 2104

I_{TRMS} = 5000 A
I_{TAVM} = 2020 A
V_{RRM}, V_{DRM} = 4800...5000 V



Typenerklärung der Thyristoren

Beispiel: **CS 2104-50 lo 1**

C = Thyristor
S = Silizium
2104 = Stromkennwert in Ampere
50 = Spannungsklasse ≙ $10^{-2} \times V_{DRM}$
l = Kritische Spannungssteilheit $(dv/dt)_c$
o = Freiwerdezeit t_{qtyp}
1 = Ausführung

Type code of thyristors

Example: **CS 2104-50 lo 1**

C = Thyristor
S = Silicon
2104 = Approximate current rating in amperes
50 = Voltage class ≙ $10^{-2} \times V_{DRM}$
l = Critical voltage rise $(dv/dt)_c$
o = Turn-off time t_{qtyp}
1 = Version

Désignation des thyristors

Exemple: **CS 2104-50 lo 1**

C = Thyristor
S = Silicium
2104 = Courant approximatif en ampères
50 = Classe de tension ≙ $10^{-2} \times V_{DRM}$
l = Vitesse critique de croissance de la tension $(dv/dt)_c$
o = Temps de désamorçage t_{qtyp}
1 = Exécution

Identifikation **Identification** **Identification**

4800 V	5000 V			Ident.-No.
CS 2104-48 lo 1				HEKS 352916 R 1048
	CS 2104-50 lo 1			HEKS 352916 R 1050

Lieferbare Leistungsnetzthyristoren im 6-Zoll-Scheibengehäuse:

Available line frequency power thyristors in a 6-inch presspack housing:

Gamme des thyristors de puissance à fréquence de réseau disponibles en boitier-disque de 6 pouces:

Type	V_{RRM}, V_{DRM} (V)			
CS 2102	3200	3800	4200	4400
CS 2402	3200	3800	4200	4400
CS 2104	4800	5000		

Änderungen vorbehalten
Modifications reserved
Modifications réservées

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Aktiengesellschaft
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Classification No. 080101

APPENDIX D

PSPICE OUTPUT MODELS

```
**** 06/08/92 17:13:24 ********* PSpice 5.1 (Jan 1992) ******** ID# 59051 ****

 bjt602

 ****     CIRCUIT DESCRIPTION

*******************************************************************************

*SPICE_NET
.INCLUDE DT600.MOD

**** INCLUDING DT600.MOD ****
* DT600 model created using Parts version 5.1 on 03/12/92 at 16:14
*
.model DT600    NPN(Is=84.59p Xti=3 Eg=1.11 Vaf=100 Bf=466.9 Ise=84.59p
+               Ne=1.192 Ikf=165.3 Nk=.6454 Xtb=1.5 Br=1.004K Isc=4.049n
+               Nc=1.626 Ikr=60.72m Rc=0 Cjc=2p Mjc=.3333 Vjc=.75 Fc=.5 Cje=5p
+               Mje=.3333 Vje=.75 Tr=10n Tf=1n Itf=1 Xtf=0 Vtf=10)

**** RESUMING PS3404.CIR ****
.INCLUDE DIRK.MOD

**** INCLUDING DIRK.MOD ****
* DIRK model created using Parts version 5.1 on 03/18/92 at 11:20
*
.model DIRK     D(Is=63.17u N=2.05 Rs=777u Ikf=54.11m Xti=3 Eg=1.11 Cjo=1p
+               M=.3333 Vj=.75 Fc=.5 Isr=100p Nr=2 Bv=599.8 Ibv=43.11u
+               Tt=599.1n)

**** RESUMING PS3404.CIR ****
.INCLUDE GATEDR.SUB

**** INCLUDING GATEDR.SUB ****
*GATEDR.SUB
*1 17 = OUTPUT
* 10 13 = INPUT SWITCH
.SUBCKT SW2 1 2 3 4 5 6
SWON 1 2 5 6 ONSW
SWOFF 3 4 5 6 OFFSW
.MODEL ONSW VSWITCH(ROFF=100 RON=1E-3 VOFF=13.5 VON=14)
.MODEL OFFSW VSWITCH(ROFF=100 RON=1E-3 VOFF=13 VON=12.5)
.ENDS
.SUBCKT GATEDR 1 17 10 13
*OUTPUT LOAD R1 1 17 .0625
R2 6 2 0.1
R3 8 5 1E-3
L2 5 2 450N IC=-2
L3 3 6 10N IC=0
V1 7 17 5
V2 17 4 15
*INPUT VOLTAGE V3 10 13 PULSE -15 15 0 60E-6 60E-6 2E-3 5E-3
R4 10 0 1E6
X1 7 3 4 8 10 13 SW2
C1 2 17 1E-6
R5 4 0 1E6
```

```
L1 2 1 50N IC=-2
.ENDS

**** RESUMING PS3404.CIR ****
.MODEL ZD30 D(BV=50 IBV=1E-4)
.OPTIONS ITL5=40000 ITL4=400 ABSTOL=.01 VNTOL=.01 RELTOL=.001
.TRAN 1E-4 35E-3 10E-3 1E-4 UIC
Q2 2 42 3 DT600
Q3 4 5 126 DT600
D2 6 8 DIRK
D3 8 5 DIRK
D4 5 6 DIRK
R1 7 9 10
D5 7 9 DIRK
C1 9 10 2.5U IC=100
V1 3 10 0
V2 7 2 0
V3 7 4 0
V4 126 42 0
R2 11 7 .001
V5 11 0 200
Q4 12 13 14 DT600
Q5 12 13 14 DT600
Q6 16 17 15 DT600
D7 18 20 DIRK
D8 20 17 DIRK
D9 17 18 DIRK
R3 19 21 10
D10 19 21 DIRK
C2 21 0 2.5U IC=100
V6 14 0 0
V7 19 12 0
V8 19 16 0
V9 15 13 0
R4 28 23 .1
R5 38 26 .1
E2 27 0 26 0 1
R6 23 0 1E6
R7 26 0 1E6
R8 22 6 1
R9 27 18 1
R10 29 30 100
R11 30 31 1
R12 0 31 1E3
C3 30 0 .1E-6
V10 32 0 PULSE 0 12 0 200E-6 200E-6 20.0E-7 400.2E-6
V11 0 33 SIN 0 10 60 0 0 0
R13 33 0 1E6
E3 29 0 33 32 1000
R14 32 0 1E6
D11 0 31 ZD30
R15 33 29 1E5
R16 34 35 100
R17 35 36 1
R18 0 36 1E3
C4 35 0 .1E-6
V12 37 0 SIN 0 10 60 0 0 0
R19 37 0 1E6
E4 34 0 37 32 1000
D12 0 36 ZD30
```

```
R20 37 34 1E5
V13 36 38 15
R21 38 0 1E6
V14 31 28 15
R22 28 0 1E6
R23 39 41 30E-5
D13 10 7 DIRK
D14 0 19 DIRK
R24 126 10 1
R25 15 0 1
R26 22 10 1E5
R27 27 0 1E5
V15 10 149 0
V16 149 19 0
Q7 43 124 44 DT600
Q8 43 124 44 DT600
Q9 46 47 45 DT600
D16 48 50 DIRK
D17 50 47 DIRK
D18 47 48 DIRK
R28 49 51 10
D19 49 51 DIRK
C5 51 52 2.5U IC=100
V17 44 52 0
V18 49 43 0
V19 49 46 0
V20 45 124 0
R29 53 49 .001
V21 53 0 200
Q10 54 55 56 DT600
Q11 54 55 56 DT600
Q12 58 59 57 DT600
D21 60 62 DIRK
D22 62 59 DIRK
D23 59 60 DIRK
R30 61 63 10
D24 61 63 DIRK
C6 63 0 2.5U IC=100
V22 56 0 0
V23 61 54 0
V24 61 58 0
V25 57 55 0
R31 70 65 .1
R32 80 68 .1
E6 69 0 68 0 1
R33 65 0 1E6
R34 68 0 1E6
R35 64 48 1
R36 69 60 1
R37 71 72 100
R38 72 73 1
R39 0 73 1E3
C7 72 0 .1E-6
V26 74 0 PULSE 0 12 0 200E-6 200E-6 20.0E-7 400.2E-6
V27 0 75 SIN 0 10 60 0 0 240
R40 75 0 1E6
E7 71 0 75 74 1000
R41 74 0 1E6
D25 0 73 ZD30
R42 75 71 1E5
```

```
R43 76 77 100
R44 77 78 1
R45 0 78 1E3
C8 77 0 .1E-6
V28 79 0 SIN 0 10 60 0 0 240
R46 79 0 1E6
E8 76 0 79 74 1000
D26 0 78 ZD30
R47 79 76 1E5
V29 78 80 15
R48 80 0 1E6
V30 73 70 15
R49 70 0 1E6
R50 81 41 30E-5
D27 52 49 DIRK
D28 0 61 DIRK
R51 45 52 1
R52 57 0 1
R53 64 52 1E5
R54 69 0 1E5
V31 52 151 0
V32 151 61 0
Q13 83 84 85 DT600
Q14 83 84 85 DT600
Q15 87 88 127 DT600
D30 89 91 DIRK
D31 91 88 DIRK
D32 88 89 DIRK
R55 90 92 10
D33 90 92 DIRK
C9 92 93 2.5U IC=100
V33 85 93 0
V34 90 83 0
V35 90 87 0
V36 127 84 0
R56 94 90 .001
V37 94 0 200
Q16 95 96 97 DT600
Q17 95 96 97 DT600
Q18 99 100 98 DT600
D35 101 103 DIRK
D36 103 100 DIRK
D37 100 101 DIRK
R57 102 104 10
D38 102 104 DIRK
C10 104 0 2.5U IC=100
V38 97 0 0
V39 102 95 0
V40 102 99 0
V41 98 96 0
R58 111 106 .1
R59 121 109 .1
E10 110 0 109 0 1
R60 106 0 1E6
R61 109 0 1E6
R62 105 89 1
R63 110 101 1
R64 112 113 100
R65 113 114 1
R66 0 114 1E3
```

```
C11 113 0 .1E-6
V42 115 0 PULSE 0 12 0 200E-6 200E-6 20.0E-7 400.2E-6
V43 0 116 SIN 0 10 60 0 0 120
R67 116 0 1E6
E11 112 0 116 115 1000
R68 115 0 1E6
D39 0 114 ZD30
R69 116 112 1E5
R70 117 118 100
R71 118 119 1
R72 0 119 1E3
C12 118 0 .1E-6
V44 120 0 SIN 0 10 60 0 0 120
R73 120 0 1E6
E12 117 0 120 115 1000
D40 0 119 ZD30
R74 120 117 1E5
V45 119 121 15
R75 121 0 1E6
V46 114 111 15
R76 111 0 1E6
R77 122 41 30E-5
D41 93 90 DIRK
D42 0 102 DIRK
R78 127 93 1
R79 98 0 1
R80 105 93 1E5
R81 110 0 1E5
V47 93 150 0
V48 150 102 0
E13 105 93 106 0 1
E14 22 10 23 0 1
E15 64 52 65 0 1
R82 10 0 1E6
R83 93 0 1E6
R84 52 0 1E6
D1 6 7 DIRK
D6 18 19 DIRK
D29 89 90 DIRK
D34 101 102 DIRK
D15 48 49 DIRK
D20 60 61 DIRK
L1 149 39 250E-6 IC=0
L2 150 122 250E-6 IC=0
L3 151 81 250E-6 IC=0
Q1 2 42 [illegible] DT600
.END
```

bjt602

**** Diode MODEL PARAMETERS

****

	DIRK	ZD30
IS	63.170000E-06	10.000000E-15
N	2.05	
ISR	100.000000E-12	
IKF	.05411	
BV	599.8	50
IBV	43.110000E-06	100.000000E-06
RS	777.000000E-06	
TT	599.100000E-09	
CJO	1.000000E-12	
VJ	.75	
M	.3333	

bjt602

**** BJT MODEL PARAMETERS

****

	DT600
	NPN
IS	84.590000E-12
BF	466.9
NF	1
VAF	100
IKF	165.3
ISE	84.590000E-12
NE	1.192
BR	1.004000E+03
NR	1
IKR	.06072
ISC	4.049000E-09
NC	1.626
NK	.6454
CJE	5.000000E-12
MJE	.3333
CJC	2.000000E-12
MJC	.3333
TF	1.000000E-09
VTF	10
ITF	1
TR	10.000000E-09
XTB	1.5

JOB CONCLUDED

TOTAL JOB TIME 7186.70

GTO603

```
****     CIRCUIT DESCRIPTION

******************************************************************************


*SPICE_NET
.OPTIONS ITL4=500 RELTOL=.001 VNTOL=.01 ABSTOL=.01 ITL5=50000
.TRAN 1E-4 35E-3 10E-3 1E-4 UIC
.INC GATEDR.SUB

**** INCLUDING GATEDR.SUB ****
*GATEDR.SUB
*1 17 = OUTPUT
* 10 13 = INPUT SWITCH
.SUBCKT SW2 1 2 3 4 5 6
SWON 1 2 5 6 ONSW
SWOFF 3 4 5 6 OFFSW
.MODEL ONSW VSWITCH(ROFF=100 RON=1E-3 VOFF=13.5 VON=14)
.MODEL OFFSW VSWITCH(ROFF=100 RON=1E-3 VOFF=13 VON=12.5)
.ENDS
.SUBCKT GATEDR 1 17 10 13
*OUTPUT LOAD R1 1 17 .0625
R2 6 2 0.1
R3 8 5 1E-3
L2 5 2 450N IC=-2
L3 3 6 10N IC=0
V1 7 17 5
V2 17 4 15
*INPUT VOLTAGE V3 10 13 PULSE -15 15 0 60E-6 60E-6 2E-3 5E-3
R4 10 0 1E6
X1 7 3 4 8 10 13 SW2
C1 2 17 1E-6
R5 4 0 1E6
L1 2 1 50N IC=-2
.ENDS

**** RESUMING PS3404.CIR ****
* .INCLUDE DFW_GTO.MOD
.INCLUDE GTO1.SUB

**** INCLUDING GTO1.SUB ****
.SUBCKT GTO1 A G C
* 2/21/92
*REVISED J3 THYRISTOR MODEL OF THE
*TOSHIBA SG3000JX24,  ITGQ=3000A, ITRMS=1200A AND VDRM=6000V
.MODEL DA D(IS=1.19E-11,CJO=1E-6,M=0.33,TT=8E-6,BV=16)
.MODEL DC D(IS=1E-5,CJO=1E-6,M=0.33,TT=8E-6,BV=6000)
.MODEL DK D(IS=1.1E-4,CJO=0.5E-6,M=0.33,TT=0.1E-6,BV=18,IBV=1E-3)
.MODEL DA1 D(IS=1.19E-11)
.MODEL DKI D(IS=1.1E-4)
R1 A 3 1.15E-3
RA 3 4 1600
```

```
RC 4 G 25E3
RK G C 1600
DA 3 4 DA
DC G 4 DC
DK G C DK
VK 13 C 0
EA 12 C 3 4 1.0
FC 4 G POLY(2) VA VK 0. 1.0 1.0
DA1 12 6 DA1 0.2
VA 6 C 0
DKI 8 13 DKI 0.95
EK 8 C G C 1.0
.ENDS

**** RESUMING PS3404.CIR ****
* .INCLUDE SNUB_GTO.MOD
.MODEL DFW D(IS=1.23E-16 RS=.56E-3 VJ=1.15 CJO=1.28E-6 M=.25 TT=2.15E-6)
.MODEL ZD30 D(BV=50 IBV=1E-3)
.MODEL DFW_GTO D(BV=6000 IBV=1E-4)
.MODEL SNUB_GTO D(BV=6000 IBV=1E-4)
V5 36 0 2400
X9 2 32 6 GTO1
D8 79 2 DFW_GTO
D9 37 79 SNUB_GTO
C1 2 37 6E-6 IC=1200
R7 79 37 5
L1 38 2 12E-6
R8 38 102 .25
R15 43 52 100
R16 52 44 1
R18 0 44 1E3
C2 52 0 1E-6
V6 42 0 PULSE 0 12 0 400E-6 400E-6 20.0E-7 800.2E-6
V7 0 46 SIN 0 10 60
R19 46 0 1E6
E4 43 0 46 42 1000
R20 42 0 1E6
D11 0 44 ZD30
R21 46 43 1E5
R22 47 48 100
R23 48 55 1
R25 0 55 1E3
C3 48 0 1E-6
V9 51 0 SIN 0 10 60
R26 51 0 1E6
E5 47 0 51 42 1000
D12 0 55 ZD30
R28 51 47 1E5
V12 55 89 15
R29 89 0 1E6
V13 44 65 15
R30 65 0 1E6
X10 50 70 89 0 GATEDR
X11 79 50 70 GTO1
D13 83 79 DFW_GTO
D14 72 83 SNUB_GTO
C4 79 72 6E-6 IC=1200
R32 83 72 5
L9 83 0 12E-6
R33 121 83 .25
```

```
L17 36 38 100E-9 IC=0
X12 64 45 66 0 GATEDR
V20 67 0 2400
X13 85 64 45 GTO1
D16 35 85 DFW_GTO
D17 81 35 SNUB_GTO
C5 85 81 6E-6 IC=1200
R42 35 81 5
L18 69 85 12E-6
R43 69 121 .25
R46 88 90 100
R47 90 91 1
R48 0 91 1E3
C6 90 0 1E-6
V21 92 0 PULSE 0 12 0 400E-6 400E-6 20.0E-7 800.2E-6
V22 0 58 SIN 0 10 60 0 0 120
R49 58 0 1E6
E6 88 0 58 92 1000
R50 92 0 1E6
D19 0 91 ZD30
R51 58 88 1E5
R52 93 94 100
R53 94 95 1
R54 0 95 1E3
C7 94 0 1E-6
V23 41 0 SIN 0 10 60 0 0 120
R55 41 0 1E6
E7 93 0 41 92 1000
D20 0 95 ZD30
R56 41 93 1E5
V24 95 96 15
R57 96 0 1E6
V25 91 66 15
R58 66 0 1E6
X14 97 98 96 0 GATEDR
X15 35 97 98 GTO1
D21 1 35 DFW_GTO
D22 101 1 SNUB_GTO
C8 35 101 6E-6 IC=1200
R59 1 101 5
L23 1 0 12E-6
R60 124 1 .25
L29 67 69 100E-9 IC=0
R63 146 49 .003
R64 176 49 .003
L42 79 146 3E-3 IC=0
L43 35 176 3E-3 IC=0
V32 98 1 0
V33 45 35 0
V34 70 83 0
X20 109 103 110 0 GATEDR
V36 80 0 2400
X17 119 109 103 GTO1
D32 113 119 DFW_GTO
D33 115 113 SNUB_GTO
C9 119 115 6E-6
R87 113 115 5
L45 84 119 12E-6
R88 84 124 .25
R91 111 112 100
```

```
R92 112 74 1
R93 0 74 1E3
C14 112 0 1E-6
V37 114 0 PULSE 0 12 0 400E-6 400E-6 20.0E-7 800.2E-6
V38 0 104 SIN 0 10 60 0 0 240
R94 104 0 1E6
E10 111 0 104 114 1000
R95 114 0 1E6
D34 0 74 ZD30
R96 104 111 1E5
R97 75 117 100
R98 117 118 1
R99 0 118 1E3
C15 117 0 1E-6
V39 128 0 SIN 0 10 60 0 0 240
R100 128 0 1E6
E11 75 0 128 114 1000
D35 0 118 ZD30
R101 128 75 1E5
V40 118 131 15
R102 131 0 1E6
V41 74 110 15
R103 110 0 1E6
X22 132 133 131 0 GATEDR
X23 113 132 133 GTO1
D36 123 113 DFW_GTO
D37 136 123 SNUB_GTO
C12 113 136 6E-6
R104 123 136 5
L46 123 0 12E-6
R105 125 123 .25
L47 80 84 100E-9 IC=0
R108 127 49 .003
L48 113 127 3E-3 IC=0
V42 133 123 0
V43 103 113 0
R109 79 146 100
R110 35 176 100
R111 113 127 100
LGTO 6 79 25E-9
R112 32 6 100
D38 2 102 SNUB_GTO
D39 0 121 SNUB_GTO
D40 85 121 SNUB_GTO
D41 0 124 SNUB_GTO
D42 119 124 SNUB_GTO
D43 0 125 SNUB_GTO
X8 32 6 65 0 GATEDR
.END
```

**** 06/03/92 17:58:14 ********* PSpice 5.1 (Jan 1992) ******** ID# 59051 ****

GTO603

**** Diode MODEL PARAMETERS

****

	DFW	ZD30	DFW_GTO	SNUB_GTO
IS	123.000000E-18	10.000000E-15	10.000000E-15	10.000000E-15
BV		50	6.000000E+03	6.000000E+03
IBV		1.000000E-03	100.000000E-06	100.000000E-06
RS	560.000000E-06			
TT	2.150000E-06			
CJO	1.280000E-06			
VJ	1.15			
M	.25			

	X9.DA	X9.DC	X9.DK	X9.DA1
IS	11.900000E-12	10.000000E-06	110.000000E-06	11.900000E-12
BV	16	6.000000E+03	18	
IBV			1.000000E-03	
TT	8.000000E-06	8.000000E-06	100.000000E-09	
CJO	1.000000E-06	1.000000E-06	500.000000E-09	
M	.33	.33	.33	

	X9.DKI	X11.DA	X11.DC	X11.DK
IS	110.000000E-06	11.900000E-12	10.000000E-06	110.000000E-06
BV		16	6.000000E+03	18
IBV				1.000000E-03
TT		8.000000E-06	8.000000E-06	100.000000E-09
CJO		1.000000E-06	1.000000E-06	500.000000E-09
M		.33	.33	.33

	X11.DA1	X11.DKI	X13.DA	X13.DC
IS	11.900000E-12	110.000000E-06	11.900000E-12	10.000000E-06
BV			16	6.000000E+03
TT			8.000000E-06	8.000000E-06
CJO			1.000000E-06	1.000000E-06
M			.33	.33

	X13.DK	X13.DA1	X13.DKI	X15.DA
IS	110.000000E-06	11.900000E-12	110.000000E-06	11.900000E-12
BV	18			16
IBV	1.000000E-03			
TT	100.000000E-09			8.000000E-06
CJO	500.000000E-09			1.000000E-06
M	.33			.33

	X15.DC	X15.DK	X15.DA1	X15.DKI
IS	10.000000E-06	110.000000E-06	11.900000E-12	110.000000E-06
BV	6.000000E+03	18		
IBV		1.000000E-03		
TT	8.000000E-06	100.000000E-09		
CJO	1.000000E-06	500.000000E-09		
M	.33	.33		

	X17.DA	X17.DC	X17.DK	X17.DA1
IS	11.900000E-12	10.000000E-06	110.000000E-06	11.900000E-12
BV	16	6.000000E+03	18	
IBV			1.000000E-03	
TT	8.000000E-06	8.000000E-06	100.000000E-09	
CJO	1.000000E-06	1.000000E-06	500.000000E-09	
M	.33	.33	.33	

	X17.DKI	X23.DA	X23.DC	X23.DK
IS	110.000000E-06	11.900000E-12	10.000000E-06	110.000000E-06
BV		16	6.000000E+03	18
IBV				1.000000E-03
TT		8.000000E-06	8.000000E-06	100.000000E-09
CJO		1.000000E-06	1.000000E-06	500.000000E-09
M		.33	.33	.33

	X23.DA1	X23.DKI
IS	11.900000E-12	110.000000E-06

**** 06/03/92 17:58:14 ********* PSpice 5.1 (Jan 1992) ******** ID# 59051 ****

GTO603

**** Voltage Controlled Switch MODEL PARAMETERS

****

	X10.X1.ONSW	X10.X1.OFFSW	X12.X1.ONSW	X12.X1.OFFSW
RON	1.000000E-03	1.000000E-03	1.000000E-03	1.000000E-03
ROFF	100	100	100	100
VON	14	12.5	14	12.5
VOFF	13.5	13	13.5	13

	X14.X1.ONSW	X14.X1.OFFSW	X20.X1.ONSW	X20.X1.OFFSW
RON	1.000000E-03	1.000000E-03	1.000000E-03	1.000000E-03
ROFF	100	100	100	100
VON	14	12.5	14	12.5
VOFF	13.5	13	13.5	13

	X22.X1.ONSW	X22.X1.OFFSW	X8.X1.ONSW	X8.X1.OFFSW
RON	1.000000E-03	1.000000E-03	1.000000E-03	1.000000E-03
ROFF	100	100	100	100
VON	14	12.5	14	12.5
VOFF	13.5	13	13.5	13

JOB CONCLUDED

TOTAL JOB TIME 14156.13

****   CIRCUIT DESCRIPTION

****

```
*SPICE_NET
.INCLUDE IGBT1.SUB

**** INCLUDING IGBT1.SUB ****
.SUBCKT IGBT1 C G E
*
*
* THIS IS THE BIPOLAR TRANSISTOR OUTPUT SECTION
* OF THE IGBT:
*
* IGBT_PNP model created using Parts version 5.1
*        on 04/23/92 at 13:11
*
.MODEL IGBT_PNP PNP(Is=921.9n Xti=3 Eg=1.11 Vaf=100
+        Bf=1.092 Ise=2.777m Ne=1.821 Ikf=.804
+        Nk=.5062 Xtb=1.5 Br=2 Isc=9.219u Nc=1.5
+        Ikr=1 Rc=10m Cjc=3.208p Mjc=.3333 Vjc=.75
+        Fc=.5 Cje=1.326p Mje=.3333 Vje=.75 Tr=10n
+        Tf=8.011u Itf=4.134 Xtf=1m Vtf=10)
*
*
* THIS IS THE MOSFET INPUT STRUCTURE OF THE IGBT:
*
* IGBT_APT model created using Parts version 5.1
*        on 04/23/92 at 15:16
*
.MODEL IGBT_APT NMOS(Level=3 Gamma=0 Delta=0 Eta=0
+        Theta=0 Kappa=0 Vmax=0 Xj=0 Tox=100n Uo=600
+        Phi=.6 Kp=20.76u W=1.4 L=2u Rs=86.27u
+        Vto=3.626 Rd=9m Rds=5K Cbd=8.589n Pb=.8
+        Mj=.5 Fc=.5 Cgso=4n Cgdo=1n Rg=0 Is=10f
+        N=1 Rb=1m)
*
*
C1 1 E 1E-12
R1 C 1 .1
M1 1 G E E IGBT_APT
Q1 E 1 C IGBT_PNP
.ENDS

**** RESUMING PS3186.CIR ****
.TRAN 1E-4 100E-3 10E-3 1E-4 UIC
.MODEL ZD20 D(BV=20 IS=1E-6)
.INCLUDE DSE1.MOD

**** INCLUDING DSE1.MOD ****
* DSE1 model created using Parts version 5.1 on 04/24/92 at 15:37
```

```
*
.model DSE1      D(Is=773.8E-24 N=1.226 Rs=4.78m Ikf=.1241 Xti=3 Eg=1.11 Cjo=1p
+                M=.3333 Vj=.75 Fc=.5 Isr=48.93u Nr=2 Bv=1K Ibv=1.724m Tt=10.33n)

**** RESUMING PS3186.CIR ****
.INCLUDE RUR.MOD

**** INCLUDING RUR.MOD ****
.model rur d(bv=1000 is=1e-6)

**** RESUMING PS3186.CIR ****
.OPTIONS RELTOL=1E-3 VNTOL=.01 ABSTOL=.01 ITL4=500 ITL5=40000
.PROBE V(33) V(51) V(36) V(84) V(85) V(99) V(82) V(103) V(7)
+ V(10) V(91) V(97) V(57) V(63) V(47) V(65) V(69) V(49) V(50) V(1)
+ V(13) V(3) V(12) I(C12) I(C11) I(D30) I(D28) I(L16) I(L21) I(L1)
+ I(V22) I(V29) I(V21) I(V4) I(V13) V(92) V(23) V(18) V(19)
+ I(V32) I(V39) I(R73) I(R72) I(D27) V(109) I(V27) I(D41) I(D42)
+ I(D29) I(R74) I(D34) I(D35) I(D36) V(77) I(C16) V(81) I(L26)
*.PROBE V(109) V(103) I(V29) I(C11) I(V22) I(D27) V(82) I(V32) V(99)
*+  V(84) V(85) V(49) V(50) V(69) V(65) I(V39) I(C15) I(C16) V(80)
*+  V(81) V(110)
V1 2 0 400
V3 5 13 0
V4 82 3 0
R3 17 24 100
R4 24 5 1
R6 12 5 1E3
C1 24 12 .1E-6
V6 18 0 PULSE 0 12 0 200E-6 200E-6 20.0E-8 400.2E-6
V7 0 19 SIN 0 10 60
R7 19 0 1E6
E1 17 12 19 18 1000
R8 18 0 1E6
D1 12 5 ZD20
R9 19 17 1E5
R10 20 21 100
R11 21 16 1
R13 0 16 1E3
C2 21 0 .1E-6
V9 23 0 SIN 0 10 60
R14 23 0 1E6
E2 20 0 23 18 1000
D2 0 16 ZD20
R16 23 20 1E5
X2 1 7 10 IGBT1
V11 22 7 0
V12 40 1 0
V13 10 0 0
R18 16 22 1
L1 77 38 1.5E-3 IC=0
R20 38 28 .06E-3
L2 28 31 .05E-6
R21 31 39 .005E-3
R22 39 36 25E-3
L3 28 36 500N
D3 1 11 RUR
C3 11 0 .1E-6 IC=200
R24 1 11 100
R25 1 0 120K
D4 0 1 DSE1
```

```
D5 82 34 RUR
C4 34 12 .1E-6 IC=200
R26 82 34 100
R27 82 12 120K
D6 12 82 DSE1
R28 12 0 1E6
D7 0 1 DSE1
D8 0 1 DSE1
D9 0 1 DSE1
D10 12 82 DSE1
D11 12 82 DSE1
D12 12 82 DSE1
R31 5 12 100
R32 22 0 100
L4 33 40 .05E-6 IC=0
L5 12 33 .05E-6
X5 83 84 85 IGBT1
V21 87 84 0
V22 82 83 0
R57 89 90 100
R58 90 87 1
R59 85 87 1E3
C9 90 85 .1E-6
V23 91 0 PULSE 0 12 0 200E-6 200E-6 20.0E-8 400.2E-6
V24 0 92 SIN 0 10 60 0 0 120
R60 92 0 1E6
E5 89 85 92 91 1000
R61 91 0 1E6
D25 85 87 ZD20
R62 92 89 1E5
R63 93 94 100
R64 94 95 1
R65 0 95 1E3
C10 94 0 .1E-6
V25 97 0 SIN 0 10 60 0 0 120
R66 97 0 1E6
E6 93 0 97 91 1000
D26 0 95 ZD20
R67 97 93 1E5
X6 103 99 100 IGBT1
V27 102 99 0
V29 100 0 0
R68 95 102 1
L16 33 105 1.5E-3 IC=0
R69 105 106 .06E-3
L17 106 107 .05E-6
R70 107 108 .005E-3
R71 108 36 25E-3
L18 106 36 500N
D27 103 109 RUR
C11 109 0 .1E-6 IC=200
R72 103 109 100
R73 103 0 120K
D28 0 103 DSE1
D29 82 110 RUR
C12 110 85 .1E-6 IC=200
R74 82 110 100
R75 82 85 120K
D30 85 82 DSE1
R76 85 0 1E6
```

```
D31 0 103 DSE1
D32 0 103 DSE1
D33 0 103 DSE1
D34 85 82 DSE1
D35 85 82 DSE1
D36 85 82 DSE1
R79 87 85 100
R80 102 0 100
L19 77 103 .05E-6 IC=0
L20 85 77 .05E-6
X7 48 49 50 IGBT1
V31 52 49 0
V32 82 48 0
R81 55 56 100
R82 56 52 1
R83 50 52 1E3
C13 56 50 .1E-6
V33 57 0 PULSE 0 12 0 200E-6 200E-6 20.0E-8 400.2E-6
V34 0 47 SIN 0 10 60 0 0 240
R84 47 0 1E6
E7 55 50 47 57 1000
R85 57 0 1E6
D37 50 52 ZD20
R86 47 55 1E5
R87 59 60 100
R88 60 61 1
R89 0 61 1E3
C14 60 0 .1E-6
V35 63 0 SIN 0 10 60 0 0 240
R90 63 0 1E6
E8 59 0 63 57 1000
D38 0 61 ZD20
R91 63 59 1E5
X8 69 65 66 IGBT1
V37 68 65 0
V39 66 0 0
R92 61 68 1
L21 51 71 1.5E-3 IC=0
R93 71 72 .06E-3
L22 72 73 .05E-6
R94 73 74 .005E-3
R95 74 36 25E-3
L23 72 36 500N
D39 69 80 RUR
C15 80 0 .1E-6 IC=200
R96 69 80 100
R97 69 0 120K
D40 0 69 DSE1
D41 82 81 RUR
C16 81 50 .1E-6 IC=200
R98 82 81 100
R99 82 50 120K
D42 50 82 DSE1
R100 50 0 1E6
D43 0 69 DSE1
D44 0 69 DSE1
D45 0 69 DSE1
D46 50 82 DSE1
D47 50 82 DSE1
D48 50 82 DSE1
```

```
R103 52 50 100
R104 68 0 100
L24 51 69 .05E-6 IC=0
L25 50 51 .05E-6
L26 2 82 .1E-6
X1 3 13 12 IGBT1
.END
```

IGBT512

**** Diode MODEL PARAMETERS

****

	ZD20	DSE1	rur
IS	1.000000E-06	773.800000E-24	1.000000E-06
N		1.226	
ISR		48.930000E-06	
IKF		.1241	
BV	20	1.000000E+03	1.000000E+03
IBV		1.724000E-03	
RS		4.780000E-03	
TT		10.830000E-09	
CJO		1.000000E-12	
VJ		.75	
M		.3333	

IGBT512

**** BJT MODEL PARAMETERS

****

	X2.IGBT_PNP PNP	X5.IGBT_PNP PNP	X6.IGBT_PNP PNP	X7.IGBT_PNP PNP
IS	921.900000E-09	921.900000E-09	921.900000E-09	921.900000E-09
BF	1.092	1.092	1.092	1.092
NF	1	1	1	1
VAF	100	100	100	100
IKF	.804	.804	.804	.804
ISE	2.777000E-03	2.777000E-03	2.777000E-03	2.777000E-03
NE	1.821	1.821	1.821	1.821
BR	2	2	2	2
NR	1	1	1	1
IKR	1	1	1	1
ISC	9.219000E-06	9.219000E-06	9.219000E-06	9.219000E-06
NC	1.5	1.5	1.5	1.5
NK	.5062	.5062	.5062	.5062
RC	.01	.01	.01	.01
CJE	1.326000E-12	1.326000E-12	1.326000E-12	1.326000E-12
MJE	.3333	.3333	.3333	.3333
CJC	3.208000E-12	3.208000E-12	3.208000E-12	3.208000E-12
MJC	.3333	.3333	.3333	.3333
TF	8.011000E-06	8.011000E-06	8.011000E-06	8.011000E-06
XTF	1.000000E-03	1.000000E-03	1.000000E-03	1.000000E-03
VTF	10	10	10	10
ITF	4.134	4.134	4.134	4.134
TR	10.000000E-09	10.000000E-09	10.000000E-09	10.000000E-09
XTB	1.5	1.5	1.5	1.5

	X8.IGBT_PNP PNP	X1.IGBT_PNP PNP
IS	921.900000E-09	921.900000E-09
BF	1.092	1.092
NF	1	1
VAF	100	100
IKF	.804	.804
ISE	2.777000E-03	2.777000E-03
NE	1.821	1.821
BR	2	2
NR	1	1
IKR	1	1
ISC	9.219000E-06	9.219000E-06
NC	1.5	1.5
NK	.5062	.5062
RC	.01	.01
CJE	1.326000E-12	1.326000E-12
MJE	.3333	.3333

CJC	3.208000E-12	3.208000E-12
MJC	.3333	.3333
TF	8.011000E-06	8.011000E-06
XTF	1.000000E-03	1.000000E-03
VTF	10	10
ITF	4.134	4.134
TR	10.000000E-09	10.000000E-09
XTB	1.5	1.5

**** 05/12/92 09:51:18 ********** PSpice 5.1 (Jan 1992) ********* ID# 59051 ****

IGBT512

****   MOSFET MODEL PARAMETERS

****

	X2.IGBT_APT	X5.IGBT_APT	X6.IGBT_APT	X7.IGBT_APT
	NMOS	NMOS	NMOS	NMOS
LEVEL	3	3	3	3
L	2.000000E-06	2.000000E-06	2.000000E-06	2.000000E-06
W	1.4	1.4	1.4	1.4
VTO	3.626	3.626	3.626	3.626
KP	20.760000E-06	20.760000E-06	20.760000E-06	20.760000E-06
GAMMA	0	0	0	0
PHI	.6	.6	.6	.6
RD	9.000000E-03	9.000000E-03	9.000000E-03	9.000000E-03
RS	86.270000E-06	86.270000E-06	86.270000E-06	86.270000E-06
RB	1.000000E-03	1.000000E-03	1.000000E-03	1.000000E-03
RDS	5.000000E+03	5.000000E+03	5.000000E+03	5.000000E+03
PBSW	.8	.8	.8	.8
CBD	8.589000E-09	8.589000E-09	8.589000E-09	8.589000E-09
CGSO	4.000000E-09	4.000000E-09	4.000000E-09	4.000000E-09
CGDO	1.000000E-09	1.000000E-09	1.000000E-09	1.000000E-09
TOX	100.000000E-09	100.000000E-09	100.000000E-09	100.000000E-09

	X8.IGBT_APT	X1.IGBT_APT
	NMOS	NMOS
LEVEL	3	3
L	2.000000E-06	2.000000E-06
W	1.4	1.4
VTO	3.626	3.626
KP	20.760000E-06	20.760000E-06
GAMMA	0	0
PHI	.6	.6
RD	9.000000E-03	9.000000E-03
RS	86.270000E-06	86.270000E-06
RB	1.000000E-03	1.000000E-03
RDS	5.000000E+03	5.000000E+03
PBSW	.8	.8
CBD	8.589000E-09	8.589000E-09
CGSO	4.000000E-09	4.000000E-09
CGDO	1.000000E-09	1.000000E-09
TOX	100.000000E-09	100.000000E-09

JOB CONCLUDED

TOTAL JOB TIME   2490.83

APPENDIX E

SIMULATION CODES FOR 40 METRIC TON AND 100 METRIC TON VEHICLES

```
10 'Magpwr.bas - 40 tons + 100 passengers (83 m/s)
20 DIM V(500),FAD(500),FL(500),FD(500),FDRAG(500),TOTF(500),PWR(500)
30 DT=1:'second
40 PL=100*250/2.2:'payload of 100 passengers/baggage
50 VM=40000!:'vehicle mass
60 M=VM+PL
70 CD=.3:'Air drag coeff
80 A=9:'Front area m^2
90 ACC=1:'m/s^2
100 P=1.2:'density of air - kg/m^3
110 V(0)=0:'m/s
120 OPEN "magpwr.dat" FOR OUTPUT AS #1
130 FOR I=0 TO 500
140 FAD(I)=.5*CD*A*P*V(I)^2
150 FAC=M*ACC
160 IF V(I)<=0 THEN V(I)=0:FL(I)=0:FAC=0:FAD(I)=0:GOTO 180
170 FL(I)=1-2.7182818#^-(V(I)/15):'normalized lift force
180 IF V(I)=0 THEN FD(I)=0:GOTO 200
190 FD(I)=2.75*FL(I)/V(I)
200 FDRAG(I)=FD(I)*M*9.810001+FAD(I)
210 TOTF(I)=FDRAG(I)+FAC
220 PWR(I)=TOTF(I)*V(I)
230 V(I+1)=V(I)+ACC*DT
240 IF V(I)>83 THEN ACC=0
250 IF I>300 THEN ACC=-2:'decelerate at .2g
260 IF I>300 AND V(I)<=0 THEN ACC=0
270 WRITE #1,I,V(I),FAD(I),FL(I),FD(I),FDRAG(I),TOTF(I),PWR(I)
280 NEXT I
290 CLOSE #1
300 END
```

```
10 'Magpwr.bas - 100 tons + 100 passengers (83 m/s)
20 DIM V(500),FAD(500),FL(500),FD(500),FDRAG(500),TOTF(500),PWR(500)
30 DT=1:'second
40 PL=100*250/2.2:'payload of 100 passengers/baggage
50 VM=100000!:'vehicle mass
60 M=VM+PL
70 CD=.3:'Air drag coeff
80 A=9:'Front area m^2
90 ACC=1:'m/s^2
100 P=1.2:'density of air - kg/m^3
110 V(0)=0:'m/s
120 OPEN "magpwr.dat" FOR OUTPUT AS #1
130 FOR I=0 TO 500
140 FAD(I)=.5*CD*A*P*V(I)^2
150 FAC=M*ACC
160 IF V(I)<=0 THEN V(I)=0:FL(I)=0:FAC=0:FAD(I)=0:GOTO 180
170 FL(I)=1-2.7182818#^-(V(I)/15):'normalized lift force
180 IF V(I)=0 THEN FD(I)=0:GOTO 200
190 FD(I)=2.75*FL(I)/V(I)
200 FDRAG(I)=FD(I)*M*9.810001+FAD(I)
210 TOTF(I)=FDRAG(I)+FAC
220 PWR(I)=TOTF(I)*V(I)
230 V(I+1)=V(I)+ACC*DT
240 IF V(I)>83 THEN ACC=0
250 IF I>300 THEN ACC=-2:'decelerate at .2g
260 IF I>300 AND V(I)<=0 THEN ACC=0
270 WRITE #1,I,V(I),FAD(I),FL(I),FD(I),FDRAG(I),TOTF(I),PWR(I)
280 NEXT I
290 CLOSE #1
300 END
```

```
10 'Magpwr.bas - 40 tons + 100 passengers (135 m/s)
20 DIM V(500),FAD(500),FL(500),FD(500),FDRAG(500),TOTF(500),PWR(500)
30 DT=1:'second
40 PL=100*250/2.2:'payload of 100 passengers/baggage
50 VM=40000!:'vehicle mass
60 M=VM+PL
70 CD=.3:'Air drag coeff
80 A=9:'Front area m^2
90 ACC=1:'m/s^2
100 P=1.2:'density of air - kg/m^3
110 V(0)=0:'m/s
120 OPEN "magpwr.dat" FOR OUTPUT AS #1
130 FOR I=0 TO 500
140 FAD(I)=.5*CD*A*P*V(I)^2
150 FAC=M*ACC
160 IF V(I)<=0 THEN V(I)=0:FL(I)=0:FAC=0:FAD(I)=0:GOTO 180
170 FL(I)=1-2.7182818#^-(V(I)/15):'normalized lift force
180 IF V(I)=0 THEN FD(I)=0:GOTO 200
190 FD(I)=2.75*FL(I)/V(I)
200 FDRAG(I)=FD(I)*M*9.810001+FAD(I)
210 TOTF(I)=FDRAG(I)+FAC
220 PWR(I)=TOTF(I)*V(I)
230 V(I+1)=V(I)+ACC*DT
240 IF V(I)>139 THEN ACC=0
250 IF I>300 THEN ACC=-2:'decelerate at .2g
260 IF I>300 AND V(I)<=0 THEN ACC=0
270 WRITE #1,I,V(I),FAD(I),FL(I),FD(I),FDRAG(I),TOTF(I),PWR(I)
280 NEXT I
290 CLOSE #1
300 END
```

```
10 'Magpwr.bas - 100 tons + 100 passengers (13 m/s)
20 DIM V(500),FAD(500),FL(500),FD(500),FDRAG(500),TOTF(500),PWR(500)
30 DT=1:'second
40 PL=100*250/2.2:'payload of 100 passengers/baggage
50 VM=100000!:'vehicle mass
60 M=VM+PL
70 CD=.3:'Air drag coeff
80 A=9:'Front area m^2
90 ACC=1:'m/s^2
100 P=1.2:'density of air - kg/m^3
110 V(0)=0:'m/s
120 OPEN "magpwr.dat" FOR OUTPUT AS #1
130 FOR I=0 TO 500
140 FAD(I)=.5*CD*A*P*V(I)^2
150 FAC=M*ACC
160 IF V(I)<=0 THEN V(I)=0:FL(I)=0:FAC=0:FAD(I)=0:GOTO 180
170 FL(I)=1-2.7182818#^-(V(I)/15):'normalized lift force
180 IF V(I)=0 THEN FD(I)=0:GOTO 200
190 FD(I)=2.75*FL(I)/V(I)
200 FDRAG(I)=FD(I)*M*9.810001+FAD(I)
210 TOTF(I)=FDRAG(I)+FAC
220 PWR(I)=TOTF(I)*V(I)
230 V(I+1)=V(I)+ACC*DT
240 IF V(I)>139 THEN ACC=0
250 IF I>300 THEN ACC=-2:'decelerate at .2g
260 IF I>300 AND V(I)<=0 THEN ACC=0
270 WRITE #1,I,V(I),FAD(I),FL(I),FD(I),FDRAG(I),TOTF(I),PWR(I)
280 NEXT I
290 CLOSE #1
300 END
```

APPENDIX F

CALCULATED POWER REQUIREMENTS FOR 40 METRIC TON AND 100 METRIC TON VEHICLES @ 83 m/s

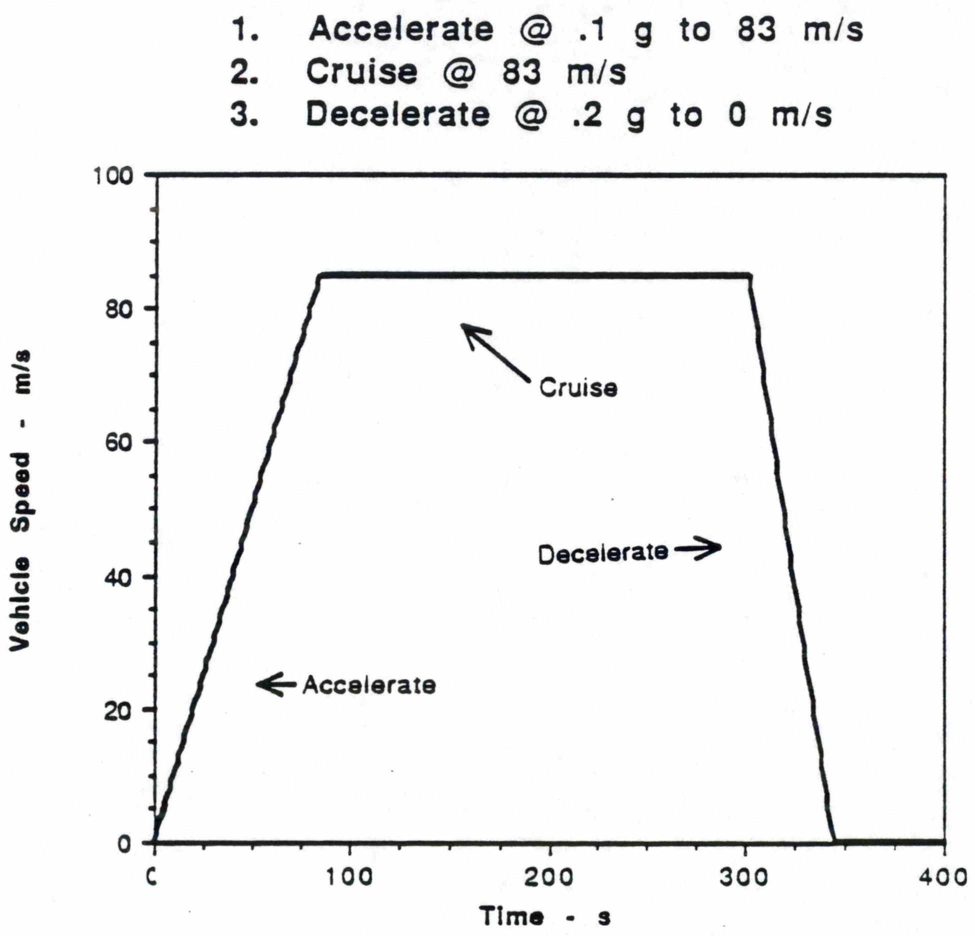

Figure F-1. Simulated trip with 83 m/s top speed

1. Accelerate @ .1 g to 83 m/s
2. Cruise @ 83 m/s
3. Decelerate @ .2 g to 0 m/s

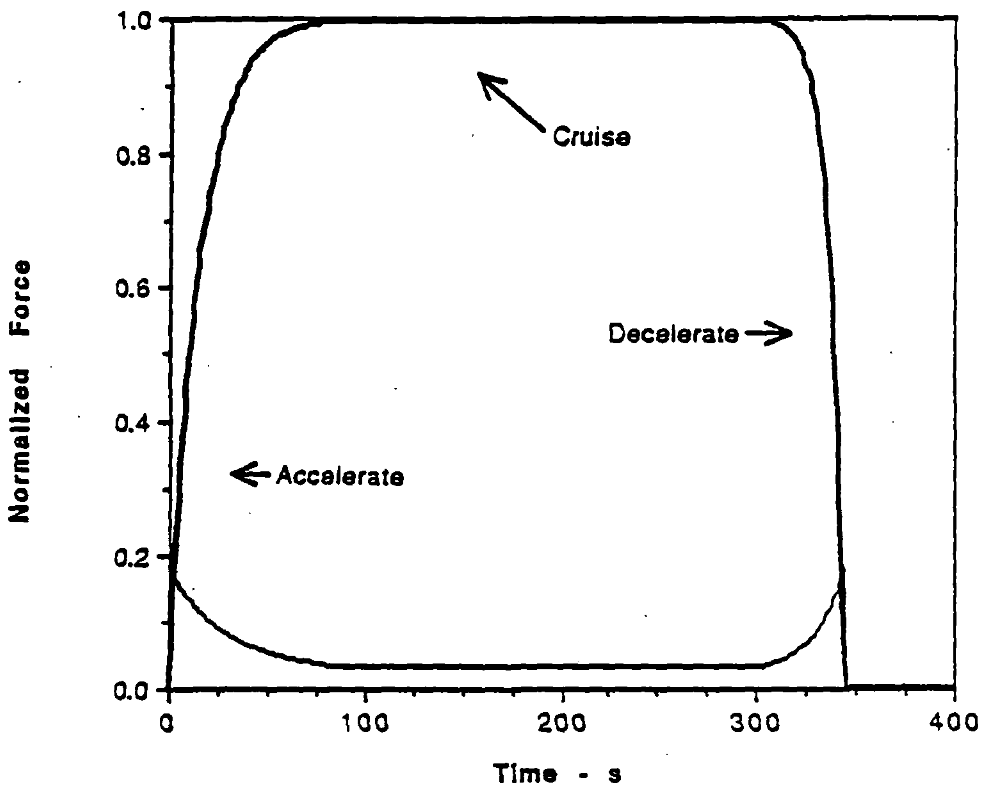

Figure F-2. Normalized magnetic lift and drag forces

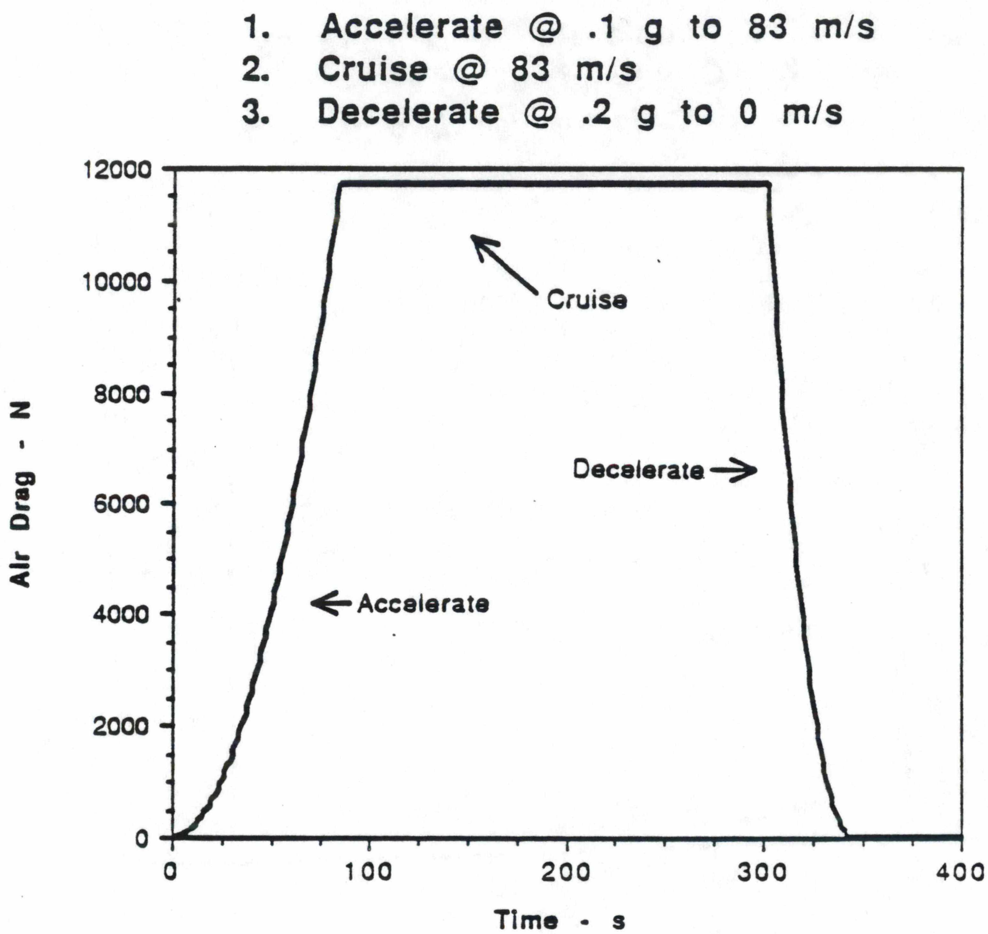

Figure F-3. Air drag force

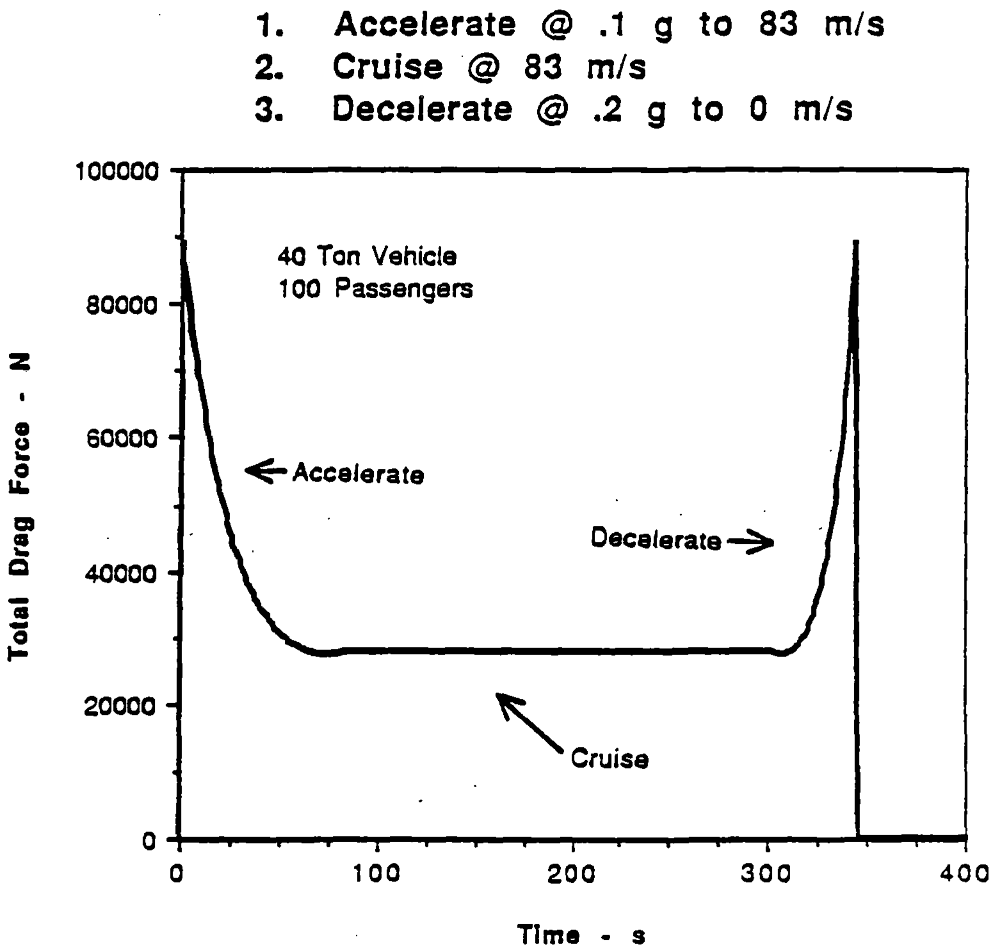

Figure F-4. Total drag force

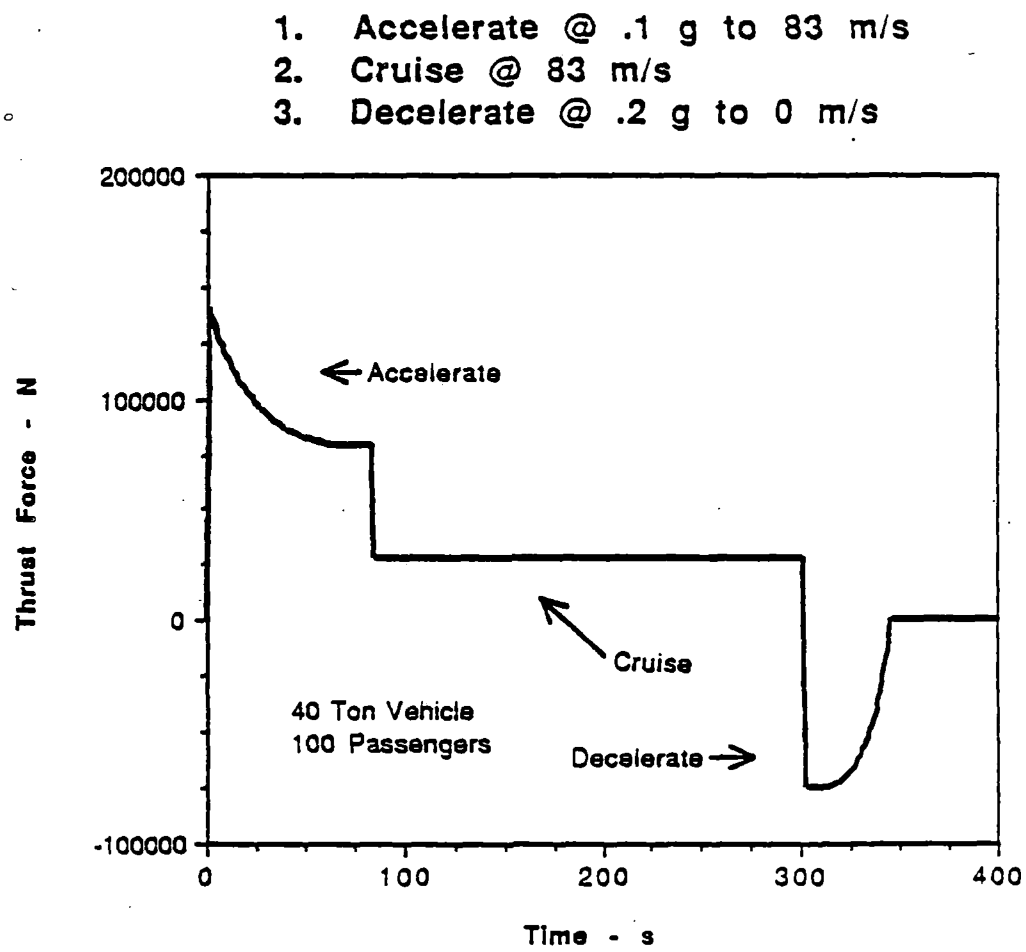

Figure F-5. Total thrust force for 40 ton vehicle

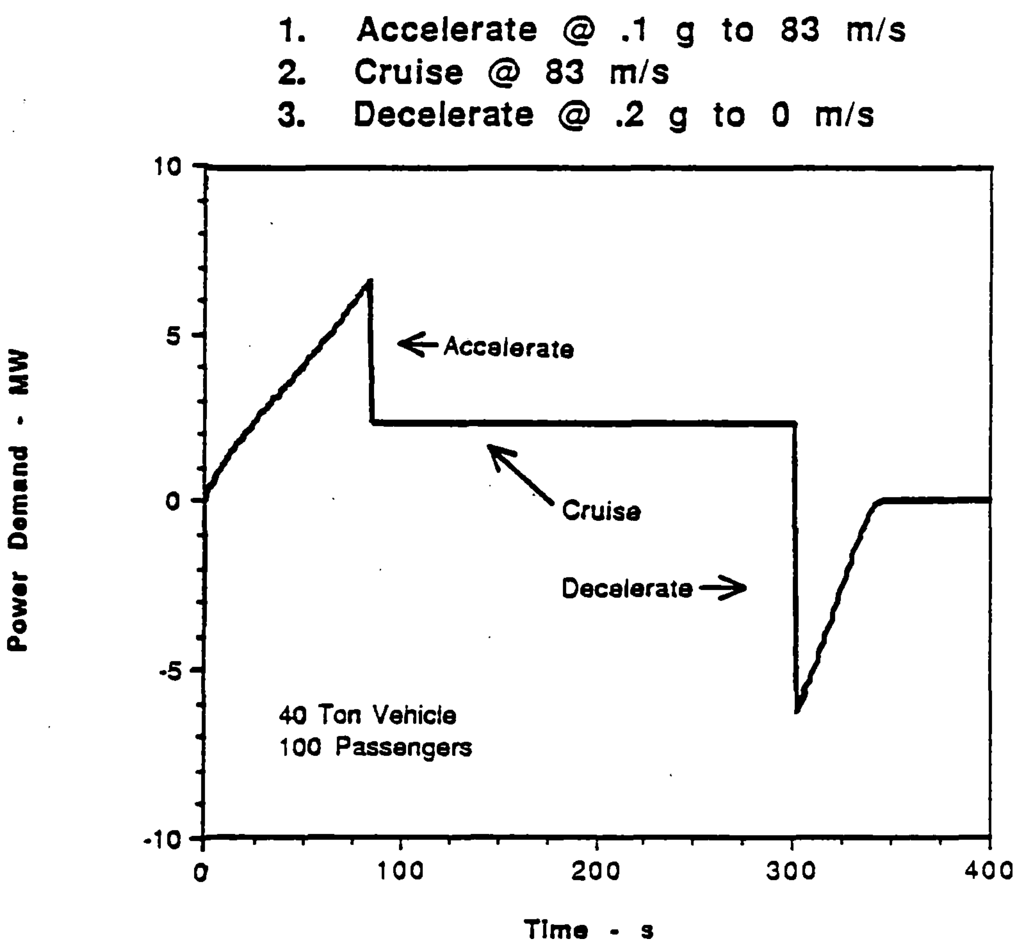

Figure F-6. Power demand for 40 ton vehicle

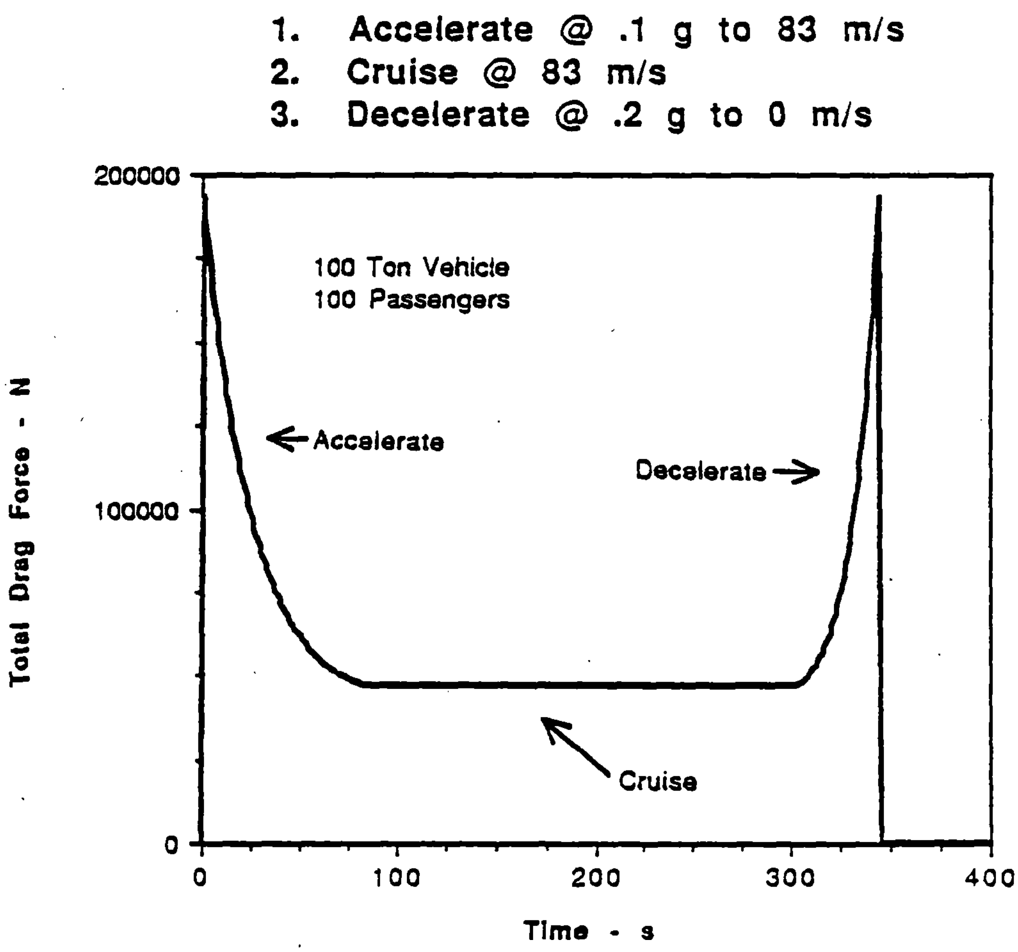

Figure F-7. Total drag force for 100 ton vehicle

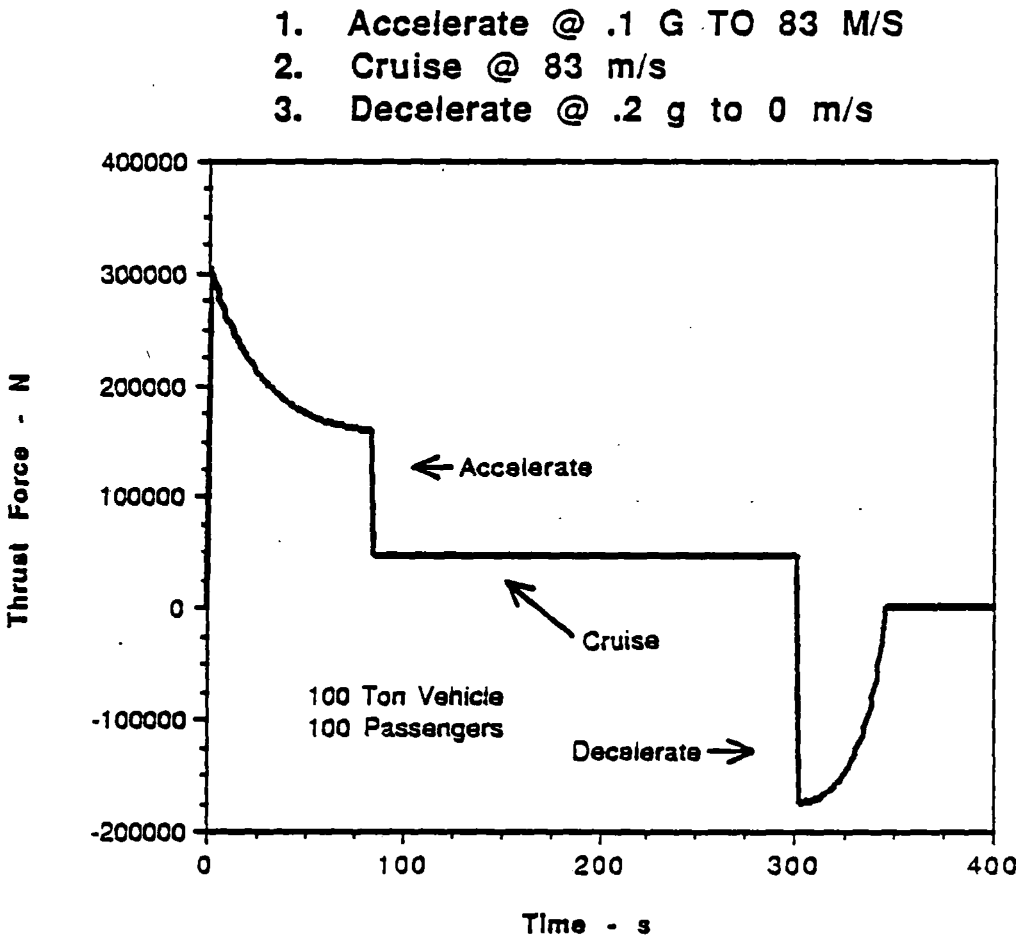

Figure F-8. Total thrust force for 100 ton vehicle

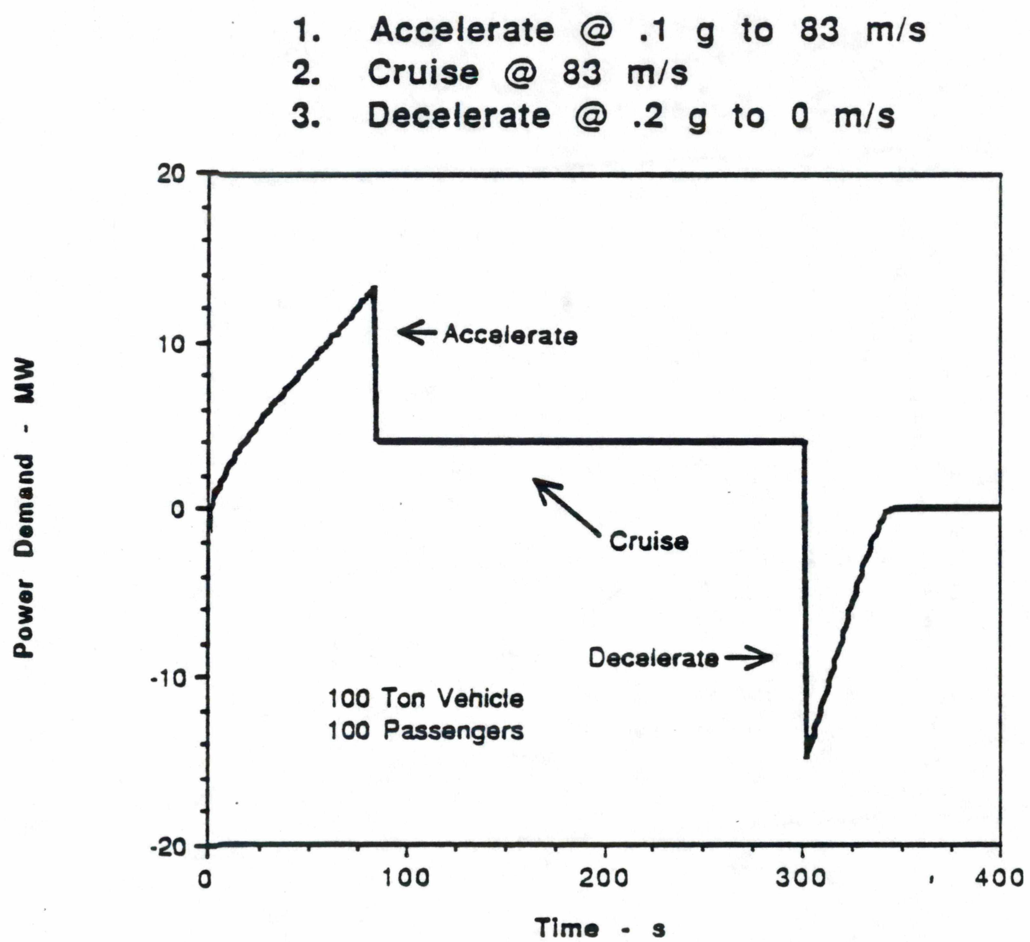

Figure F-9. Power demand for 100 ton vehicle

APPENDIX G

CALCULATED POWER REQUIREMENTS FOR 40 METRIC TON AND 100 METRIC TON VEHICLES @ 135 m/s

1. Accelerate @ .1 g to 135 m/s
2. Cruise @ 135 m/s
3. Decelerate @ .2 g to 0 m/s

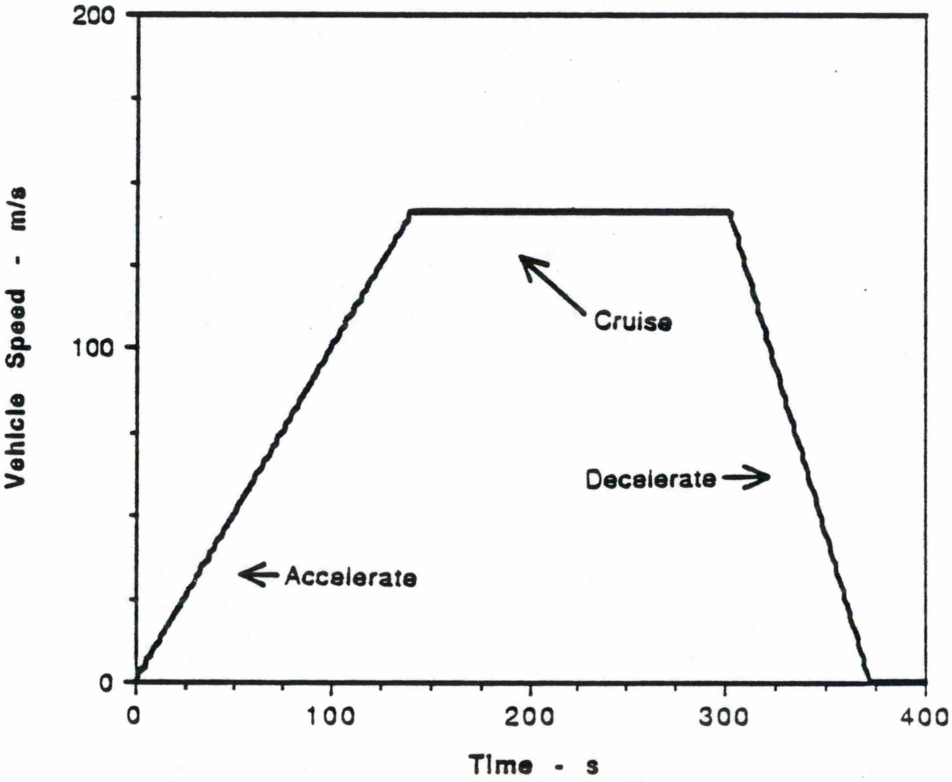

Figure G-1. Simulated trip with ~~129~~ 135 m/s top speed

1. Accelerate @ .1 g to 135 m/s
2. Cruise @ 135 m/s
3. Decelerate @ .2 g to 0 m/s

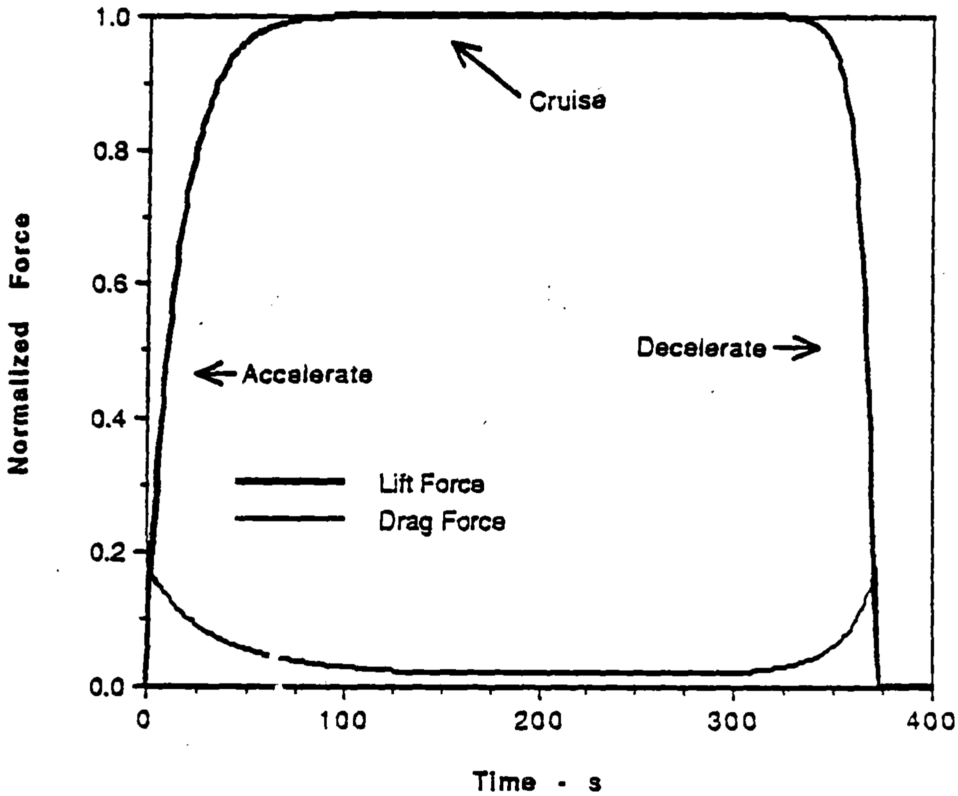

Figure G-2. Normalized magnetic lift and drag forces

1. Accelerate @ .1 g to 135 m/s
2. Cruise @ 135 m/s
3. Decelerate @ .2 g to 0 m/s

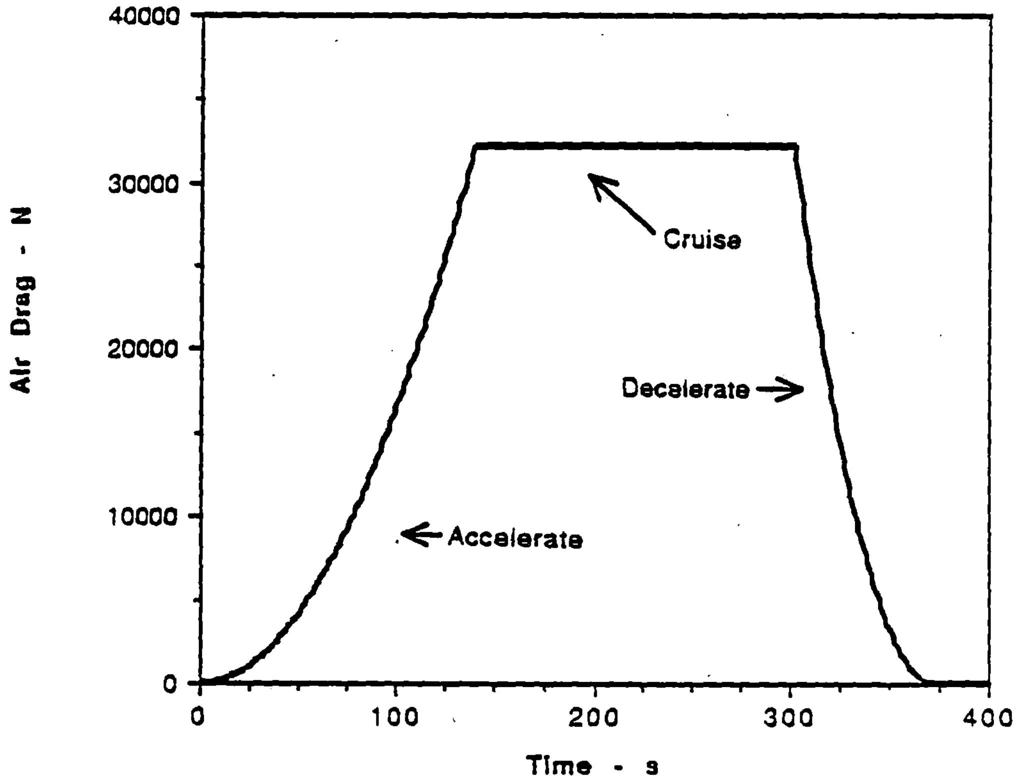

Figure G-3. Air drag force

1. Accelerate @ .1 g to 135 m/s
2. Cruise @ 135 m/s
3. Decelerate @ .2 g to 0 m/s

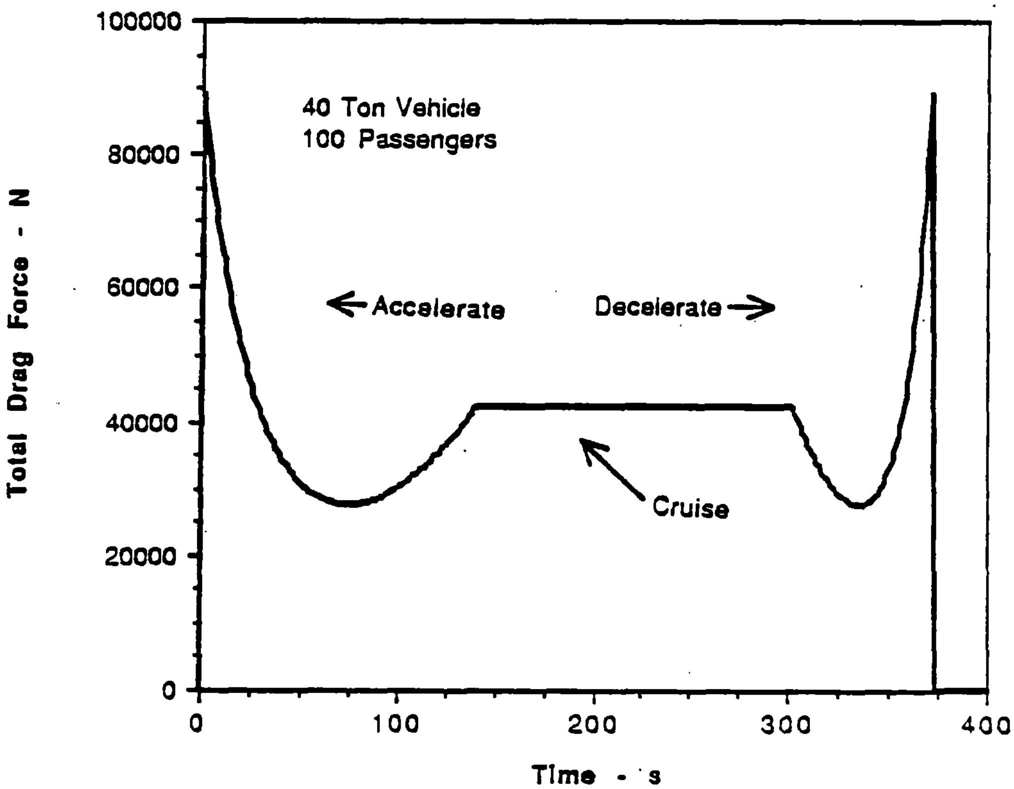

Figure G-4. Total drag force

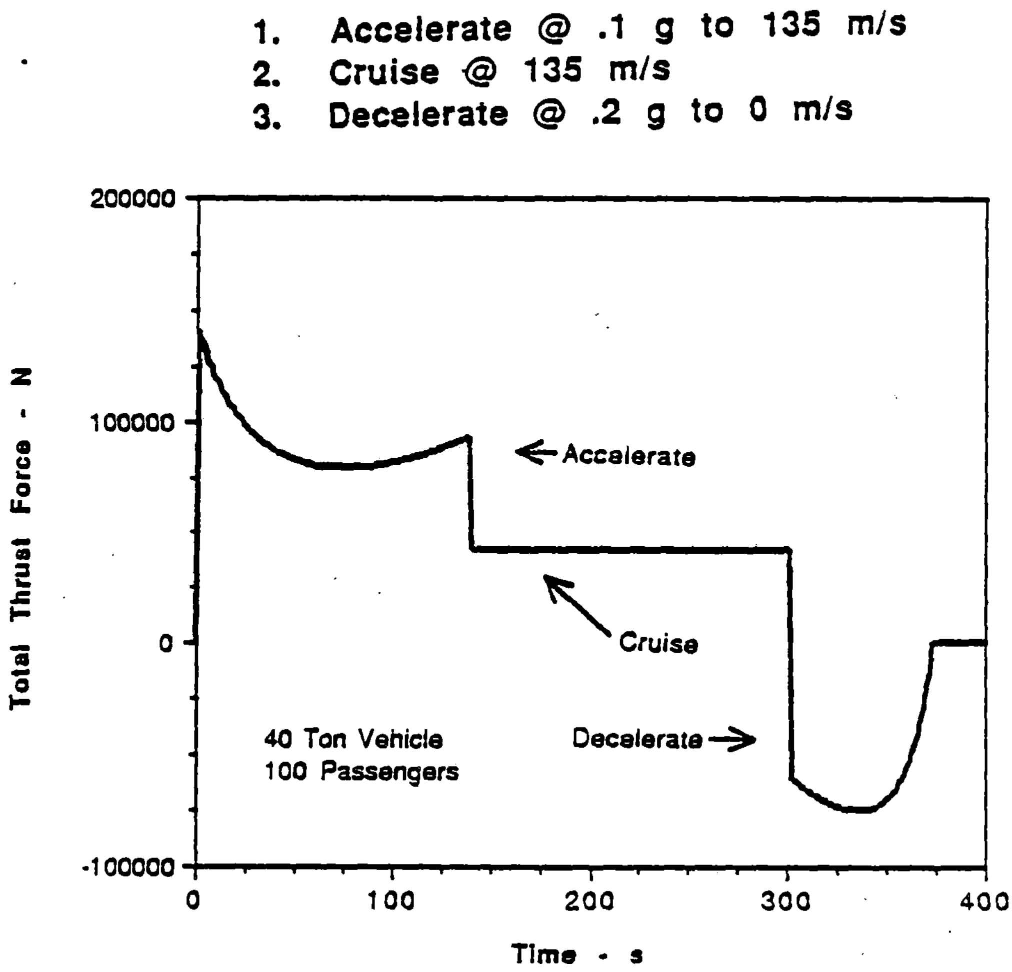

Figure G-5. Total thrust force for 40 ton vehicle

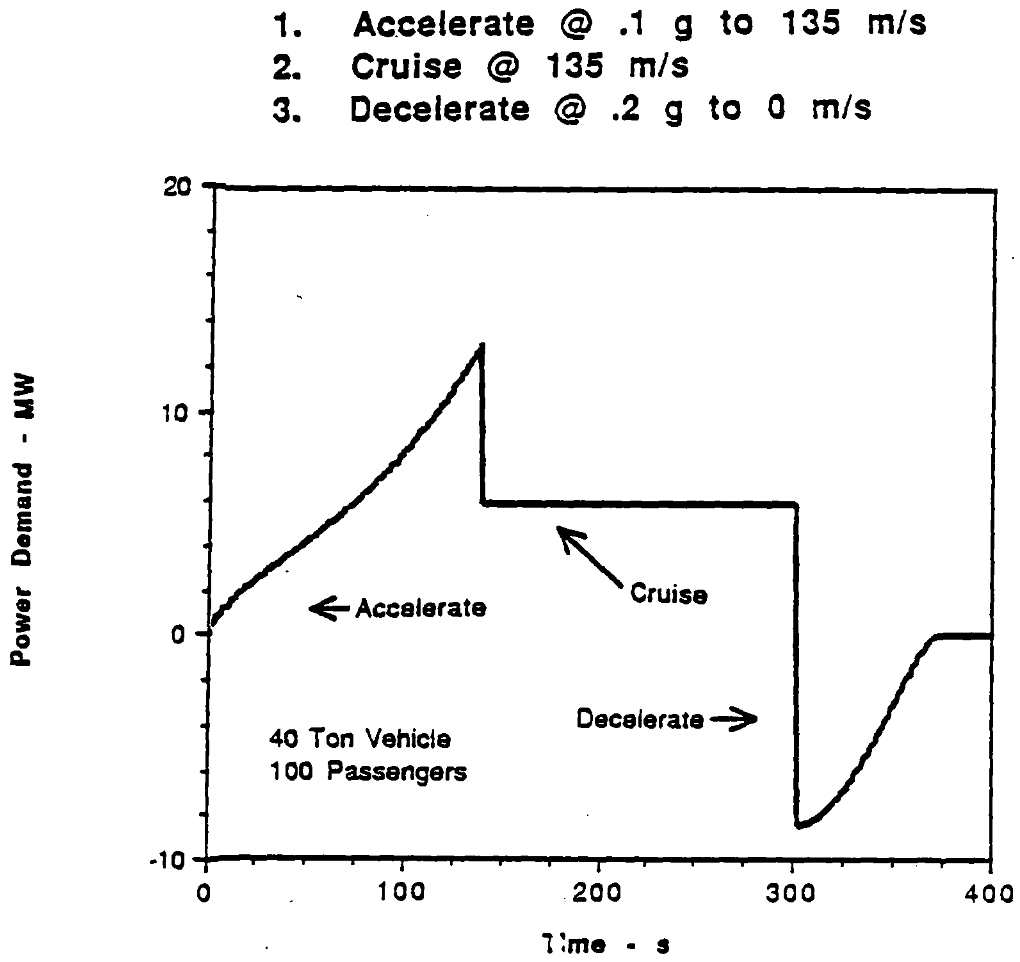

Figure G-6. Power demand for 40 ton vehicle

1. Accelerate @ .1 g to 135 m/s
2. Cruise @ 135 m/s
3. Decelerate @ .2 g to 0 m/s

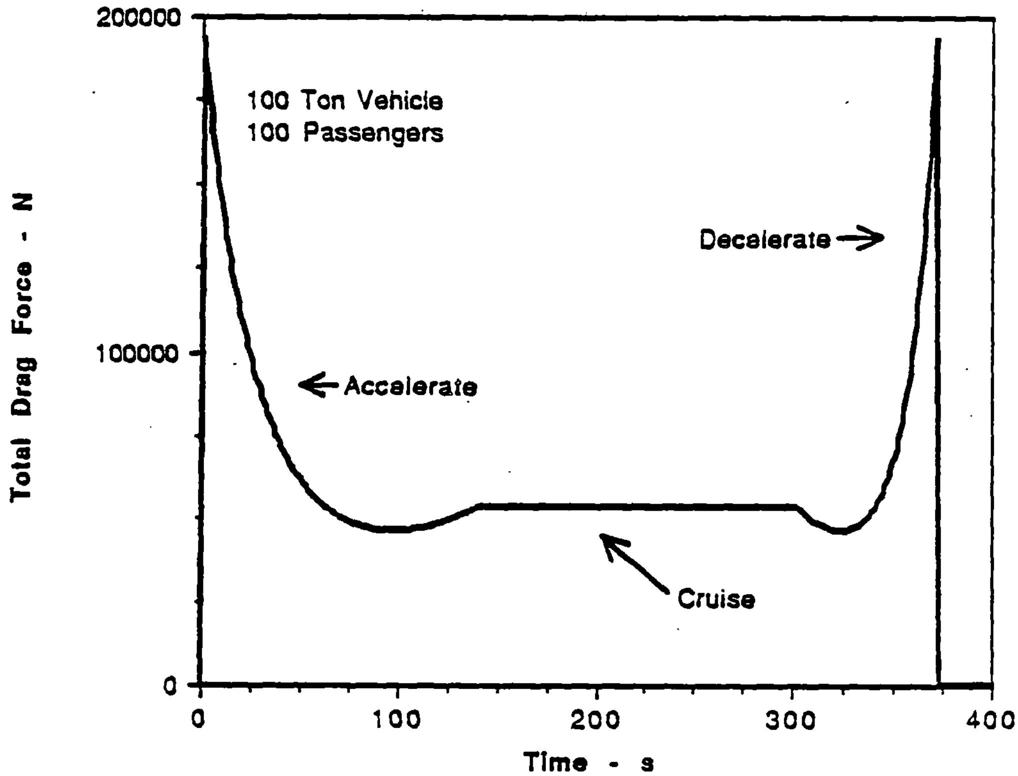

Figure G-7. Total drag force for 100 ton vehicle

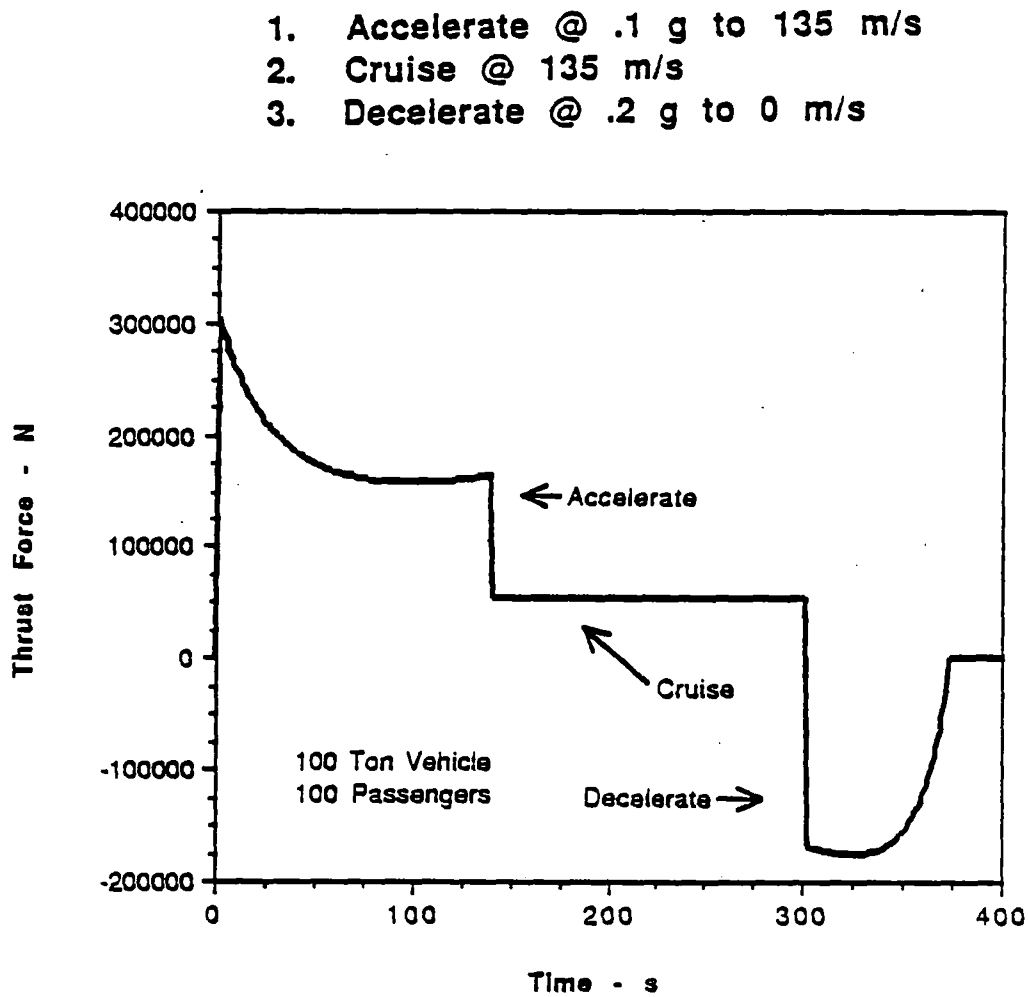

Figure G-8. Total thrust force for 100 ton vehicle

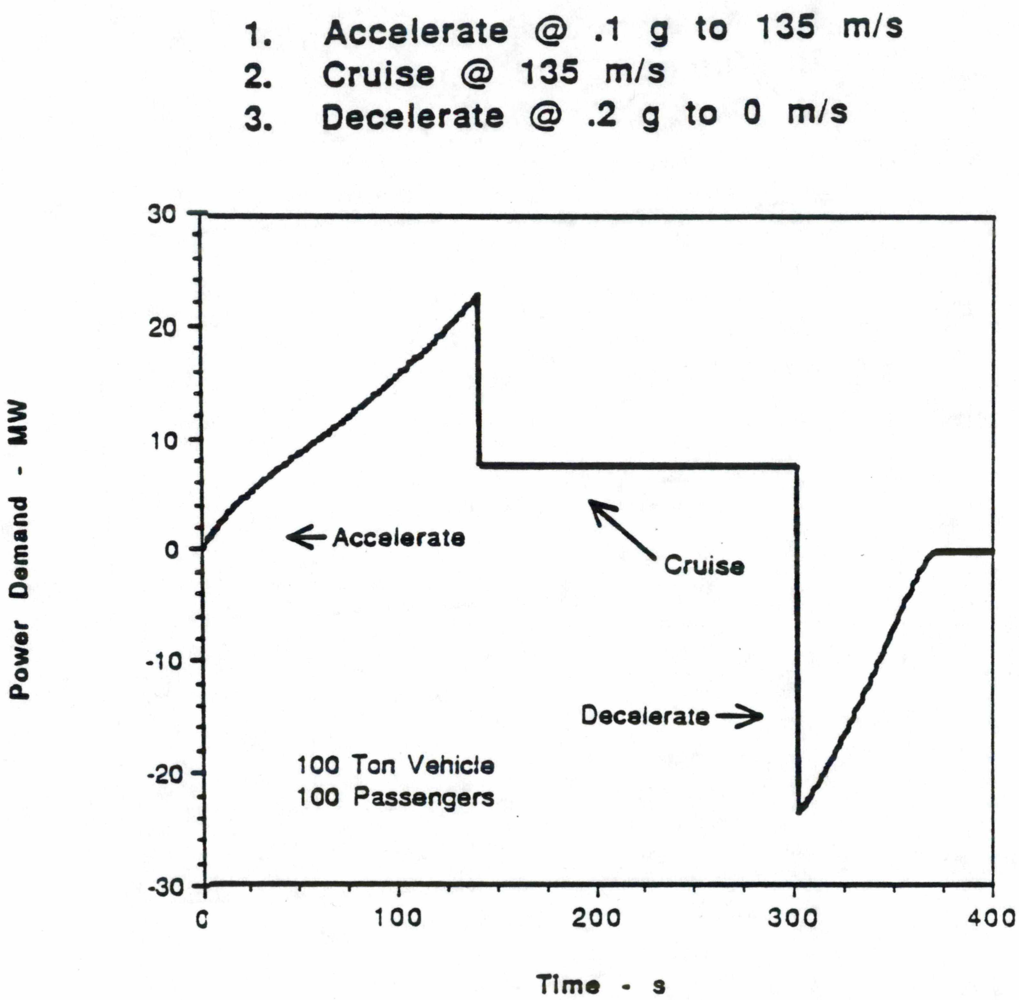

Figure G-9. Power demand for 100 ton vehicle

APPENDIX H

SPREADSHEETS FOR CASES ANALYZED

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
7	10	100	6520.69	22.74	$869,385.37	137.16	109.28	98.65%	97.59%	0.98	15.40
7	10	150	6783.99	23.31	$888,948.50	166.63	132.76	98.36%	97.09%	0.97	14.91
7	10	200	7048.18	23.88	$908,577.01	196.20	156.31	98.08%	96.59%	0.96	14.44
7	10	250	7313.28	24.45	$928,273.38	225.87	179.95	97.79%	96.10%	0.96	13.99
7	10	300	7579.35	25.03	$948,040.25	255.64	203.67	97.51%	95.61%	0.95	13.55
7	10	350	8062.88	26.07	$978,557.64	285.59	227.53	97.22%	95.12%	0.94	13.13
7	10	400	8330.96	26.65	$998,473.29	315.59	251.43	96.94%	94.63%	0.93	12.72
7	10	450	8600.13	27.23	$1,018,468.11	345.70	275.42	96.66%	94.15%	0.92	12.32
7	10	500	8870.40	27.81	$1,038,545.26	375.94	299.51	96.38%	93.67%	0.91	11.94
7	10	550	9141.85	28.39	$1,058,708.08	406.31	323.71	96.10%	93.20%	0.90	11.57
7	10	600	9414.50	28.98	$1,078,960.08	436.81	348.01	95.81%	92.72%	0.89	11.22
7	10	650	9688.41	29.57	$1,099,304.95	467.45	372.42	95.53%	92.25%	0.88	10.87
7	10	700	10180.12	30.63	$1,130,423.67	498.29	396.99	95.25%	91.78%	0.88	10.54
7	10	750	10456.72	31.23	$1,150,965.46	529.23	421.64	94.97%	91.32%	0.87	10.22
7	10	800	16084.78	41.91	$1,919,324.50	924.21	736.32	91.54%	85.76%	0.86	19.82
7	10	850	16580.82	42.97	$1,955,763.94	978.57	779.63	91.09%	85.05%	0.85	19.22
7	10	900	17077.78	44.02	$1,992,271.29	1033.04	823.02	90.64%	84.35%	0.84	18.64
7	10	950	17575.71	45.08	$2,028,849.41	1087.60	866.49	90.19%	83.65%	0.83	18.08
7	10	1000	18074.64	46.15	$2,065,501.31	1142.28	910.06	89.75%	82.97%	0.82	17.54
7	10	1050	18791.09	47.68	$2,112,906.99	1197.14	953.76	89.31%	82.30%	0.81	17.02
7	10	1100	19292.16	48.74	$2,149,715.29	1252.05	997.51	88.87%	81.64%	0.81	16.51
7	10	1150	19794.38	49.81	$2,186,607.37	1307.08	1041.35	88.44%	80.98%	0.80	16.02
7	10	1200	20297.78	50.88	$2,223,586.97	1362.25	1085.30	88.01%	80.34%	0.79	15.55
7	10	1250	21018.91	52.42	$2,271,335.16	1417.61	1129.41	87.58%	79.70%	0.78	15.09
7	10	1300	21524.86	53.50	$2,308,500.98	1473.06	1173.58	87.16%	79.07%	0.77	14.65
7	10	1350	22032.18	54.58	$2,345,766.78	1528.65	1217.87	86.74%	78.45%	0.76	14.22

Figure H-1.1 GTO inverter summary - Sheet 1 for 10 MVA, variable frequency

GTO PARAMETERS							
VOLTAGE RATING (kV)	POWER DISS PER GTO (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS PER AMP (J/A)	FIXED SW LOSS (J)	MINIMUM OFF TIME (s)	MAXIMUM Itgq (A)
6	2900	1.77	0.00118	0.003167	1.05	1.77E-04	3000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
21.15	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$9,304.40	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL(Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	10	100	245.18	0.27	$32,925.32	22.08	2031.19	1606.25	1	3	3
7	10	150	272.73	0.29	$33,430.40	26.98	1984.87	1562.53	1	3	3
7	10	200	300.38	0.30	$33,937.18	31.91	1939.91	1520.18	1	3	3
7	10	250	328.12	0.32	$34,445.72	36.85	1896.29	1479.17	1	3	3
7	10	300	355.95	0.34	$34,956.11	41.81	1853.98	1439.45	1	3	3
7	10	350	383.90	0.36	$35,468.40	46.78	1812.95	1401.00	1	3	3
7	10	400	411.95	0.38	$35,982.68	51.78	1773.16	1363.78	1	3	3
7	10	450	440.11	0.39	$36,499.02	56.79	1734.59	1327.74	1	3	3
7	10	500	468.39	0.41	$37,017.51	61.83	1697.19	1292.85	1	3	3
7	10	550	496.80	0.43	$37,538.24	66.88	1660.93	1259.08	1	3	3
7	10	600	525.33	0.45	$38,061.29	71.96	1625.79	1226.38	1	3	3
7	10	650	553.99	0.47	$38,586.77	77.06	1591.72	1194.72	1	3	3
7	10	700	582.79	0.48	$39,114.78	82.19	1558.70	1164.07	1	3	3
7	10	750	611.74	0.50	$39,645.42	87.34	1526.69	1134.39	1	3	3
7	10	800	1202.79	0.99	$77,811.75	153.13	1495.66	1105.65	2	3	6
7	10	850	1254.83	1.03	$78,765.78	162.18	1465.57	1077.81	2	3	6
7	10	900	1306.97	1.06	$79,721.59	171.25	1436.41	1050.84	2	3	6
7	10	950	1359.20	1.09	$80,679.25	180.34	1408.12	1024.72	2	3	6
7	10	1000	1411.54	1.13	$81,638.85	189.45	1380.70	999.40	2	3	6
7	10	1050	1464.00	1.16	$82,600.46	198.57	1354.10	974.86	2	3	6
7	10	1100	1516.56	1.19	$83,564.17	207.72	1328.29	951.07	2	3	6
7	10	1150	1569.25	1.23	$84,530.08	216.88	1303.26	928.01	2	3	6
7	10	1200	1622.06	1.26	$85,498.28	226.07	1278.97	905.64	2	3	6
7	10	1250	1675.00	1.30	$86,468.88	235.28	1255.40	883.94	2	3	6
7	10	1300	1728.08	1.33	$87,441.99	244.51	1232.52	862.88	2	3	6
7	10	1350	1781.30	1.36	$88,417.72	253.77	1210.31	842.45	2	3	6

Figure H-1.2 GTO switch quantity characterization - Sheet 2 for 10 MVA, variable frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
6	2.4

ANTI-PARALLEL DIODE PARAMETERS		
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)
1.1	0.001583	380

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	10	100	7.36	1318.92	1.37	0.18	1.55	1.31	2.70	0.35	1.44
7	10	150	8.99	1330.91	1.38	0.27	1.65	1.32	4.05	0.53	1.44
7	10	200	10.64	1343.12	1.38	0.37	1.75	1.33	5.40	0.71	1.44
7	10	250	12.28	1355.55	1.39	0.46	1.85	1.34	6.75	0.90	1.44
7	10	300	13.94	1368.22	1.40	0.55	1.95	1.35	8.10	1.10	1.44
7	10	350	15.59	1381.13	1.40	0.64	2.04	1.36	9.45	1.30	1.44
7	10	400	17.26	1394.29	1.41	0.73	2.14	1.36	10.80	1.51	1.44
7	10	450	18.93	1407.69	1.41	0.82	2.24	1.37	12.15	1.73	1.44
7	10	500	20.61	1421.36	1.42	0.92	2.34	1.38	13.50	1.95	1.44
7	10	550	22.29	1435.30	1.43	1.01	2.44	1.39	14.85	2.17	1.44
7	10	600	23.99	1449.51	1.44	1.10	2.53	1.40	16.20	2.41	1.44
7	10	650	25.69	1464.00	1.44	1.19	2.63	1.41	17.55	2.65	1.44
7	10	700	27.40	1478.79	1.45	1.28	2.73	1.42	18.90	2.90	1.44
7	10	750	29.11	1493.88	1.46	1.37	2.83	1.43	20.25	3.16	1.44
7	10	800	25.52	754.64	0.55	0.94	1.49	0.47	21.60	1.24	0.72
7	10	850	27.03	762.50	0.55	1.00	1.55	0.48	22.95	1.33	0.72
7	10	900	28.54	770.53	0.55	1.06	1.61	0.48	24.30	1.43	0.72
7	10	950	30.06	778.73	0.55	1.12	1.67	0.48	25.65	1.53	0.72
7	10	1000	31.57	787.10	0.56	1.18	1.73	0.48	27.00	1.63	0.72
7	10	1050	33.10	795.66	0.56	1.24	1.80	0.49	28.35	1.74	0.72
7	10	1100	34.62	804.40	0.56	1.30	1.86	0.49	29.70	1.85	0.72
7	10	1150	36.15	813.34	0.56	1.35	1.92	0.49	31.05	1.97	0.72
7	10	1200	37.68	822.48	0.57	1.41	1.98	0.50	32.40	2.08	0.72
7	10	1250	39.21	831.83	0.57	1.47	2.04	0.50	33.75	2.20	0.72
7	10	1300	40.75	841.39	0.57	1.53	2.10	0.50	35.10	2.33	0.72
7	10	1350	42.29	851.17	0.57	1.59	2.16	0.50	36.45	2.46	0.72

Figure H-1.3 GTO switch loss estimation - Sheet 3 for 10 MVA, variable frequency.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
506	4	150	0.875	0.7	4.72E-03	150000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
47	6.27E-02

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$1,788.40	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS FILTER CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
7	10	100	2753.73	4.90	$72,896.01	4.70	1830.44	130.46	111.57	18	2	36
7	10	150	2753.73	4.90	$72,896.01	4.72	1844.08	131.19	111.57	18	2	36
7	10	200	2753.73	4.90	$72,896.01	4.75	1857.91	131.93	111.57	18	2	36
7	10	250	2753.73	4.90	$72,896.01	4.78	1871.92	132.69	111.57	18	2	36
7	10	300	2753.73	4.90	$72,896.01	4.80	1886.12	133.47	111.57	18	2	36
7	10	350	2906.72	5.17	$76,945.79	4.90	1900.52	128.87	117.77	19	2	38
7	10	400	2906.72	5.17	$76,945.79	4.92	1915.11	129.60	117.77	19	2	38
7	10	450	2906.72	5.17	$76,945.79	4.95	1929.91	130.34	117.77	19	2	38
7	10	500	2906.72	5.17	$76,945.79	4.98	1944.92	131.10	117.77	19	2	38
7	10	550	2906.72	5.17	$76,945.79	5.01	1960.16	131.88	117.77	19	2	38
7	10	600	2906.72	5.17	$76,945.79	5.04	1975.60	132.68	117.77	19	2	38
7	10	650	2906.72	5.17	$76,945.79	5.07	1991.28	133.49	117.77	19	2	38
7	10	700	3059.70	5.44	$80,995.57	5.17	2007.20	129.19	123.97	20	2	40
7	10	750	3059.70	5.44	$80,995.57	5.20	2023.36	129.95	123.97	20	2	40
7	10	800	3212.69	5.72	$85,045.34	5.43	2110.04	129.30	130.17	21	2	42
7	10	850	3212.69	5.72	$85,045.34	5.47	2131.56	130.28	130.17	21	2	42
7	10	900	3212.69	5.72	$85,045.34	5.51	2153.37	131.28	130.17	21	2	42
7	10	950	3212.69	5.72	$85,045.34	5.56	2175.50	132.30	130.17	21	2	42
7	10	1000	3212.69	5.72	$85,045.34	5.60	2197.95	133.35	130.17	21	2	42
7	10	1050	3365.67	5.99	$89,095.12	5.71	2220.73	129.74	136.37	22	2	44
7	10	1100	3365.67	5.99	$89,095.12	5.76	2243.84	130.75	136.37	22	2	44
7	10	1150	3365.67	5.99	$89,095.12	5.80	2267.31	131.78	136.37	22	2	44
7	10	1200	3365.67	5.99	$89,095.12	5.84	2291.13	132.84	136.37	22	2	44
7	10	1250	3518.66	6.26	$93,144.90	5.96	2315.32	129.48	142.57	23	2	46
7	10	1300	3518.66	6.26	$93,144.90	6.00	2339.90	130.50	142.57	23	2	46
7	10	1350	3518.66	6.26	$93,144.90	6.05	2364.86	131.55	142.57	23	2	46

Figure H-1.4 GTO input filter sizing - Sheet 4 for 10 MVA, variable frequency.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
7	25	600	25116.70	61.75	$2,852,486.71	1217.94	970.33	95.35%	91.95%	0.89	33.65
7	26	600	25618.69	62.96	$2,882,525.86	1235.69	984.47	95.46%	92.13%	0.89	33.65
7	27	600	25906.12	63.70	$2,902,090.56	1253.76	998.87	95.56%	92.30%	0.89	33.65
7	28	600	26411.94	64.92	$2,932,533.44	1272.27	1013.62	95.65%	92.45%	0.89	33.65
7	29	600	26919.69	66.14	$2,963,178.30	1291.16	1028.67	95.74%	92.59%	0.89	33.65
7	30	600	27429.35	67.37	$2,994,025.14	1310.43	1044.02	95.81%	92.72%	0.89	33.65
7	31	600	27940.94	68.61	$3,025,073.96	1330.08	1059.67	95.89%	92.84%	0.89	33.65
7	32	600	28454.45	69.85	$3,056,324.75	1350.11	1075.63	95.95%	92.95%	0.89	33.65
7	33	600	28753.40	70.63	$3,077,101.28	1370.46	1091.84	96.01%	93.06%	0.89	33.65
7	34	600	33615.42	79.72	$3,779,273.31	1635.67	1303.14	95.41%	92.04%	0.89	44.86
7	35	600	34118.13	80.93	$3,809,388.14	1653.56	1317.39	95.49%	92.18%	0.89	44.86
7	36	600	34405.80	81.67	$3,828,978.23	1671.68	1331.83	95.56%	92.30%	0.89	44.86
7	37	600	34911.38	82.89	$3,859,395.86	1690.14	1346.54	95.63%	92.42%	0.89	44.86
7	38	600	35418.41	84.11	$3,889,964.98	1708.89	1361.47	95.70%	92.52%	0.89	44.86
7	39	600	35926.87	85.34	$3,920,685.59	1727.92	1376.64	95.76%	92.63%	0.89	44.86
7	40	600	36436.78	86.57	$3,951,557.68	1747.24	1392.03	95.81%	92.72%	0.89	44.86
7	41	600	36948.13	87.80	$3,982,581.25	1766.84	1407.64	95.87%	92.81%	0.89	44.86
7	42	600	37244.44	88.58	$4,003,080.18	1786.67	1423.44	95.92%	92.90%	0.89	44.86
7	43	600	37758.67	89.82	$4,034,406.57	1806.84	1439.51	95.97%	92.98%	0.89	44.86
7	44	600	38274.33	91.07	$4,065,884.44	1827.30	1455.81	96.01%	93.06%	0.89	44.86
7	45	600	42905.48	99.64	$4,755,865.90	2089.60	1664.78	95.56%	92.30%	0.89	56.08
7	46	600	43410.92	100.86	$4,786,268.38	2108.03	1679.47	95.62%	92.39%	0.89	56.08
7	47	600	43917.51	102.08	$4,816,792.05	2126.70	1694.34	95.67%	92.48%	0.89	56.08
7	48	600	44425.26	103.30	$4,847,436.92	2145.59	1709.39	95.72%	92.57%	0.89	56.08
7	49	600	44934.16	104.53	$4,878,202.97	2164.70	1724.62	95.77%	92.65%	0.89	56.08
7	50	600	45444.21	105.76	$4,909,090.21	2184.05	1740.03	95.81%	92.72%	0.89	56.08

Figure H-1.5 GTO inverter summary - Sheet 1 for 600 Hz, variable MVA.

GTO PARAMETERS							
VOLTAGE RATING (kV)	POWER DISS PER GTO (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS PER AMP (J/A)	FIXED SW LOSS (J)	MINIMUM OFF TIME (s)	MAXIMUM Itgq (A)
6	2900	1.77	0.00118	0.003167	1.05	1.77E-04	3000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
21.15	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$9,304.40	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL(Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	25	600	1543.89	1.32	$111,395.39	200.88	1625.79	1226.38	3	3	9
7	26	600	1549.94	1.33	$111,506.43	203.75	1625.79	1226.38	3	3	9
7	27	600	1556.18	1.33	$111,620.80	206.69	1625.79	1226.38	3	3	9
7	28	600	1562.60	1.34	$111,738.50	209.69	1625.79	1226.38	3	3	9
7	29	600	1569.20	1.34	$111,859.52	212.76	1625.79	1226.38	3	3	9
7	30	600	1575.99	1.34	$111,983.87	215.88	1625.79	1226.38	3	3	9
7	31	600	1582.95	1.35	$112,111.56	219.08	1625.79	1226.38	3	3	9
7	32	600	1590.10	1.35	$112,242.57	222.33	1625.79	1226.38	3	3	9
7	33	600	1597.42	1.36	$112,376.90	225.65	1625.79	1226.38	3	3	9
7	34	600	2062.52	1.77	$148,233.99	269.74	1625.79	1226.38	4	3	12
7	35	600	2068.65	1.77	$148,346.28	272.64	1625.79	1226.38	4	3	12
7	36	600	2074.91	1.78	$148,461.06	275.59	1625.79	1226.38	4	3	12
7	37	600	2081.31	1.78	$148,578.35	278.58	1625.79	1226.38	4	3	12
7	38	600	2087.84	1.78	$148,698.12	281.62	1625.79	1226.38	4	3	12
7	39	600	2094.51	1.79	$148,820.40	284.71	1625.79	1226.38	4	3	12
7	40	600	2101.31	1.79	$148,945.17	287.85	1625.79	1226.38	4	3	12
7	41	600	2108.26	1.80	$149,072.43	291.03	1625.79	1226.38	4	3	12
7	42	600	2115.33	1.80	$149,202.19	294.26	1625.79	1226.38	4	3	12
7	43	600	2122.55	1.81	$149,334.45	297.54	1625.79	1226.38	4	3	12
7	44	600	2129.90	1.81	$149,469.21	300.86	1625.79	1226.38	4	3	12
7	45	600	2593.64	2.22	$185,301.33	344.48	1625.79	1226.38	5	3	15
7	46	600	2600.02	2.22	$185,418.36	347.47	1625.79	1226.38	5	3	15
7	47	600	2606.51	2.23	$185,537.39	350.50	1625.79	1226.38	5	3	15
7	48	600	2613.11	2.23	$185,658.42	353.56	1625.79	1226.38	5	3	15
7	49	600	2619.82	2.24	$185,781.44	356.67	1625.79	1226.38	5	3	15
7	50	600	2626.64	2.24	$185,906.46	359.81	1625.79	1226.38	5	3	15

Figure H-1.6 GTO inverter summary - Sheet 1 for 600 Hz, variable MVA.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	di/dt SNUBBER INDUCTOR (uH)
6	2.4

ANTI-PARALLEL DIODE PARAMETERS		
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)
1.1	0.001583	380

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	25	600	22.32	1207.92	1.10	0.97	2.07	1.04	16.20	1.82	1.20
7	26	600	22.64	1256.24	1.16	0.99	2.16	1.10	16.20	1.93	1.25
7	27	600	22.97	1304.56	1.23	1.02	2.25	1.17	16.20	2.04	1.30
7	28	600	23.30	1352.87	1.30	1.05	2.34	1.25	16.20	2.16	1.35
7	29	600	23.64	1401.19	1.36	1.07	2.44	1.32	16.20	2.28	1.40
7	30	600	23.99	1449.51	1.44	1.10	2.53	1.40	16.20	2.41	1.44
7	31	600	24.34	1497.83	1.51	1.12	2.63	1.48	16.20	2.54	1.49
7	32	600	24.70	1546.14	1.58	1.15	2.73	1.56	16.20	2.67	1.54
7	33	600	25.07	1594.46	1.66	1.18	2.83	1.64	16.20	2.81	1.59
7	34	600	22.48	1232.08	1.13	0.98	2.11	1.07	16.20	1.87	1.23
7	35	600	22.72	1268.32	1.18	1.00	2.18	1.12	16.20	1.96	1.26
7	36	600	22.97	1304.56	1.23	1.02	2.25	1.17	16.20	2.04	1.30
7	37	600	23.21	1340.80	1.28	1.04	2.32	1.23	16.20	2.13	1.34
7	38	600	23.47	1377.03	1.33	1.06	2.39	1.28	16.20	2.22	1.37
7	39	600	23.73	1413.27	1.38	1.08	2.46	1.34	16.20	2.32	1.41
7	40	600	23.99	1449.51	1.44	1.10	2.53	1.40	16.20	2.41	1.44
7	41	600	24.25	1485.75	1.49	1.12	2.61	1.46	16.20	2.51	1.48
7	42	600	24.52	1521.98	1.54	1.14	2.68	1.52	16.20	2.60	1.52
7	43	600	24.79	1558.22	1.60	1.16	2.76	1.58	16.20	2.70	1.55
7	44	600	25.07	1594.46	1.66	1.18	2.83	1.64	16.20	2.81	1.59
7	45	600	22.97	1304.56	1.23	1.02	2.25	1.17	16.20	2.04	1.30
7	46	600	23.16	1333.55	1.27	1.04	2.30	1.22	16.20	2.11	1.33
7	47	600	23.37	1362.54	1.31	1.05	2.36	1.26	16.20	2.19	1.36
7	48	600	23.57	1391.53	1.35	1.07	2.42	1.31	16.20	2.26	1.39
7	49	600	23.78	1420.52	1.39	1.08	2.48	1.35	16.20	2.33	1.41
7	50	600	23.99	1449.51	1.44	1.10	2.53	1.40	16.20	2.41	1.44

Figure H-1.7 GTO switch loss estimation - Sheet 3 for 600 Hz, variable MVA.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
506	4	150	0.875	0.7	4.72E-03	150000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
47	6.27E-02

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$1,788.40	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS FILTER CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
7	25	600	7343.28	13.06	$194,389.36	12.68	4962.84	132.10	297.53	48	2	96
7	26	600	7649.25	13.61	$202,488.91	13.18	5155.49	131.83	309.93	50	2	100
7	27	600	7802.24	13.88	$206,538.69	13.62	5348.21	133.55	316.12	51	2	102
7	28	600	8108.21	14.43	$214,638.25	14.12	5541.00	133.24	328.52	53	2	106
7	29	600	8414.18	14.97	$222,737.81	14.62	5733.87	132.94	340.92	55	2	110
7	30	600	8720.15	15.51	$230,837.36	15.13	5926.81	132.68	353.31	57	2	114
7	31	600	9026.12	16.06	$238,936.92	15.63	6119.82	132.43	365.71	59	2	118
7	32	600	9332.09	16.60	$247,036.48	16.13	6312.90	132.20	378.11	61	2	122
7	33	600	9485.07	16.87	$251,086.25	16.57	6506.05	133.62	384.31	62	2	124
7	34	600	9944.03	17.69	$263,235.59	17.22	6745.54	132.48	402.90	65	2	130
7	35	600	10250.00	18.24	$271,335.15	17.72	6938.22	132.26	415.30	67	2	134
7	36	600	10402.98	18.51	$275,384.92	18.16	7130.95	133.55	421.50	68	2	136
7	37	600	10708.95	19.05	$283,484.48	18.66	7323.73	133.31	433.90	70	2	140
7	38	600	11014.92	19.60	$291,584.04	19.16	7516.57	133.09	446.29	72	2	144
7	39	600	11320.89	20.14	$299,683.59	19.67	7709.46	132.88	458.69	74	2	148
7	40	600	11626.86	20.69	$307,783.15	20.17	7902.41	132.68	471.09	76	2	152
7	41	600	11932.83	21.23	$315,882.71	20.67	8095.41	132.49	483.48	78	2	156
7	42	600	12085.82	21.50	$319,932.49	21.11	8288.47	133.60	489.68	79	2	158
7	43	600	12391.79	22.05	$328,032.04	21.61	8481.58	133.40	502.08	81	2	162
7	44	600	12697.76	22.59	$336,131.60	22.11	8674.74	133.20	514.48	83	2	166
7	45	600	13003.73	23.13	$344,231.16	22.70	8913.68	133.55	526.87	85	2	170
7	46	600	13309.70	23.68	$352,330.71	23.20	9106.46	133.36	539.27	87	2	174
7	47	600	13615.67	24.22	$360,430.27	23.71	9299.29	133.17	551.67	89	2	178
7	48	600	13921.64	24.77	$368,529.83	24.21	9492.15	133.00	564.06	91	2	182
7	49	600	14227.61	25.31	$376,629.38	24.71	9685.06	132.83	576.46	93	2	186
7	50	600	14533.58	25.86	$384,728.94	25.21	9878.01	132.68	588.86	95	2	190

Figure H-1.8 GTO input filter sizing - Sheet 4 for 600 Hz, variable MVA.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
7	10	100	8068.82	23.47	$1,683,072.92	203.86	162.42	98.00%	96.47%	0.9997	15.11
7	10	150	8080.54	23.50	$1,684,167.67	205.80	163.96	97.98%	96.43%	0.9996	15.05
7	10	200	8092.27	23.54	$1,685,262.62	207.73	165.50	97.96%	96.40%	0.9994	15.00
7	10	250	8103.99	23.57	$1,686,357.75	209.67	167.04	97.95%	96.37%	0.9993	14.95
7	10	300	8115.72	23.60	$1,687,453.08	211.61	168.59	97.93%	96.34%	0.9991	14.90
7	10	350	8127.46	23.64	$1,688,548.60	213.54	170.13	97.91%	96.31%	0.9990	14.85
7	10	400	8139.19	23.67	$1,689,644.32	215.48	171.67	97.89%	96.27%	0.9988	14.80
7	10	450	8150.93	23.70	$1,690,740.22	217.42	173.22	97.87%	96.24%	0.9987	14.75
7	10	500	8162.67	23.73	$1,691,836.32	219.35	174.76	97.85%	96.21%	0.9985	14.69
7	10	550	8174.41	23.77	$1,692,932.62	221.29	176.30	97.84%	96.18%	0.9984	14.64
7	10	600	8186.15	23.80	$1,694,029.10	223.23	177.85	97.82%	96.14%	0.9982	14.59
7	10	650	8197.90	23.83	$1,695,125.78	225.17	179.39	97.80%	96.11%	0.9981	14.54
7	10	700	8209.65	23.87	$1,696,222.66	227.10	180.93	97.78%	96.08%	0.9979	14.49
7	10	750	8221.41	23.90	$1,697,319.73	229.04	182.48	97.76%	96.05%	0.9978	14.44
7	10	800	8233.16	23.93	$1,698,416.99	230.98	184.02	97.74%	96.02%	0.9976	14.40
7	10	850	8244.92	23.97	$1,699,514.44	232.92	185.57	97.72%	95.98%	0.9975	14.35
7	10	900	8256.68	24.00	$1,700,612.09	234.86	187.11	97.71%	95.95%	0.9973	14.30
7	10	950	8268.45	24.03	$1,701,709.94	236.80	188.66	97.69%	95.92%	0.9972	14.25
7	10	1000	8280.21	24.07	$1,702,807.98	238.74	190.20	97.67%	95.89%	0.9970	14.20
7	10	1050	8291.98	24.10	$1,703,906.21	240.68	191.75	97.65%	95.85%	0.9969	14.15
7	10	1100	8303.75	24.13	$1,705,004.64	242.62	193.29	97.63%	95.82%	0.9967	14.10
7	10	1150	8315.53	24.16	$1,706,103.26	244.56	194.84	97.61%	95.79%	0.9966	14.06
7	10	1200	8327.31	24.20	$1,707,202.08	246.50	196.39	97.59%	95.76%	0.9964	14.01
7	10	1250	8339.09	24.23	$1,708,301.09	248.44	197.93	97.58%	95.73%	0.9963	13.96
7	10	1300	8350.87	24.26	$1,709,400.30	250.38	199.48	97.56%	95.70%	0.9961	13.91
7	10	1350	8362.65	24.30	$1,710,499.70	252.33	201.03	97.54%	95.66%	0.9960	13.87

Figure H-2.1 IGBT inverter summary - Sheet 1 for 10 MVA, variable frequency.

IGBT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER IGBT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	IGBTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itgq
1	187.5	0.9	0.0106	0.000346	0	10	3.00E-06	300

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
7.73	2	0.00819	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$4,090.19	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	10	100	419.73	0.25	$82,821.02	33.20	195.77	1561.79	1	18	18
7	10	150	420.88	0.25	$82,842.16	33.52	195.12	1556.51	1	18	18
7	10	200	422.03	0.26	$82,863.30	33.84	194.48	1551.25	1	18	18
7	10	250	423.18	0.26	$82,884.45	34.16	193.84	1546.01	1	18	18
7	10	300	424.34	0.26	$82,905.61	34.49	193.20	1540.80	1	18	18
7	10	350	425.49	0.26	$82,926.77	34.81	192.56	1535.61	1	18	18
7	10	400	426.65	0.26	$82,947.93	35.13	191.93	1530.43	1	18	18
7	10	450	427.80	0.26	$82,969.10	35.45	191.30	1525.28	1	18	18
7	10	500	428.96	0.26	$82,990.27	35.78	190.67	1520.16	1	18	18
7	10	550	430.11	0.26	$83,011.45	36.10	190.04	1515.05	1	18	18
7	10	600	431.27	0.26	$83,032.64	36.42	189.42	1509.96	1	18	18
7	10	650	432.42	0.26	$83,053.83	36.74	188.80	1504.90	1	18	18
7	10	700	433.58	0.26	$83,075.02	37.07	188.18	1499.86	1	18	18
7	10	750	434.74	0.26	$83,096.22	37.39	187.56	1494.84	1	18	18
7	10	800	435.89	0.26	$83,117.43	37.71	186.95	1489.84	1	18	18
7	10	850	437.05	0.27	$83,138.64	38.04	186.34	1484.86	1	18	18
7	10	900	438.21	0.27	$83,159.85	38.36	185.73	1479.90	1	18	18
7	10	950	439.36	0.27	$83,181.07	38.68	185.12	1474.97	1	18	18
7	10	1000	440.52	0.27	$83,202.30	39.01	184.52	1470.05	1	18	18
7	10	1050	441.68	0.27	$83,223.53	39.33	183.92	1465.16	1	18	18
7	10	1100	442.84	0.27	$83,244.77	39.65	183.32	1460.29	1	18	18
7	10	1150	444.00	0.27	$83,266.01	39.98	182.73	1455.44	1	18	18
7	10	1200	445.16	0.27	$83,287.25	40.30	182.13	1450.60	1	18	18
7	10	1250	446.32	0.27	$83,308.50	40.62	181.54	1445.80	1	18	18
7	10	1300	447.47	0.27	$83,329.76	40.95	180.96	1441.01	1	18	18
7	10	1350	448.63	0.27	$83,351.02	41.27	180.37	1436.24	1	18	18

Figure H-2.2 IGBT switch quantity characterization - Sheet 2 for 10 MVA, variable frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dl/dt SNUBBER INDUCTOR (uH)
1	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
1.6	0.00556	34	34

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	10	100	1.84	1295.96	0.94	0.01	0.95	0.75	0.01	0.01	0.12
7	10	150	1.86	1296.15	0.94	0.02	0.96	0.75	0.02	0.01	0.12
7	10	200	1.88	1296.35	0.94	0.03	0.97	0.75	0.03	0.02	0.12
7	10	250	1.90	1296.54	0.94	0.04	0.97	0.75	0.03	0.02	0.12
7	10	300	1.92	1296.74	0.94	0.04	0.98	0.75	0.04	0.03	0.12
7	10	350	1.93	1296.93	0.94	0.05	0.99	0.75	0.04	0.03	0.12
7	10	400	1.95	1297.13	0.94	0.06	1.00	0.75	0.05	0.04	0.12
7	10	450	1.97	1297.32	0.94	0.06	1.00	0.75	0.06	0.04	0.12
7	10	500	1.99	1297.52	0.94	0.07	1.01	0.75	0.06	0.04	0.12
7	10	550	2.01	1297.71	0.94	0.08	1.02	0.75	0.07	0.05	0.12
7	10	600	2.02	1297.91	0.94	0.09	1.02	0.75	0.08	0.05	0.12
7	10	650	2.04	1298.10	0.94	0.09	1.03	0.75	0.08	0.06	0.12
7	10	700	2.06	1298.30	0.94	0.10	1.04	0.75	0.09	0.06	0.12
7	10	750	2.08	1298.49	0.94	0.11	1.05	0.75	0.09	0.07	0.12
7	10	800	2.10	1298.69	0.94	0.11	1.05	0.75	0.10	0.07	0.12
7	10	850	2.11	1298.88	0.94	0.12	1.06	0.75	0.11	0.08	0.12
7	10	900	2.13	1299.08	0.94	0.13	1.07	0.75	0.11	0.08	0.12
7	10	950	2.15	1299.27	0.94	0.14	1.07	0.75	0.12	0.08	0.12
7	10	1000	2.17	1299.47	0.94	0.14	1.08	0.75	0.13	0.09	0.12
7	10	1050	2.18	1299.66	0.94	0.15	1.09	0.75	0.13	0.09	0.12
7	10	1100	2.20	1299.86	0.94	0.16	1.10	0.75	0.14	0.10	0.12
7	10	1150	2.22	1300.06	0.94	0.16	1.10	0.75	0.14	0.10	0.12
7	10	1200	2.24	1300.25	0.94	0.17	1.11	0.75	0.15	0.11	0.12
7	10	1250	2.26	1300.45	0.94	0.18	1.12	0.75	0.16	0.11	0.12
7	10	1300	2.27	1300.64	0.94	0.19	1.13	0.75	0.16	0.12	0.12
7	10	1350	2.29	1300.84	0.94	0.19	1.13	0.75	0.17	0.12	0.12

Figure H-2.3 IGBT switch loss estimation - Sheet 3 for 10 MVA, variable frequency.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
506	4	150	0.875	0.7	4.72E-03	150000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
47	6.27E-02

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$1,788.40	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
7	10	100	2753.73	4.90	$72,896.01	4.69	1826.38	130.24	111.57	18	2	36
7	10	150	2753.73	4.90	$72,896.01	4.69	1826.87	130.27	111.57	18	2	36
7	10	200	2753.73	4.90	$72,896.01	4.69	1827.35	130.29	111.57	18	2	36
7	10	250	2753.73	4.90	$72,896.01	4.69	1827.83	130.32	111.57	18	2	36
7	10	300	2753.73	4.90	$72,896.01	4.69	1828.32	130.34	111.57	18	2	36
7	10	350	2753.73	4.90	$72,896.01	4.69	1828.80	130.37	111.57	18	2	36
7	10	400	2753.73	4.90	$72,896.01	4.69	1829.29	130.39	111.57	18	2	36
7	10	450	2753.73	4.90	$72,896.01	4.70	1829.77	130.42	111.57	18	2	36
7	10	500	2753.73	4.90	$72,896.01	4.70	1830.26	130.45	111.57	18	2	36
7	10	550	2753.73	4.90	$72,896.01	4.70	1830.74	130.47	111.57	18	2	36
7	10	600	2753.73	4.90	$72,896.01	4.70	1831.22	130.50	111.57	18	2	36
7	10	650	2753.73	4.90	$72,896.01	4.70	1831.71	130.52	111.57	18	2	36
7	10	700	2753.73	4.90	$72,896.01	4.70	1832.19	130.55	111.57	18	2	36
7	10	750	2753.73	4.90	$72,896.01	4.70	1832.68	130.58	111.57	18	2	36
7	10	800	2753.73	4.90	$72,896.01	4.70	1833.16	130.60	111.57	18	2	36
7	10	850	2753.73	4.90	$72,896.01	4.70	1833.65	130.63	111.57	18	2	36
7	10	900	2753.73	4.90	$72,896.01	4.70	1834.13	130.65	111.57	18	2	36
7	10	950	2753.73	4.90	$72,896.01	4.70	1834.62	130.68	111.57	18	2	36
7	10	1000	2753.73	4.90	$72,896.01	4.71	1835.11	130.70	111.57	18	2	36
7	10	1050	2753.73	4.90	$72,896.01	4.71	1835.59	130.73	111.57	18	2	36
7	10	1100	2753.73	4.90	$72,896.01	4.71	1836.08	130.76	111.57	18	2	36
7	10	1150	2753.73	4.90	$72,896.01	4.71	1836.56	130.78	111.57	18	2	36
7	10	1200	2753.73	4.90	$72,896.01	4.71	1837.05	130.81	111.57	18	2	36
7	10	1250	2753.73	4.90	$72,896.01	4.71	1837.54	130.83	111.57	18	2	36
7	10	1300	2753.73	4.90	$72,896.01	4.71	1838.02	130.86	111.57	18	2	36
7	10	1350	2753.73	4.90	$72,896.01	4.71	1838.51	130.89	111.57	18	2	36

Figure H-2.4 IGBT input filter sizing - Sheet 4 for 10 MVA, variable frequency.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
7	25	600	17905.00	43.62	$3,414,687.22	601.59	479.28	97.65%	95.86%	0.9982	29.19
7	26	600	18383.22	45.00	$3,449,515.93	634.92	505.84	97.62%	95.80%	0.9982	29.19
7	27	600	18862.66	46.39	$3,484,660.30	669.02	533.01	97.58%	95.74%	0.9982	29.19
7	28	600	19126.85	47.32	$3,509,443.91	703.82	560.74	97.55%	95.68%	0.9982	29.19
7	29	600	19608.75	48.73	$3,545,219.23	739.45	589.12	97.51%	95.62%	0.9982	29.19
7	30	600	23527.84	51.36	$4,828,554.90	669.62	533.49	97.82%	96.14%	0.9982	43.78
7	31	600	23999.73	52.69	$4,861,753.21	699.02	556.91	97.79%	96.11%	0.9982	43.78
7	32	600	24255.96	53.55	$4,884,485.48	728.87	580.69	97.77%	96.07%	0.9982	43.78
7	33	600	24729.48	54.89	$4,918,104.39	759.28	604.92	97.75%	96.03%	0.9982	43.78
7	34	600	25203.82	56.24	$4,951,933.76	790.21	629.56	97.73%	95.99%	0.9982	43.78
7	35	600	25678.97	57.59	$4,985,973.58	821.64	654.60	97.71%	95.95%	0.9982	43.78
7	36	600	25938.47	58.48	$5,009,547.49	853.52	680.00	97.68%	95.91%	0.9982	43.78
7	37	600	26415.26	59.85	$5,044,007.92	885.96	705.85	97.66%	95.88%	0.9982	43.78
7	38	600	26892.86	61.23	$5,078,678.80	918.92	732.10	97.64%	95.84%	0.9982	43.78
7	39	600	27371.29	62.61	$5,113,560.12	952.38	758.76	97.62%	95.80%	0.9982	43.78
7	40	600	27634.05	63.53	$5,137,975.68	986.30	785.78	97.59%	95.76%	0.9982	43.78
7	41	600	28114.11	64.92	$5,173,277.63	1020.78	813.25	97.57%	95.72%	0.9982	43.78
7	42	600	28594.98	66.32	$5,208,790.02	1055.76	841.13	97.55%	95.68%	0.9982	43.78
7	43	600	29076.67	67.73	$5,244,512.86	1091.26	869.41	97.52%	95.64%	0.9982	43.78
7	44	600	32764.79	69.77	$6,513,438.03	1012.35	806.54	97.75%	96.03%	0.9982	58.38
7	45	600	33239.03	71.12	$6,547,241.01	1043.21	831.13	97.73%	96.00%	0.9982	58.38
7	46	600	33713.87	72.47	$6,581,201.83	1074.46	856.02	97.72%	95.97%	0.9982	58.38
7	47	600	34189.34	73.82	$6,615,320.50	1106.08	881.21	97.70%	95.94%	0.9982	58.38
7	48	600	34448.94	74.72	$6,638,920.81	1138.02	906.66	97.68%	95.91%	0.9982	58.38
7	49	600	34925.62	76.08	$6,673,354.93	1170.41	932.46	97.67%	95.89%	0.9982	58.38
7	50	600	35402.92	77.45	$6,707,946.89	1203.17	958.57	97.65%	95.86%	0.9982	58.38

Figure H-2.5 IGBT inverter summary - Sheet 1 for 600 Hz, variable MVA.

IGBT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER IGBT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	IGBTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itgq
1	187.5	0.9	0.0106	0.000346	0	10	3.00E-06	300

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
7.73	2	0.00819	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$4,090.19	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	25	600	868.82	0.53	$165,080.46	98.31	189.42	1509.96	2	18	36
7	26	600	870.24	0.53	$165,106.50	103.79	189.42	1509.96	2	18	36
7	27	600	871.71	0.53	$165,133.55	109.39	189.42	1509.96	2	18	36
7	28	600	873.24	0.53	$165,161.59	115.12	189.42	1509.96	2	18	36
7	29	600	874.83	0.53	$165,190.63	120.98	189.42	1509.96	2	18	36
7	30	600	1293.80	0.78	$246,897.91	109.26	189.42	1509.96	3	18	54
7	31	600	1294.94	0.79	$246,918.78	114.08	189.42	1509.96	3	18	54
7	32	600	1296.12	0.79	$246,940.32	118.99	189.42	1509.96	3	18	54
7	33	600	1297.33	0.79	$246,962.52	123.98	189.42	1509.96	3	18	54
7	34	600	1298.57	0.79	$246,985.39	129.05	189.42	1509.96	3	18	54
7	35	600	1299.86	0.79	$247,008.93	134.21	189.42	1509.96	3	18	54
7	36	600	1301.18	0.79	$247,033.14	139.45	189.42	1509.96	3	18	54
7	37	600	1302.54	0.79	$247,058.01	144.78	189.42	1509.96	3	18	54
7	38	600	1303.93	0.79	$247,083.55	150.19	189.42	1509.96	3	18	54
7	39	600	1305.36	0.79	$247,109.76	155.69	189.42	1509.96	3	18	54
7	40	600	1306.82	0.79	$247,136.63	161.27	189.42	1509.96	3	18	54
7	41	600	1308.33	0.79	$247,164.17	166.93	189.42	1509.96	3	18	54
7	42	600	1309.87	0.80	$247,192.38	172.68	189.42	1509.96	3	18	54
7	43	600	1311.44	0.80	$247,221.26	178.52	189.42	1509.96	3	18	54
7	44	600	1729.77	1.05	$328,916.69	165.30	189.42	1509.96	4	18	72
7	45	600	1731.01	1.05	$328,939.48	170.36	189.42	1509.96	4	18	72
7	46	600	1732.28	1.05	$328,962.77	175.49	189.42	1509.96	4	18	72
7	47	600	1733.58	1.05	$328,986.56	180.68	189.42	1509.96	4	18	72
7	48	600	1734.91	1.05	$329,010.85	185.93	189.42	1509.96	4	18	72
7	49	600	1736.26	1.05	$329,035.64	191.25	189.42	1509.96	4	18	72
7	50	600	1737.64	1.05	$329,060.93	196.63	189.42	1509.96	4	18	72

Figure H-2.6 IGBT switch quantity characterization - Sheet 2 for 600 Hz, variable MVA.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
1	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
1.6	0.00556	34	34

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	25	600	2.73	1622.38	1.35	0.11	1.46	0.96	0.08	0.08	0.15
7	26	600	2.88	1687.28	1.44	0.11	1.55	1.01	0.08	0.09	0.16
7	27	600	3.04	1752.17	1.54	0.12	1.65	1.05	0.08	0.10	0.17
7	28	600	3.20	1817.07	1.63	0.12	1.75	1.10	0.08	0.10	0.17
7	29	600	3.36	1881.97	1.73	0.12	1.86	1.14	0.08	0.11	0.18
7	30	600	2.02	1297.91	0.94	0.09	1.02	0.75	0.08	0.05	0.12
7	31	600	2.11	1341.17	0.99	0.09	1.08	0.78	0.08	0.06	0.13
7	32	600	2.20	1384.43	1.04	0.09	1.13	0.80	0.08	0.06	0.13
7	33	600	2.30	1427.70	1.09	0.09	1.19	0.83	0.08	0.06	0.14
7	34	600	2.39	1470.96	1.15	0.10	1.25	0.86	0.08	0.07	0.14
7	35	600	2.49	1514.23	1.21	0.10	1.31	0.89	0.08	0.07	0.14
7	36	600	2.58	1557.49	1.26	0.10	1.37	0.92	0.08	0.08	0.15
7	37	600	2.68	1600.75	1.32	0.11	1.43	0.95	0.08	0.08	0.15
7	38	600	2.78	1644.02	1.38	0.11	1.49	0.98	0.08	0.08	0.16
7	39	600	2.88	1687.28	1.44	0.11	1.55	1.01	0.08	0.09	0.16
7	40	600	2.99	1730.54	1.50	0.11	1.62	1.04	0.08	0.09	0.16
7	41	600	3.09	1773.81	1.57	0.12	1.68	1.07	0.08	0.10	0.17
7	42	600	3.20	1817.07	1.63	0.12	1.75	1.10	0.08	0.10	0.17
7	43	600	3.31	1860.33	1.70	0.12	1.82	1.13	0.08	0.11	0.18
7	44	600	2.30	1427.70	1.09	0.09	1.19	0.83	0.08	0.06	0.14
7	45	600	2.37	1460.15	1.14	0.10	1.23	0.85	0.08	0.07	0.14
7	46	600	2.44	1492.59	1.18	0.10	1.28	0.87	0.08	0.07	0.14
7	47	600	2.51	1525.04	1.22	0.10	1.32	0.90	0.08	0.07	0.15
7	48	600	2.58	1557.49	1.26	0.10	1.37	0.92	0.08	0.08	0.15
7	49	600	2.66	1589.94	1.31	0.10	1.41	0.94	0.08	0.08	0.15
7	50	600	2.73	1622.38	1.35	0.11	1.46	0.96	0.08	0.08	0.15

Figure H-2.7 IGBT switch loss estimation - Sheet 3 for 600 Hz, variable MVA.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
506	4	150	0.875	0.7	4.72E-03	150000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
47	6.27E-02

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$1,788.40	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
7	25	600	6731.34	11.98	$178,190.25	11.70	4585.87	132.92	272.73	44	2	88
7	26	600	7037.31	12.52	$186,289.80	12.18	4770.96	132.42	285.13	46	2	92
7	27	600	7343.28	13.06	$194,389.36	12.67	4956.19	131.97	297.53	48	2	96
7	28	600	7496.27	13.34	$198,439.14	13.09	5141.56	133.61	303.73	49	2	98
7	29	600	7802.24	13.88	$206,538.69	13.58	5327.06	133.14	316.12	51	2	102
7	30	600	8108.21	14.43	$214,638.25	14.03	5493.67	132.36	328.52	53	2	106
7	31	600	8414.18	14.97	$222,737.81	14.51	5678.06	131.95	340.92	55	2	110
7	32	600	8567.16	15.24	$226,787.58	14.94	5862.54	133.37	347.12	56	2	112
7	33	600	8873.13	15.79	$234,887.14	15.42	6047.11	132.95	359.51	58	2	116
7	34	600	9179.10	16.33	$242,986.70	15.91	6231.77	132.56	371.91	60	2	120
7	35	600	9485.07	16.87	$251,086.25	16.39	6416.52	132.20	384.31	62	2	124
7	36	600	9638.06	17.15	$255,136.03	16.82	6601.37	133.47	390.51	63	2	126
7	37	600	9944.03	17.69	$263,235.59	17.30	6786.30	133.09	402.90	65	2	130
7	38	600	10250.00	18.24	$271,335.15	17.79	6971.33	132.75	415.30	67	2	134
7	39	600	10555.97	18.78	$279,434.70	18.27	7156.44	132.42	427.70	69	2	138
7	40	600	10708.95	19.05	$283,484.48	18.70	7341.65	133.56	433.90	70	2	140
7	41	600	11014.92	19.60	$291,584.04	19.18	7526.95	133.23	446.29	72	2	144
7	42	600	11320.89	20.14	$299,683.59	19.67	7712.34	132.91	458.69	74	2	148
7	43	600	11626.86	20.69	$307,783.15	20.16	7897.82	132.62	471.09	76	2	152
7	44	600	11779.85	20.96	$311,832.93	20.54	8062.81	133.40	477.28	77	2	154
7	45	600	12085.82	21.50	$319,932.49	21.03	8247.46	133.09	489.68	79	2	158
7	46	600	12391.79	22.05	$328,032.04	21.51	8432.18	132.80	502.08	81	2	162
7	47	600	12697.76	22.59	$336,131.60	22.00	8616.97	132.52	514.48	83	2	166
7	48	600	12850.74	22.86	$340,181.38	22.42	8801.82	133.47	520.67	84	2	168
7	49	600	13156.71	23.41	$348,280.93	22.91	8986.74	133.19	533.07	86	2	172
7	50	600	13462.68	23.95	$356,380.49	23.39	9171.74	132.92	545.47	88	2	176

Figure H-2.8 IGBT input filter sizing - Sheet 4 for 600 Hz, variable MVA.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
7	10	100	21667.15	47.99	$3,422,133.58	320.12	255.04	96.90%	94.56%	0.9990	15.42
7	10	150	21695.62	48.17	$3,427,700.17	332.91	265.23	96.78%	94.36%	0.9985	15.41
7	10	200	21724.10	48.35	$3,433,267.98	345.71	275.43	96.66%	94.15%	0.9980	15.41
7	10	250	21752.60	48.53	$3,438,837.01	358.51	285.62	96.54%	93.95%	0.9975	15.40
7	10	300	21781.12	48.71	$3,444,407.27	371.30	295.82	96.42%	93.75%	0.9970	15.39
7	10	350	21809.65	48.89	$3,449,978.75	384.11	306.02	96.30%	93.54%	0.9965	15.38
7	10	400	21838.20	49.07	$3,455,551.46	396.91	316.22	96.18%	93.34%	0.9960	15.38
7	10	450	21866.77	49.25	$3,461,125.40	409.71	326.42	96.06%	93.14%	0.9955	15.37
7	10	500	21895.36	49.43	$3,466,700.58	422.52	336.62	95.95%	92.94%	0.9950	15.36
7	10	550	21923.96	49.61	$3,472,277.00	435.33	346.82	95.83%	92.75%	0.9945	15.35
7	10	600	21952.58	49.79	$3,477,854.65	448.14	357.03	95.71%	92.55%	0.9940	15.34
7	10	650	21981.21	49.97	$3,483,433.55	460.95	367.24	95.59%	92.35%	0.9935	15.34
7	10	700	22009.86	50.15	$3,489,013.69	473.76	377.45	95.48%	92.16%	0.9930	15.29
7	10	750	22038.53	50.33	$3,494,595.08	486.58	387.65	95.36%	91.96%	0.9925	14.97
7	10	800	22067.22	50.51	$3,500,177.73	499.39	397.87	95.24%	91.77%	0.9920	14.67
7	10	850	22095.92	50.69	$3,505,761.62	512.21	408.08	95.13%	91.57%	0.9915	14.37
7	10	900	22341.12	51.34	$3,522,024.39	525.10	418.35	95.01%	91.38%	0.9910	14.08
7	10	950	22369.86	51.52	$3,527,610.68	537.92	428.56	94.90%	91.19%	0.9905	13.80
7	10	1000	22398.61	51.70	$3,533,198.24	550.74	438.78	94.78%	91.00%	0.9900	13.53
7	10	1050	22427.39	51.88	$3,538,787.07	563.57	449.00	94.66%	90.81%	0.9895	13.27
7	10	1100	22456.18	52.06	$3,544,377.16	576.40	459.22	94.55%	90.62%	0.9890	13.01
7	10	1150	22484.98	52.24	$3,549,968.52	589.23	469.44	94.44%	90.43%	0.9885	12.76
7	10	1200	22513.81	52.42	$3,555,561.16	602.06	479.66	94.32%	90.24%	0.9880	12.52
7	10	1250	22542.65	52.60	$3,561,155.07	614.89	489.89	94.21%	90.05%	0.9875	12.29
7	10	1300	22571.51	52.78	$3,566,750.26	627.73	500.11	94.09%	89.86%	0.9870	12.06
7	10	1350	22600.39	52.96	$3,572,346.74	640.57	510.34	93.98%	89.68%	0.9865	11.84

Figure H-3.1 BJT inverter summary - Sheet 1 for 10 MVA, variable frequency.

BJT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER BJT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	BJTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itgg
0.55	1500	1	0.001838	0.00275	0	2	1.00E-05	1000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
20.88	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$5,332.87	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	10	100	2008.17	2.49	$190,116.64	52.57	1000.00	1594.97	1	32	32
7	10	150	2010.01	2.49	$190,150.50	54.70	1000.00	1594.57	1	32	32
7	10	200	2011.86	2.49	$190,184.39	56.83	1000.00	1594.17	1	32	32
7	10	250	2013.71	2.49	$190,218.31	58.96	1000.00	1593.77	1	32	32
7	10	300	2015.57	2.49	$190,252.26	61.09	1000.00	1593.37	1	32	32
7	10	350	2017.42	2.50	$190,286.24	63.22	1000.00	1592.97	1	32	32
7	10	400	2019.27	2.50	$190,320.26	65.36	1000.00	1592.57	1	32	32
7	10	450	2021.13	2.50	$190,354.31	67.49	1000.00	1592.17	1	32	32
7	10	500	2022.99	2.50	$190,388.39	69.62	1000.00	1591.77	1	32	32
7	10	550	2024.85	2.50	$190,422.51	71.76	1000.00	1591.37	1	32	32
7	10	600	2026.71	2.50	$190,456.65	73.89	1000.00	1590.97	1	32	32
7	10	650	2028.58	2.50	$190,490.83	76.03	1000.00	1590.57	1	32	32
7	10	700	2030.44	2.50	$190,525.05	78.16	997.36	1585.98	1	32	32
7	10	750	2032.31	2.51	$190,559.29	80.30	977.23	1553.57	1	32	32
7	10	800	2034.18	2.51	$190,593.57	82.43	957.69	1522.13	1	32	32
7	10	850	2036.05	2.51	$190,627.88	84.57	938.75	1491.64	1	32	32
7	10	900	2037.93	2.51	$190,662.23	86.70	920.36	1462.07	1	32	32
7	10	950	2039.80	2.51	$190,696.60	88.84	902.53	1433.38	1	32	32
7	10	1000	2041.68	2.51	$190,731.01	90.98	885.24	1405.56	1	32	32
7	10	1050	2043.56	2.51	$190,765.46	93.11	868.46	1378.57	1	32	32
7	10	1100	2045.44	2.51	$190,799.93	95.25	852.18	1352.38	1	32	32
7	10	1150	2047.32	2.52	$190,834.45	97.39	836.39	1326.98	1	32	32
7	10	1200	2049.21	2.52	$190,868.99	99.52	821.06	1302.34	1	32	32
7	10	1250	2051.09	2.52	$190,903.57	101.66	806.19	1278.42	1	32	32
7	10	1300	2052.98	2.52	$190,938.18	103.80	791.75	1255.21	1	32	32
7	10	1350	2054.87	2.52	$190,972.82	105.94	777.74	1232.69	1	32	32

Figure H-3.2 BJT switch quantity characterization - Sheet 2 for 10 MVA, variable frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
2.5	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
0.998	0.000265	100	2

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	10	100	1.64	1296.87	0.90	0.11	1.02	0.48	0.01	0.01	0.12
7	10	150	1.71	1297.52	0.90	0.17	1.07	0.48	0.01	0.01	0.12
7	10	200	1.78	1298.17	0.90	0.23	1.13	0.48	0.02	0.02	0.12
7	10	250	1.84	1298.82	0.90	0.28	1.19	0.48	0.02	0.02	0.12
7	10	300	1.91	1299.47	0.90	0.34	1.25	0.48	0.03	0.03	0.12
7	10	350	1.98	1300.12	0.91	0.40	1.30	0.48	0.03	0.03	0.12
7	10	400	2.04	1300.77	0.91	0.45	1.36	0.48	0.04	0.04	0.12
7	10	450	2.11	1301.43	0.91	0.51	1.42	0.48	0.04	0.04	0.12
7	10	500	2.18	1302.08	0.91	0.57	1.47	0.48	0.05	0.05	0.12
7	10	550	2.24	1302.74	0.91	0.62	1.53	0.48	0.05	0.05	0.12
7	10	600	2.31	1303.39	0.91	0.68	1.59	0.48	0.06	0.06	0.12
7	10	650	2.38	1304.05	0.91	0.74	1.64	0.48	0.06	0.06	0.12
7	10	700	2.44	1304.70	0.91	0.79	1.70	0.48	0.07	0.07	0.12
7	10	750	2.51	1305.36	0.91	0.85	1.76	0.48	0.07	0.07	0.12
7	10	800	2.58	1306.02	0.91	0.91	1.81	0.48	0.08	0.08	0.12
7	10	850	2.64	1306.68	0.91	0.96	1.87	0.48	0.08	0.08	0.12
7	10	900	2.71	1307.34	0.91	1.02	1.93	0.48	0.09	0.09	0.12
7	10	950	2.78	1308.00	0.91	1.08	1.99	0.48	0.09	0.09	0.12
7	10	1000	2.84	1308.66	0.91	1.13	2.04	0.48	0.09	0.10	0.12
7	10	1050	2.91	1309.32	0.91	1.19	2.10	0.48	0.10	0.10	0.12
7	10	1100	2.98	1309.98	0.91	1.25	2.16	0.48	0.10	0.11	0.12
7	10	1150	3.04	1310.64	0.91	1.30	2.21	0.48	0.11	0.11	0.12
7	10	1200	3.11	1311.31	0.91	1.36	2.27	0.48	0.11	0.12	0.12
7	10	1250	3.18	1311.97	0.91	1.42	2.33	0.48	0.12	0.12	0.12
7	10	1300	3.24	1312.64	0.91	1.47	2.38	0.48	0.12	0.13	0.12
7	10	1350	3.31	1313.30	0.91	1.53	2.44	0.48	0.13	0.13	0.12

Figure H-3.3 BJT switch loss estimation - Sheet 3 for 10 MVA, variable frequency.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
506	4	150	0.875	0.7	4.72E-03	150000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
47	6.27E-02

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$1,788.40	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS										
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
7	10	100	2753.73	4.90	$72,896.01	4.73	1847.84	131.39	111.57	18	2	36
7	10	150	2753.73	4.90	$72,896.01	4.74	1850.60	131.54	111.57	18	2	36
7	10	200	2753.73	4.90	$72,896.01	4.74	1853.35	131.68	111.57	18	2	36
7	10	250	2753.73	4.90	$72,896.01	4.75	1856.11	131.83	111.57	18	2	36
7	10	300	2753.73	4.90	$72,896.01	4.75	1858.87	131.98	111.57	18	2	36
7	10	350	2753.73	4.90	$72,896.01	4.76	1861.63	132.13	111.57	18	2	36
7	10	400	2753.73	4.90	$72,896.01	4.76	1864.39	132.28	111.57	18	2	36
7	10	450	2753.73	4.90	$72,896.01	4.77	1867.16	132.43	111.57	18	2	36
7	10	500	2753.73	4.90	$72,896.01	4.77	1869.92	132.58	111.57	18	2	36
7	10	550	2753.73	4.90	$72,896.01	4.78	1872.69	132.73	111.57	18	2	36
7	10	600	2753.73	4.90	$72,896.01	4.78	1875.46	132.89	111.57	18	2	36
7	10	650	2753.73	4.90	$72,896.01	4.79	1878.24	133.04	111.57	18	2	36
7	10	700	2753.73	4.90	$72,896.01	4.79	1881.01	133.19	111.57	18	2	36
7	10	750	2753.73	4.90	$72,896.01	4.80	1883.79	133.34	111.57	18	2	36
7	10	800	2753.73	4.90	$72,896.01	4.81	1886.56	133.49	111.57	18	2	36
7	10	850	2753.73	4.90	$72,896.01	4.81	1889.34	133.65	111.57	18	2	36
7	10	900	2906.72	5.17	$76,945.79	4.88	1892.12	128.46	117.77	19	2	38
7	10	950	2906.72	5.17	$76,945.79	4.89	1894.91	128.59	117.77	19	2	38
7	10	1000	2906.72	5.17	$76,945.79	4.89	1897.69	128.73	117.77	19	2	38
7	10	1050	2906.72	5.17	$76,945.79	4.90	1900.48	128.87	117.77	19	2	38
7	10	1100	2906.72	5.17	$76,945.79	4.90	1903.27	129.01	117.77	19	2	38
7	10	1150	2906.72	5.17	$76,945.79	4.91	1906.06	129.15	117.77	19	2	38
7	10	1200	2906.72	5.17	$76,945.79	4.91	1908.85	129.29	117.77	19	2	38
7	10	1250	2906.72	5.17	$76,945.79	4.92	1911.65	129.43	117.77	19	2	38
7	10	1300	2906.72	5.17	$76,945.79	4.92	1914.44	129.57	117.77	19	2	38
7	10	1350	2906.72	5.17	$76,945.79	4.93	1917.24	129.71	117.77	19	2	38

Figure H-3.4 BJT input filter sizing - Sheet 4 for 10 MVA, variable frequency.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
7	25	600	45838.16	97.91	$7,048,632.00	1188.83	947.14	95.46%	92.13%	0.9940	30.69
7	26	600	46355.51	99.67	$7,095,118.73	1250.90	996.59	95.41%	92.04%	0.9940	30.69
7	27	600	46874.87	101.45	$7,142,099.33	1314.16	1046.99	95.36%	91.96%	0.9940	30.69
7	28	600	47396.25	103.25	$7,189,573.79	1378.60	1098.33	95.31%	91.87%	0.9940	30.69
7	29	600	47919.65	105.06	$7,237,542.10	1444.22	1150.61	95.26%	91.79%	0.9940	30.69
7	30	600	48228.58	106.42	$7,275,327.79	1510.97	1203.79	95.20%	91.70%	0.9940	30.69
7	31	600	65550.53	131.48	$10,234,644.22	1400.37	1115.67	95.68%	92.49%	0.9940	46.03
7	32	600	66058.82	133.17	$10,278,908.84	1457.11	1160.88	95.64%	92.44%	0.9940	46.03
7	33	600	66568.45	134.87	$10,323,502.70	1514.65	1206.72	95.61%	92.38%	0.9940	46.03
7	34	600	66862.95	136.12	$10,357,749.37	1572.92	1253.14	95.58%	92.33%	0.9940	46.03
7	35	600	67375.27	137.84	$10,403,001.52	1632.03	1300.24	95.54%	92.27%	0.9940	46.03
7	36	600	67888.93	139.58	$10,448,582.92	1691.94	1347.97	95.51%	92.21%	0.9940	46.03
7	37	600	68403.93	141.32	$10,494,493.56	1752.63	1396.32	95.48%	92.16%	0.9940	46.03
7	38	600	68920.27	143.08	$10,540,733.46	1814.11	1445.30	95.44%	92.10%	0.9940	46.03
7	39	600	69221.49	144.38	$10,576,626.34	1876.32	1494.87	95.41%	92.04%	0.9940	46.03
7	40	600	69740.52	146.15	$10,623,524.53	1939.38	1545.11	95.38%	91.99%	0.9940	46.03
7	41	600	70260.89	147.94	$10,670,751.97	2003.23	1595.97	95.34%	91.93%	0.9940	46.03
7	42	600	70782.61	149.74	$10,718,308.65	2067.87	1647.47	95.31%	91.87%	0.9940	46.03
7	43	600	71305.67	151.55	$10,766,194.58	2133.30	1699.60	95.27%	91.82%	0.9940	46.03
7	44	600	71613.59	152.90	$10,803,733.67	2199.45	1752.30	95.24%	91.76%	0.9940	46.03
7	45	600	72139.34	154.73	$10,852,277.91	2266.46	1805.69	95.20%	91.70%	0.9940	46.03
7	46	600	72666.42	156.58	$10,901,151.39	2334.25	1859.70	95.17%	91.64%	0.9940	46.03
7	47	600	89941.21	181.26	$13,848,904.23	2195.93	1749.50	95.54%	92.26%	0.9940	61.38
7	48	600	90238.56	182.53	$13,883,850.75	2255.88	1797.26	95.51%	92.21%	0.9940	61.38
7	49	600	90753.40	184.27	$13,929,720.13	2316.47	1845.53	95.49%	92.17%	0.9940	61.38
7	50	600	91269.24	186.02	$13,975,836.46	2377.66	1894.28	95.46%	92.13%	0.9940	61.38

Figure H-3.5 BJT inverter summary - Sheet 1 for 600 Hz, variable MVA.

BJT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER BJT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	BJTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itgq
0.55	1500	1	0.001838	0.00275	0	2	1.00E-05	1000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
20.88	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$5,332.87	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR/ PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	25	600	4065.19	5.01	$380,028.89	196.14	1000.00	1590.97	2	32	64
7	26	600	4067.83	5.01	$380,077.39	206.40	1000.00	1590.97	2	32	64
7	27	600	4070.58	5.02	$380,127.68	216.86	1000.00	1590.97	2	32	64
7	28	600	4073.42	5.02	$380,179.77	227.52	1000.00	1590.97	2	32	64
7	29	600	4076.36	5.02	$380,233.65	238.38	1000.00	1590.97	2	32	64
7	30	600	4079.39	5.02	$380,289.33	249.43	1000.00	1590.97	2	32	64
7	31	600	6082.28	7.51	$569,209.19	230.92	1000.00	1590.97	3	32	96
7	32	600	6084.49	7.51	$569,249.62	240.30	1000.00	1590.97	3	32	96
7	33	600	6086.76	7.51	$569,291.24	249.80	1000.00	1590.97	3	32	96
7	34	600	6089.09	7.51	$569,334.06	259.44	1000.00	1590.97	3	32	96
7	35	600	6091.49	7.51	$569,378.07	269.21	1000.00	1590.97	3	32	96
7	36	600	6093.96	7.52	$569,423.28	279.11	1000.00	1590.97	3	32	96
7	37	600	6096.49	7.52	$569,469.69	289.15	1000.00	1590.97	3	32	96
7	38	600	6099.09	7.52	$569,517.29	299.31	1000.00	1590.97	3	32	96
7	39	600	6101.75	7.52	$569,566.09	309.61	1000.00	1590.97	3	32	96
7	40	600	6104.48	7.52	$569,616.08	320.03	1000.00	1590.97	3	32	96
7	41	600	6107.27	7.52	$569,667.27	330.59	1000.00	1590.97	3	32	96
7	42	600	6110.13	7.53	$569,719.66	341.28	1000.00	1590.97	3	32	96
7	43	600	6113.05	7.53	$569,773.24	352.10	1000.00	1590.97	3	32	96
7	44	600	6116.04	7.53	$569,828.02	363.06	1000.00	1590.97	3	32	96
7	45	600	6119.09	7.53	$569,883.99	374.14	1000.00	1590.97	3	32	96
7	46	600	6122.21	7.53	$569,941.16	385.36	1000.00	1590.97	3	32	96
7	47	600	8122.81	10.02	$758,819.02	362.23	1000.00	1590.97	4	32	128
7	48	600	8125.28	10.02	$758,864.38	372.15	1000.00	1590.97	4	32	128
7	49	600	8127.80	10.02	$758,910.63	382.17	1000.00	1590.97	4	32	128
7	50	600	8130.38	10.02	$758,957.79	392.28	1000.00	1590.97	4	32	128

Figure H-3.6 BJT switch quantity characterization - Sheet 2 for 600 Hz, variable MVA.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
2.5	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
0.998	0.000265	100	2

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	25	600	3.06	1629.24	1.29	0.85	2.14	0.63	0.06	0.09	0.15
7	26	600	3.23	1694.41	1.37	0.88	2.26	0.66	0.06	0.10	0.16
7	27	600	3.39	1759.58	1.46	0.92	2.38	0.69	0.06	0.10	0.17
7	28	600	3.56	1824.75	1.55	0.95	2.50	0.72	0.06	0.11	0.17
7	29	600	3.72	1889.92	1.64	0.99	2.62	0.75	0.06	0.12	0.18
7	30	600	3.90	1955.09	1.73	1.02	2.75	0.78	0.06	0.13	0.19
7	31	600	2.41	1346.84	0.95	0.70	1.66	0.50	0.06	0.06	0.13
7	32	600	2.50	1390.28	1.00	0.73	1.73	0.52	0.06	0.07	0.13
7	33	600	2.60	1433.73	1.05	0.75	1.80	0.54	0.06	0.07	0.14
7	34	600	2.70	1477.18	1.10	0.77	1.87	0.56	0.06	0.07	0.14
7	35	600	2.80	1520.62	1.15	0.79	1.95	0.58	0.06	0.08	0.14
7	36	600	2.91	1564.07	1.21	0.82	2.02	0.60	0.06	0.08	0.15
7	37	600	3.01	1607.52	1.26	0.84	2.10	0.62	0.06	0.09	0.15
7	38	600	3.12	1650.96	1.31	0.86	2.18	0.64	0.06	0.09	0.16
7	39	600	3.23	1694.41	1.37	0.88	2.26	0.66	0.06	0.10	0.16
7	40	600	3.33	1737.86	1.43	0.91	2.34	0.68	0.06	0.10	0.16
7	41	600	3.44	1781.30	1.49	0.93	2.42	0.70	0.06	0.11	0.17
7	42	600	3.56	1824.75	1.55	0.95	2.50	0.72	0.06	0.11	0.17
7	43	600	3.67	1868.19	1.61	0.98	2.58	0.74	0.06	0.12	0.18
7	44	600	3.78	1911.64	1.67	1.00	2.67	0.76	0.06	0.12	0.18
7	45	600	3.90	1955.09	1.73	1.02	2.75	0.78	0.06	0.13	0.19
7	46	600	4.01	1998.53	1.79	1.04	2.84	0.80	0.06	0.13	0.19
7	47	600	2.83	1531.48	1.17	0.80	1.97	0.58	0.06	0.08	0.15
7	48	600	2.91	1564.07	1.21	0.82	2.02	0.60	0.06	0.08	0.15
7	49	600	2.99	1596.65	1.25	0.83	2.08	0.61	0.06	0.09	0.15
7	50	600	3.06	1629.24	1.29	0.85	2.14	0.63	0.06	0.09	0.15

Figure H-3.7 BJT switch loss estimation - Sheet 3 for 600 Hz, variable MVA.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
506	4	150	0.875	0.7	4.72E-03	150000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
47	6.27E-02

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$1,788.40	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
7	25	600	6884.33	12.25	$182,240.02	11.98	4700.95	133.15	278.93	45	2	90
7	26	600	7190.30	12.79	$190,339.58	12.48	4891.60	132.77	291.33	47	2	94
7	27	600	7496.27	13.34	$198,439.14	12.98	5082.45	132.43	303.73	49	2	98
7	28	600	7802.24	13.88	$206,538.69	13.48	5273.52	132.11	316.12	51	2	102
7	29	600	8108.21	14.43	$214,638.25	13.97	5464.80	131.83	328.52	53	2	106
7	30	600	8261.19	14.70	$218,688.03	14.41	5656.29	133.43	334.72	54	2	108
7	31	600	8567.16	15.24	$226,787.58	14.85	5815.94	132.56	347.12	56	2	112
7	32	600	8873.13	15.79	$234,887.14	15.34	6005.62	132.25	359.51	58	2	116
7	33	600	9179.10	16.33	$242,986.70	15.84	6195.45	131.97	371.91	60	2	120
7	34	600	9332.09	16.60	$247,036.48	16.27	6385.42	133.37	378.11	61	2	122
7	35	600	9638.06	17.15	$255,136.03	16.77	6575.53	133.06	390.51	63	2	126
7	36	600	9944.03	17.69	$263,235.59	17.26	6765.79	132.78	402.90	65	2	130
7	37	600	10250.00	18.24	$271,335.15	17.76	6956.18	132.52	415.30	67	2	134
7	38	600	10555.97	18.78	$279,434.70	18.25	7146.72	132.28	427.70	69	2	138
7	39	600	10708.95	19.05	$283,484.48	18.69	7337.39	133.50	433.90	70	2	140
7	40	600	11014.92	19.60	$291,584.04	19.19	7528.21	133.25	446.29	72	2	144
7	41	600	11320.89	20.14	$299,683.59	19.68	7719.18	133.00	458.69	74	2	148
7	42	600	11626.86	20.69	$307,783.15	20.18	7910.28	132.78	471.09	76	2	152
7	43	600	11932.83	21.23	$315,882.71	20.68	8101.52	132.56	483.48	78	2	156
7	44	600	12085.82	21.50	$319,932.49	21.12	8292.91	133.66	489.68	79	2	158
7	45	600	12391.79	22.05	$328,032.04	21.62	8484.44	133.43	502.08	81	2	162
7	46	600	12697.76	22.59	$336,131.60	22.11	8676.11	133.22	514.48	83	2	166
7	47	600	13003.73	23.13	$344,231.16	22.54	8830.78	132.59	526.87	85	2	170
7	48	600	13156.71	23.41	$348,280.93	22.98	9021.05	133.58	533.07	86	2	172
7	49	600	13462.68	23.95	$356,380.49	23.47	9211.42	133.36	545.47	88	2	176
7	50	600	13768.65	24.50	$364,480.05	23.97	9401.91	133.15	557.87	90	2	180

Figure H-3.8 BJT input filter sizing - Sheet 4 for 600 Hz, variable MVA.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$5,900.00	0	0.7967	200	0	0.6	0

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$1,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
0.35	0.1	600	898.70	2.74	$109,904.42	8.97	7.15	91.77%	86.12%	0.94	0.30
0.35	0.106	600	923.06	2.78	$110,411.83	9.36	7.46	91.88%	86.30%	0.94	0.30
0.35	0.112	600	947.12	2.83	$110,914.82	9.76	7.78	91.98%	86.46%	0.94	0.30
0.35	0.118	600	970.90	2.87	$111,413.68	10.16	8.09	92.07%	86.60%	0.94	0.30
0.35	0.124	600	997.65	2.92	$112,101.66	10.57	8.42	92.14%	86.71%	0.94	0.30
0.35	0.13	600	1020.92	2.96	$112,593.02	10.98	8.74	92.21%	86.83%	0.94	0.30
0.35	0.136	600	1043.97	3.00	$113,080.96	11.38	9.06	92.28%	86.93%	0.94	0.30
0.35	0.142	600	1066.80	3.04	$113,565.66	11.78	9.39	92.34%	87.03%	0.94	0.30
0.35	0.148	600	1089.42	3.08	$114,047.29	12.19	9.71	92.39%	87.11%	0.94	0.30
0.35	0.154	600	1111.85	3.12	$114,526.02	12.60	10.03	92.44%	87.19%	0.94	0.30
0.35	0.16	600	1134.09	3.16	$115,001.97	13.00	10.36	92.48%	87.26%	0.94	0.30
0.35	0.166	600	1156.15	3.20	$115,475.28	13.42	10.69	92.52%	87.32%	0.94	0.30
0.35	0.172	600	1178.05	3.24	$115,946.07	13.83	11.02	92.56%	87.38%	0.94	0.30
0.35	0.178	600	1199.78	3.28	$116,414.45	14.24	11.35	92.59%	87.43%	0.94	0.30
0.35	0.184	600	1224.59	3.33	$117,073.50	14.68	11.69	92.61%	87.46%	0.94	0.30
0.35	0.19	600	1246.01	3.37	$117,537.35	15.10	12.03	92.64%	87.51%	0.94	0.30
0.35	0.196	600	1267.30	3.40	$117,999.06	15.52	12.36	92.66%	87.55%	0.94	0.30
0.35	0.202	600	1288.44	3.44	$118,458.73	15.94	12.70	92.69%	87.58%	0.94	0.30
0.35	0.208	600	1309.46	3.48	$118,916.43	16.36	13.04	92.71%	87.62%	0.94	0.30
0.35	0.214	600	1330.35	3.52	$119,372.22	16.79	13.38	92.72%	87.64%	0.94	0.30
0.35	0.22	600	1351.11	3.55	$119,826.18	17.22	13.72	92.74%	87.67%	0.94	0.30
0.35	0.226	600	1371.75	3.59	$120,278.36	17.65	14.06	92.76%	87.69%	0.94	0.30
0.35	0.232	600	1392.28	3.63	$120,728.83	18.09	14.41	92.77%	87.71%	0.94	0.30
0.35	0.238	600	1415.93	3.67	$121,370.62	18.54	14.77	92.77%	87.72%	0.94	0.30
0.35	0.244	600	1436.24	3.71	$121,817.82	18.97	15.12	92.78%	87.74%	0.94	0.30
0.35	0.25	600	1456.44	3.75	$122,263.47	19.41	15.47	92.79%	87.76%	0.94	0.30

Figure H-4.1 GTO auxiliary inverter summary - Sheet 1 for 600 Hz, variable MVA.

GTO PARAMETERS							
VOLTAGE RATING (kV)	POWER DISS PER GTO (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS PER AMP (J/A)	FIXED SW LOSS (J)	MINIMUM OFF TIME (s)	MAXIMUM Itgq (A)
1.3	900	1.68	0.00152	0.00067	0.25	9.80E-05	1200

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER dv/dt LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER dv/dt LOSS (m^3/kW)
12.6	2	0.0671	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER dv/dt LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$3,582.08	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL(Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
0.35	0.1	600	18.54	0.12	$5,106.67	1.02	825.33	638.87	1	1	1
0.35	0.106	600	18.54	0.12	$5,106.67	1.06	825.33	638.87	1	1	1
0.35	0.112	600	18.54	0.12	$5,106.67	1.11	825.33	638.87	1	1	1
0.35	0.118	600	18.54	0.12	$5,106.67	1.15	825.33	638.87	1	1	1
0.35	0.124	600	18.54	0.12	$5,106.67	1.20	825.33	638.87	1	1	1
0.35	0.13	600	18.54	0.12	$5,106.67	1.24	825.33	638.87	1	1	1
0.35	0.136	600	18.54	0.12	$5,106.67	1.29	825.33	638.87	1	1	1
0.35	0.142	600	18.54	0.12	$5,106.67	1.33	825.33	638.87	1	1	1
0.35	0.148	600	18.54	0.12	$5,106.67	1.38	825.33	638.87	1	1	1
0.35	0.154	600	18.54	0.12	$5,106.67	1.43	825.33	638.87	1	1	1
0.35	0.16	600	18.54	0.12	$5,106.67	1.47	825.33	638.87	1	1	1
0.35	0.166	600	18.54	0.12	$5,106.67	1.52	825.33	638.87	1	1	1
0.35	0.172	600	18.54	0.12	$5,106.67	1.57	825.33	638.87	1	1	1
0.35	0.178	600	18.54	0.12	$5,106.67	1.62	825.33	638.87	1	1	1
0.35	0.184	600	18.54	0.12	$5,106.67	1.67	825.33	638.87	1	1	1
0.35	0.19	600	18.54	0.12	$5,106.67	1.72	825.33	638.87	1	1	1
0.35	0.196	600	18.54	0.12	$5,106.67	1.77	825.33	638.87	1	1	1
0.35	0.202	600	18.54	0.12	$5,106.67	1.82	825.33	638.87	1	1	1
0.35	0.208	600	18.54	0.12	$5,106.67	1.87	825.33	638.87	1	1	1
0.35	0.214	600	18.54	0.12	$5,106.67	1.92	825.33	638.87	1	1	1
0.35	0.22	600	18.54	0.12	$5,106.67	1.97	825.33	638.87	1	1	1
0.35	0.226	600	18.54	0.12	$5,106.67	2.03	825.33	638.87	1	1	1
0.35	0.232	600	18.54	0.12	$5,106.67	2.08	825.33	638.87	1	1	1
0.35	0.238	600	18.54	0.12	$5,106.67	2.13	825.33	638.87	1	1	1
0.35	0.244	600	18.54	0.12	$5,106.67	2.19	825.33	638.87	1	1	1
0.35	0.25	600	18.54	0.12	$5,106.67	2.24	825.33	638.87	1	1	1

Figure H-4.2 GTO auxiliary inverter switch quantity characterization - Sheet 2 for 600 Hz, variable MVA.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
2	0.6

ANTI-PARALLEL DIODE PARAMETERS		
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)
1.17	0.00058	420

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
0.35	0.1	600	1.02	275.30	0.17	0.11	0.28	0.11	0.25	0.09	0.29
0.35	0.106	600	1.06	291.82	0.19	0.11	0.30	0.12	0.25	0.09	0.31
0.35	0.112	600	1.11	308.34	0.20	0.11	0.31	0.12	0.25	0.10	0.32
0.35	0.118	600	1.15	324.86	0.21	0.11	0.33	0.13	0.25	0.10	0.34
0.35	0.124	600	1.20	341.37	0.22	0.12	0.34	0.14	0.25	0.10	0.36
0.35	0.13	600	1.24	357.89	0.24	0.12	0.36	0.15	0.25	0.11	0.38
0.35	0.136	600	1.29	374.41	0.25	0.12	0.37	0.16	0.25	0.11	0.39
0.35	0.142	600	1.33	390.93	0.27	0.12	0.39	0.16	0.25	0.12	0.41
0.35	0.148	600	1.38	407.45	0.28	0.12	0.40	0.17	0.25	0.12	0.43
0.35	0.154	600	1.43	423.97	0.30	0.13	0.42	0.18	0.25	0.13	0.44
0.35	0.16	600	1.47	440.48	0.31	0.13	0.44	0.19	0.25	0.13	0.46
0.35	0.166	600	1.52	457.00	0.33	0.13	0.46	0.20	0.25	0.14	0.48
0.35	0.172	600	1.57	473.52	0.34	0.13	0.47	0.20	0.25	0.14	0.50
0.35	0.178	600	1.62	490.04	0.36	0.13	0.49	0.21	0.25	0.15	0.51
0.35	0.184	600	1.67	506.56	0.37	0.14	0.51	0.22	0.25	0.15	0.53
0.35	0.19	600	1.72	523.07	0.39	0.14	0.53	0.23	0.25	0.16	0.55
0.35	0.196	600	1.77	539.59	0.40	0.14	0.54	0.24	0.25	0.17	0.57
0.35	0.202	600	1.82	556.11	0.42	0.14	0.56	0.25	0.25	0.17	0.58
0.35	0.208	600	1.87	572.63	0.44	0.14	0.58	0.26	0.25	0.18	0.60
0.35	0.214	600	1.92	589.15	0.45	0.15	0.60	0.27	0.25	0.18	0.62
0.35	0.22	600	1.97	605.66	0.47	0.15	0.62	0.28	0.25	0.19	0.64
0.35	0.226	600	2.03	622.18	0.49	0.15	0.64	0.29	0.25	0.20	0.65
0.35	0.232	600	2.08	638.70	0.51	0.15	0.66	0.29	0.25	0.20	0.67
0.35	0.238	600	2.13	655.22	0.53	0.15	0.68	0.30	0.25	0.21	0.69
0.35	0.244	600	2.19	671.74	0.54	0.16	0.70	0.31	0.25	0.21	0.70
0.35	0.25	600	2.24	688.25	0.56	0.16	0.72	0.32	0.25	0.22	0.72

Figure H-4.3 GTO auxiliary inverter switch loss estimation - Sheet 3 for 600 Hz, variable MVA.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
5600	0.45	30	0.875	0.7	2.10E-02	5000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
1.403	2.52E-03

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$60.90	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS FILTER CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
0.35	0.1	600	43.38	0.10	$1,394.03	0.64	391.70	33.43	6.52	19	1	19
0.35	0.106	600	45.67	0.11	$1,467.40	0.67	414.81	33.53	6.86	20	1	20
0.35	0.112	600	47.95	0.11	$1,540.77	0.71	437.93	33.63	7.20	21	1	21
0.35	0.118	600	50.23	0.12	$1,614.14	0.74	461.06	33.72	7.55	22	1	22
0.35	0.124	600	54.80	0.13	$1,760.88	0.79	484.19	33.05	8.23	24	1	24
0.35	0.13	600	57.08	0.14	$1,834.25	0.83	507.34	33.15	8.58	25	1	25
0.35	0.136	600	59.37	0.14	$1,907.62	0.86	530.50	33.24	8.92	26	1	26
0.35	0.142	600	61.65	0.15	$1,980.99	0.90	553.67	33.33	9.26	27	1	27
0.35	0.148	600	63.93	0.15	$2,054.36	0.94	576.85	33.41	9.60	28	1	28
0.35	0.154	600	66.22	0.16	$2,127.73	0.97	600.04	33.49	9.95	29	1	29
0.35	0.16	600	68.50	0.16	$2,201.10	1.01	623.23	33.56	10.29	30	1	30
0.35	0.166	600	70.78	0.17	$2,274.47	1.04	646.44	33.63	10.63	31	1	31
0.35	0.172	600	73.07	0.17	$2,347.84	1.08	669.66	33.70	10.98	32	1	32
0.35	0.178	600	75.35	0.18	$2,421.21	1.11	692.88	33.76	11.32	33	1	33
0.35	0.184	600	79.92	0.19	$2,567.96	1.17	716.12	33.29	12.01	35	1	35
0.35	0.19	600	82.20	0.20	$2,641.33	1.20	739.37	33.36	12.35	36	1	36
0.35	0.196	600	84.49	0.20	$2,714.70	1.24	762.62	33.42	12.69	37	1	37
0.35	0.202	600	86.77	0.21	$2,788.07	1.27	785.89	33.48	13.03	38	1	38
0.35	0.208	600	89.05	0.21	$2,861.44	1.31	809.16	33.54	13.38	39	1	39
0.35	0.214	600	91.34	0.22	$2,934.81	1.34	832.45	33.60	13.72	40	1	40
0.35	0.22	600	93.62	0.22	$3,008.18	1.38	855.75	33.65	14.06	41	1	41
0.35	0.226	600	95.90	0.23	$3,081.55	1.42	879.05	33.70	14.41	42	1	42
0.35	0.232	600	98.19	0.24	$3,154.92	1.45	902.37	33.75	14.75	43	1	43
0.35	0.238	600	102.75	0.25	$3,301.66	1.50	925.69	33.39	15.44	45	1	45
0.35	0.244	600	105.04	0.25	$3,375.03	1.54	949.02	33.44	15.78	46	1	46
0.35	0.25	600	107.32	0.26	$3,448.40	1.57	972.37	33.49	16.12	47	1	47

Figure H-4.4 GTO auxiliary inverter input filter sizing - Sheet 4 for 600 Hz, variable MVA.

BASIS TRANSFORMER PARAMETERS					
MVA RATING	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
0.15	453.1	0.5947	60	3.00	$3,627.00

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
0.35	0.1	60	334.29	0.44	$2,675.96	2.21	0.10
0.35	0.106	60	349.22	0.46	$2,795.49	2.31	0.11
0.35	0.112	60	363.95	0.48	$2,913.35	2.41	0.11
0.35	0.118	60	378.47	0.50	$3,029.64	2.51	0.12
0.35	0.124	60	392.82	0.52	$3,144.45	2.60	0.12
0.35	0.13	60	406.99	0.53	$3,257.89	2.69	0.13
0.35	0.136	60	421.00	0.55	$3,370.03	2.79	0.14
0.35	0.142	60	434.85	0.57	$3,480.93	2.88	0.14
0.35	0.148	60	448.56	0.59	$3,590.67	2.97	0.15
0.35	0.154	60	462.13	0.61	$3,699.30	3.06	0.15
0.35	0.16	60	475.57	0.62	$3,806.88	3.15	0.16
0.35	0.166	60	488.88	0.64	$3,913.45	3.24	0.17
0.35	0.172	60	502.08	0.66	$4,019.07	3.32	0.17
0.35	0.178	60	515.16	0.68	$4,123.77	3.41	0.18
0.35	0.184	60	528.13	0.69	$4,227.59	3.50	0.18
0.35	0.19	60	540.99	0.71	$4,330.56	3.58	0.19
0.35	0.196	60	553.76	0.73	$4,432.73	3.67	0.20
0.35	0.202	60	566.42	0.74	$4,534.12	3.75	0.20
0.35	0.208	60	578.99	0.76	$4,634.75	3.83	0.21
0.35	0.214	60	591.47	0.78	$4,734.67	3.92	0.21
0.35	0.22	60	603.87	0.79	$4,833.88	4.00	0.22
0.35	0.226	60	616.18	0.81	$4,932.42	4.08	0.23
0.35	0.232	60	628.41	0.82	$5,030.31	4.16	0.23
0.35	0.238	60	640.56	0.84	$5,127.57	4.24	0.24
0.35	0.244	60	652.63	0.86	$5,224.22	4.32	0.24
0.35	0.25	60	664.63	0.87	$5,320.28	4.40	0.25

Figure H-4.5 GTO auxiliary inverter output transformer sizing - Sheet 5 for 600 Hz, variable MVA.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$5,900.00	0	0.7967	200	0	0.6	0

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$1,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
0.35	0.2	100	1270.95	3.40	$117,617.35	12.86	10.24	93.96%	89.64%	0.99	0.34
0.35	0.2	150	1271.46	3.41	$117,654.03	13.15	10.47	93.83%	89.44%	0.99	0.34
0.35	0.2	200	1271.97	3.41	$117,690.70	13.43	10.70	93.71%	89.23%	0.98	0.34
0.35	0.2	250	1275.71	3.42	$117,920.36	13.74	10.94	93.57%	89.01%	0.98	0.33
0.35	0.2	300	1276.21	3.42	$117,957.03	14.03	11.18	93.45%	88.81%	0.97	0.33
0.35	0.2	350	1276.72	3.42	$117,993.71	14.32	11.41	93.32%	88.60%	0.97	0.32
0.35	0.2	400	1277.23	3.42	$118,030.38	14.61	11.64	93.19%	88.40%	0.96	0.32
0.35	0.2	450	1277.74	3.42	$118,067.05	14.90	11.87	93.07%	88.19%	0.96	0.31
0.35	0.2	500	1278.24	3.42	$118,103.73	15.20	12.11	92.94%	87.99%	0.95	0.31
0.35	0.2	550	1278.75	3.42	$118,140.40	15.49	12.34	92.81%	87.78%	0.95	0.30
0.35	0.2	600	1282.49	3.43	$118,370.06	15.80	12.59	92.68%	87.57%	0.94	0.30
0.35	0.2	650	1282.99	3.43	$118,406.73	16.10	12.83	92.55%	87.36%	0.94	0.30
0.35	0.2	700	1283.50	3.43	$118,443.41	16.40	13.07	92.42%	87.16%	0.93	0.29
0.35	0.2	750	1284.01	3.43	$118,480.08	16.70	13.30	92.29%	86.95%	0.93	0.29
0.35	0.2	800	1284.52	3.43	$118,516.75	17.00	13.54	92.17%	86.75%	0.92	0.28
0.35	0.2	850	1285.02	3.44	$118,553.43	17.30	13.79	92.04%	86.55%	0.92	0.28
0.35	0.2	900	1285.53	3.44	$118,590.10	17.61	14.03	91.91%	86.34%	0.91	0.28
0.35	0.2	950	1289.27	3.45	$118,819.76	17.93	14.28	91.77%	86.13%	0.91	0.27
0.35	0.2	1000	1289.78	3.45	$118,856.43	18.23	14.53	91.65%	85.93%	0.90	0.27
0.35	0.2	1050	1290.28	3.45	$118,893.11	18.54	14.77	91.52%	85.72%	0.90	0.26
0.35	0.2	1100	1290.79	3.45	$118,929.78	18.85	15.02	91.39%	85.52%	0.89	0.26
0.35	0.2	1150	1291.30	3.45	$118,966.45	19.16	15.27	91.26%	85.31%	0.89	0.26
0.35	0.2	1200	1291.80	3.45	$119,003.13	19.47	15.51	91.13%	85.11%	0.88	0.25
0.35	0.2	1250	1295.54	3.46	$119,232.79	19.80	15.78	90.99%	84.90%	0.88	0.25
0.35	0.2	1300	1296.05	3.46	$119,269.46	20.12	16.03	90.86%	84.69%	0.87	0.24
0.35	0.2	1350	1296.56	3.46	$119,306.13	20.43	16.28	90.73%	84.49%	0.87	0.24

Figure H-4.6 GTO auxiliary inverter summary - Sheet 1 for 0.2 MVA, variable frequency.

GTO PARAMETERS							
VOLTAGE RATING (kV)	POWER DISS PER GTO (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS PER AMP (J/A)	FIXED SW LOSS (J)	MINIMUM OFF TIME (s)	MAXIMUM Itgq (A)
1.3	900	1.68	0.00152	0.00067	0.25	9.80E-05	1200

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER dv/dt LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER dv/dt LOSS (m^3/kW)
12.6	2	0.0671	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER dv/dt LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$3,582.08	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL(Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
0.35	0.2	100	17.94	0.12	$5,083.44	1.32	902.73	716.74	1	1	1
0.35	0.2	150	18.00	0.12	$5,085.76	1.37	894.72	708.61	1	1	1
0.35	0.2	200	18.06	0.12	$5,088.08	1.42	886.77	700.57	1	1	1
0.35	0.2	250	18.12	0.12	$5,090.41	1.46	878.88	692.60	1	1	1
0.35	0.2	300	18.18	0.12	$5,092.73	1.51	871.05	684.70	1	1	1
0.35	0.2	350	18.24	0.12	$5,095.05	1.56	863.28	676.88	1	1	1
0.35	0.2	400	18.30	0.12	$5,097.38	1.61	855.57	669.13	1	1	1
0.35	0.2	450	18.36	0.12	$5,099.70	1.66	847.93	661.46	1	1	1
0.35	0.2	500	18.42	0.12	$5,102.03	1.70	840.34	653.86	1	1	1
0.35	0.2	550	18.48	0.12	$5,104.35	1.75	832.81	646.33	1	1	1
0.35	0.2	600	18.54	0.12	$5,106.67	1.80	825.33	638.87	1	1	1
0.35	0.2	650	18.60	0.12	$5,109.00	1.85	817.92	631.48	1	1	1
0.35	0.2	700	18.66	0.12	$5,111.32	1.90	810.56	624.16	1	1	1
0.35	0.2	750	18.72	0.12	$5,113.64	1.95	803.26	616.90	1	1	1
0.35	0.2	800	18.78	0.12	$5,115.97	2.00	796.01	609.72	1	1	1
0.35	0.2	850	18.84	0.12	$5,118.29	2.05	788.82	602.60	1	1	1
0.35	0.2	900	18.90	0.12	$5,120.62	2.10	781.68	595.55	1	1	1
0.35	0.2	950	18.96	0.12	$5,122.94	2.15	774.59	588.56	1	1	1
0.35	0.2	1000	19.02	0.12	$5,125.26	2.20	767.56	581.64	1	1	1
0.35	0.2	1050	19.08	0.12	$5,127.59	2.25	760.58	574.78	1	1	1
0.35	0.2	1100	19.14	0.12	$5,129.91	2.30	753.65	567.99	1	1	1
0.35	0.2	1150	19.20	0.12	$5,132.23	2.35	746.77	561.25	1	1	1
0.35	0.2	1200	19.26	0.12	$5,134.56	2.41	739.94	554.58	1	1	1
0.35	0.2	1250	19.32	0.12	$5,136.88	2.46	733.16	547.97	1	1	1
0.35	0.2	1300	19.38	0.12	$5,139.21	2.51	726.42	541.42	1	1	1
0.35	0.2	1350	19.44	0.12	$5,141.53	2.56	719.74	534.93	1	1	1

Figure H-4.7 GTO auxiliary inverter switch quantity characterization - Sheet 2 for 0.2 MVA, variable frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
2	0.6

ANTI-PARALLEL DIODE PARAMETERS		
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)
1.17	0.00058	420

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
0.35	0.2	100	1.32	523.36	0.41	0.02	0.43	0.24	0.04	0.03	0.58
0.35	0.2	150	1.37	525.96	0.41	0.04	0.44	0.24	0.06	0.04	0.58
0.35	0.2	200	1.42	528.59	0.41	0.05	0.46	0.24	0.08	0.05	0.58
0.35	0.2	250	1.46	531.24	0.41	0.06	0.47	0.24	0.11	0.07	0.58
0.35	0.2	300	1.51	533.93	0.41	0.07	0.48	0.24	0.13	0.08	0.58
0.35	0.2	350	1.56	536.63	0.41	0.08	0.49	0.24	0.15	0.10	0.58
0.35	0.2	400	1.61	539.37	0.41	0.09	0.51	0.24	0.17	0.11	0.58
0.35	0.2	450	1.66	542.14	0.41	0.11	0.52	0.24	0.19	0.12	0.58
0.35	0.2	500	1.70	544.93	0.41	0.12	0.53	0.25	0.21	0.14	0.58
0.35	0.2	550	1.75	547.75	0.41	0.13	0.54	0.25	0.23	0.15	0.58
0.35	0.2	600	1.80	550.60	0.42	0.14	0.56	0.25	0.25	0.17	0.58
0.35	0.2	650	1.85	553.49	0.42	0.15	0.57	0.25	0.27	0.18	0.58
0.35	0.2	700	1.90	556.40	0.42	0.16	0.58	0.25	0.30	0.20	0.58
0.35	0.2	750	1.95	559.34	0.42	0.18	0.59	0.25	0.32	0.22	0.58
0.35	0.2	800	2.00	562.31	0.42	0.19	0.61	0.25	0.34	0.23	0.58
0.35	0.2	850	2.05	565.32	0.42	0.20	0.62	0.25	0.36	0.25	0.58
0.35	0.2	900	2.10	568.36	0.42	0.21	0.63	0.25	0.38	0.26	0.58
0.35	0.2	950	2.15	571.43	0.42	0.22	0.64	0.25	0.40	0.28	0.58
0.35	0.2	1000	2.20	574.53	0.42	0.24	0.66	0.25	0.42	0.30	0.58
0.35	0.2	1050	2.25	577.67	0.42	0.25	0.67	0.25	0.44	0.31	0.58
0.35	0.2	1100	2.30	580.84	0.42	0.26	0.68	0.25	0.46	0.33	0.58
0.35	0.2	1150	2.35	584.05	0.42	0.27	0.69	0.25	0.49	0.35	0.58
0.35	0.2	1200	2.41	587.29	0.42	0.28	0.71	0.25	0.51	0.37	0.58
0.35	0.2	1250	2.46	590.57	0.43	0.29	0.72	0.25	0.53	0.38	0.58
0.35	0.2	1300	2.51	593.89	0.43	0.31	0.73	0.25	0.55	0.40	0.58
0.35	0.2	1350	2.56	597.24	0.43	0.32	0.74	0.25	0.57	0.42	0.58

Figure H-4.8 GTO auxiliary inverter switch loss estimation - Sheet 3 for 0.2 MVA, variable frequency.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
5600	0.45	30	0.875	0.7	2.10E-02	5000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
1.403	2.52E-03

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$60.90	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS FILTER CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
0.36	0.2	100	82.20	0.20	$2,641.33	1.21	748.24	33.57	12.36	36	1	36
0.36	0.2	150	82.20	0.20	$2,641.33	1.21	751.13	33.64	12.36	36	1	36
0.36	0.2	200	82.20	0.20	$2,641.33	1.21	754.03	33.71	12.36	36	1	36
0.36	0.2	250	84.49	0.20	$2,714.70	1.23	756.96	33.29	12.69	37	1	37
0.36	0.2	300	84.49	0.20	$2,714.70	1.23	759.91	33.36	12.69	37	1	37
0.36	0.2	350	84.49	0.20	$2,714.70	1.24	762.89	33.43	12.69	37	1	37
0.36	0.2	400	84.49	0.20	$2,714.70	1.24	765.89	33.50	12.69	37	1	37
0.36	0.2	450	84.49	0.20	$2,714.70	1.24	768.91	33.57	12.69	37	1	37
0.36	0.2	500	84.49	0.20	$2,714.70	1.24	771.96	33.64	12.69	37	1	37
0.36	0.2	550	84.49	0.20	$2,714.70	1.26	775.03	33.71	12.69	37	1	37
0.36	0.2	600	86.77	0.21	$2,788.07	1.27	778.13	33.31	13.03	38	1	38
0.36	0.2	650	86.77	0.21	$2,788.07	1.27	781.26	33.38	13.03	38	1	38
0.36	0.2	700	86.77	0.21	$2,788.07	1.27	784.41	33.45	13.03	38	1	38
0.36	0.2	750	86.77	0.21	$2,788.07	1.27	787.58	33.52	13.03	38	1	38
0.36	0.2	800	86.77	0.21	$2,788.07	1.28	790.79	33.59	13.03	38	1	38
0.36	0.2	850	86.77	0.21	$2,788.07	1.28	794.02	33.67	13.03	38	1	38
0.36	0.2	900	86.77	0.21	$2,788.07	1.28	797.28	33.74	13.03	38	1	38
0.36	0.2	950	89.05	0.21	$2,861.44	1.30	800.56	33.35	13.38	39	1	39
0.36	0.2	1000	89.05	0.21	$2,861.44	1.30	803.88	33.42	13.38	39	1	39
0.36	0.2	1050	89.05	0.21	$2,861.44	1.31	807.22	33.50	13.38	39	1	39
0.36	0.2	1100	89.05	0.21	$2,861.44	1.31	810.60	33.57	13.38	39	1	39
0.36	0.2	1150	89.05	0.21	$2,861.44	1.31	814.00	33.65	13.38	39	1	39
0.36	0.2	1200	89.05	0.21	$2,861.44	1.32	817.44	33.73	13.38	39	1	39
0.36	0.2	1250	91.34	0.22	$2,934.81	1.33	820.90	33.34	13.72	40	1	40
0.36	0.2	1300	91.34	0.22	$2,934.81	1.34	824.40	33.42	13.72	40	1	40
0.36	0.2	1350	91.34	0.22	$2,934.81	1.34	827.93	33.50	13.72	40	1	40

Figure H-4.9 GTO auxiliary inverter input filter sizing - Sheet 4 for 0.2 MVA, variable frequency.

BASIS TRANSFORMER PARAMETERS					
MVA RATING	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
0.15	453.1	0.5947	60	3.00	$3,627.00

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20

Figure H-4.10 GTO auxiliary inverter output transformer sizing - Sheet 5 for 0.2 MVA, variable switching frequency.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$5,900.00	0	0.7967	200	0	0.6	0

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$1,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
0.35	0.1	600	803.18	1.61	$89,723.70	5.08	4.05	95.17%	91.64%	0.9982	0.36
0.35	0.106	600	827.53	1.66	$90,231.10	5.34	4.26	95.20%	91.70%	0.9982	0.36
0.35	0.112	600	851.59	1.70	$90,734.09	5.61	4.47	95.23%	91.75%	0.9982	0.36
0.35	0.118	600	875.37	1.74	$91,232.95	5.87	4.68	95.26%	91.79%	0.9982	0.36
0.35	0.124	600	898.89	1.78	$91,727.94	6.14	4.89	95.28%	91.83%	0.9982	0.36
0.35	0.13	600	922.17	1.82	$92,219.31	6.41	5.10	95.30%	91.87%	0.9982	0.36
0.35	0.136	600	945.21	1.86	$92,707.24	6.68	5.32	95.32%	91.90%	0.9982	0.36
0.35	0.142	600	968.04	1.91	$93,191.94	6.95	5.53	95.34%	91.92%	0.9982	0.36
0.35	0.148	600	990.67	1.95	$93,673.58	7.22	5.75	95.35%	91.94%	0.9982	0.36
0.35	0.154	600	1013.09	1.99	$94,152.30	7.49	5.97	95.36%	91.96%	0.9982	0.36
0.35	0.16	600	1035.33	2.02	$94,628.25	7.77	6.19	95.37%	91.98%	0.9982	0.36
0.35	0.166	600	1057.40	2.06	$95,101.57	8.04	6.41	95.38%	91.99%	0.9982	0.36
0.35	0.172	600	1082.52	2.11	$95,765.34	8.33	6.64	95.38%	91.99%	0.9982	0.36
0.35	0.178	600	1104.25	2.15	$96,233.72	8.61	6.86	95.38%	92.00%	0.9982	0.36
0.35	0.184	600	1125.83	2.19	$96,699.78	8.90	7.09	95.39%	92.01%	0.9982	0.36
0.35	0.19	600	1147.26	2.23	$97,163.63	9.18	7.31	95.39%	92.01%	0.9982	0.36
0.35	0.196	600	1168.54	2.27	$97,625.35	9.46	7.54	95.39%	92.02%	0.9982	0.36
0.35	0.202	600	1189.69	2.30	$98,085.02	9.75	7.77	95.40%	92.02%	0.9982	0.36
0.35	0.208	600	1210.70	2.34	$98,542.71	10.04	8.00	95.40%	92.02%	0.9982	0.36
0.35	0.214	600	1231.59	2.38	$98,998.50	10.33	8.23	95.40%	92.02%	0.9982	0.36
0.35	0.22	600	1252.35	2.42	$99,452.46	10.62	8.46	95.40%	92.02%	0.9982	0.36
0.35	0.226	600	1273.00	2.45	$99,904.64	10.91	8.69	95.39%	92.02%	0.9982	0.36
0.35	0.232	600	1293.53	2.49	$100,355.11	11.20	8.93	95.39%	92.02%	0.9982	0.36
0.35	0.238	600	1313.94	2.53	$100,803.92	11.50	9.16	95.39%	92.01%	0.9982	0.36
0.35	0.244	600	1334.25	2.56	$101,251.12	11.80	9.40	95.39%	92.01%	0.9982	0.36
0.35	0.25	600	1354.46	2.60	$101,696.76	12.10	9.64	95.38%	92.00%	0.9982	0.36

Figure H-5.1 IGBT auxiliary inverter summary - Sheet 1 for 600 Hz, variable MVA.

IGBT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER IGBT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	IGBTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itgq
1	187.5	0.9	0.0106	0.000346	0	5	3.00E-06	300

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER dv/dt LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER dv/dt LOSS (m^3/kW)
5.27	2	0.004095	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER dv/dt LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$2,448.57	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
0.35	0.1	600	7.67	0.01	$3,840.18	0.38	189.42	754.98	1	1	1
0.35	0.106	600	7.67	0.01	$3,840.18	0.40	189.42	754.98	1	1	1
0.35	0.112	600	7.67	0.01	$3,840.18	0.42	189.42	754.98	1	1	1
0.35	0.118	600	7.67	0.01	$3,840.18	0.44	189.42	754.98	1	1	1
0.35	0.124	600	7.67	0.01	$3,840.18	0.47	189.42	754.98	1	1	1
0.35	0.13	600	7.67	0.01	$3,840.18	0.49	189.42	754.98	1	1	1
0.35	0.136	600	7.67	0.01	$3,840.18	0.51	189.42	754.98	1	1	1
0.35	0.142	600	7.67	0.01	$3,840.18	0.54	189.42	754.98	1	1	1
0.35	0.148	600	7.67	0.01	$3,840.18	0.56	189.42	754.98	1	1	1
0.35	0.154	600	7.67	0.01	$3,840.18	0.59	189.42	754.98	1	1	1
0.35	0.16	600	7.67	0.01	$3,840.18	0.61	189.42	754.98	1	1	1
0.35	0.166	600	7.67	0.01	$3,840.18	0.64	189.42	754.98	1	1	1
0.35	0.172	600	7.67	0.01	$3,840.18	0.66	189.42	754.98	1	1	1
0.35	0.178	600	7.67	0.01	$3,840.18	0.69	189.42	754.98	1	1	1
0.35	0.184	600	7.67	0.01	$3,840.18	0.72	189.42	754.98	1	1	1
0.35	0.19	600	7.67	0.01	$3,840.18	0.74	189.42	754.98	1	1	1
0.35	0.196	600	7.67	0.01	$3,840.18	0.77	189.42	754.98	1	1	1
0.35	0.202	600	7.67	0.01	$3,840.18	0.80	189.42	754.98	1	1	1
0.35	0.208	600	7.67	0.01	$3,840.18	0.83	189.42	754.98	1	1	1
0.35	0.214	600	7.67	0.01	$3,840.18	0.86	189.42	754.98	1	1	1
0.35	0.22	600	7.67	0.01	$3,840.18	0.89	189.42	754.98	1	1	1
0.35	0.226	600	7.67	0.01	$3,840.18	0.91	189.42	754.98	1	1	1
0.35	0.232	600	7.67	0.01	$3,840.18	0.94	189.42	754.98	1	1	1
0.35	0.238	600	7.67	0.01	$3,840.18	0.97	189.42	754.98	1	1	1
0.35	0.244	600	7.67	0.01	$3,840.18	1.01	189.42	754.98	1	1	1
0.35	0.25	600	7.67	0.01	$3,840.18	1.04	189.42	754.98	1	1	1

Figure H-5.2 IGBT auxiliary inverter switch quantity characterization - Sheet 2 for 600 Hz, variable MVA.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
1	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
1.6	0.00556	34	17

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
0.35	0.1	600	0.38	259.58	0.12	0.02	0.14	0.14	0.08	0.00	0.02
0.35	0.106	600	0.40	275.16	0.13	0.02	0.15	0.15	0.08	0.00	0.03
0.35	0.112	600	0.42	290.73	0.14	0.02	0.16	0.16	0.08	0.00	0.03
0.35	0.118	600	0.44	306.31	0.15	0.02	0.17	0.17	0.08	0.00	0.03
0.35	0.124	600	0.47	321.88	0.16	0.02	0.18	0.17	0.08	0.00	0.03
0.35	0.13	600	0.49	337.46	0.17	0.02	0.20	0.18	0.08	0.00	0.03
0.35	0.136	600	0.51	353.03	0.18	0.02	0.21	0.19	0.08	0.00	0.03
0.35	0.142	600	0.54	368.61	0.20	0.02	0.22	0.20	0.08	0.00	0.04
0.35	0.148	600	0.56	384.18	0.21	0.03	0.23	0.21	0.08	0.01	0.04
0.35	0.154	600	0.59	399.76	0.22	0.03	0.25	0.22	0.08	0.01	0.04
0.35	0.16	600	0.61	415.33	0.23	0.03	0.26	0.23	0.08	0.01	0.04
0.35	0.166	600	0.64	430.91	0.25	0.03	0.28	0.24	0.08	0.01	0.04
0.35	0.172	600	0.66	446.48	0.26	0.03	0.29	0.25	0.08	0.01	0.04
0.35	0.178	600	0.69	462.05	0.28	0.03	0.31	0.26	0.08	0.01	0.04
0.35	0.184	600	0.72	477.63	0.29	0.03	0.32	0.27	0.08	0.01	0.05
0.35	0.19	600	0.74	493.20	0.30	0.03	0.34	0.28	0.08	0.01	0.05
0.35	0.196	600	0.77	508.78	0.32	0.03	0.35	0.29	0.08	0.01	0.05
0.35	0.202	600	0.80	524.35	0.34	0.03	0.37	0.30	0.08	0.01	0.05
0.35	0.208	600	0.83	539.93	0.35	0.04	0.39	0.30	0.08	0.01	0.05
0.35	0.214	600	0.86	555.50	0.37	0.04	0.40	0.31	0.08	0.01	0.05
0.35	0.22	600	0.89	571.08	0.38	0.04	0.42	0.32	0.08	0.01	0.05
0.35	0.226	600	0.91	586.65	0.40	0.04	0.44	0.33	0.08	0.01	0.06
0.35	0.232	600	0.94	602.23	0.42	0.04	0.46	0.34	0.08	0.01	0.06
0.35	0.238	600	0.97	617.80	0.43	0.04	0.47	0.35	0.08	0.01	0.06
0.35	0.244	600	1.01	633.38	0.45	0.04	0.49	0.36	0.08	0.01	0.06
0.35	0.25	600	1.04	648.95	0.47	0.04	0.51	0.37	0.08	0.01	0.06

Figure H-5.3 IGBT auxiliary inverter switch loss estimation - Sheet 3 for 600 Hz, variable MVA.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
5600	0.45	30	0.875	0.7	2.10E-02	5000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
1.403	2.52E-03

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$60.90	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
0.35	0.1	600	41.10	0.10	$1,320.66	0.60	366.54	33.21	6.17	18	1	18
0.35	0.106	600	43.38	0.10	$1,394.03	0.63	388.51	33.28	6.52	19	1	19
0.35	0.112	600	45.67	0.11	$1,467.40	0.67	410.49	33.35	6.86	20	1	20
0.35	0.118	600	47.96	0.11	$1,540.77	0.70	432.48	33.41	7.20	21	1	21
0.35	0.124	600	50.23	0.12	$1,614.14	0.74	454.47	33.46	7.55	22	1	22
0.35	0.13	600	52.52	0.13	$1,687.51	0.77	476.48	33.51	7.89	23	1	23
0.35	0.136	600	54.80	0.13	$1,760.88	0.81	498.49	33.56	8.23	24	1	24
0.35	0.142	600	57.08	0.14	$1,834.25	0.84	520.51	33.60	8.58	25	1	25
0.35	0.148	600	59.37	0.14	$1,907.62	0.87	542.54	33.64	8.92	26	1	26
0.35	0.154	600	61.65	0.15	$1,980.99	0.91	564.58	33.68	9.26	27	1	27
0.35	0.16	600	63.93	0.15	$2,054.36	0.94	586.62	33.72	9.60	28	1	28
0.35	0.166	600	66.22	0.16	$2,127.73	0.98	608.68	33.75	9.95	29	1	29
0.35	0.172	600	70.78	0.17	$2,274.47	1.03	630.74	33.19	10.63	31	1	31
0.35	0.178	600	73.07	0.17	$2,347.84	1.06	652.81	33.24	10.98	32	1	32
0.35	0.184	600	75.35	0.18	$2,421.21	1.10	674.89	33.28	11.32	33	1	33
0.35	0.19	600	77.64	0.19	$2,494.58	1.13	696.98	33.32	11.66	34	1	34
0.35	0.196	600	79.92	0.19	$2,567.95	1.17	719.08	33.36	12.01	35	1	35
0.35	0.202	600	82.20	0.20	$2,641.33	1.20	741.18	33.40	12.35	36	1	36
0.35	0.208	600	84.49	0.20	$2,714.70	1.24	763.29	33.44	12.69	37	1	37
0.35	0.214	600	86.77	0.21	$2,788.07	1.27	785.42	33.47	13.03	38	1	38
0.35	0.22	600	89.05	0.21	$2,861.44	1.31	807.55	33.50	13.38	39	1	39
0.35	0.226	600	91.34	0.22	$2,934.81	1.34	829.68	33.53	13.72	40	1	40
0.35	0.232	600	93.62	0.22	$3,008.18	1.38	851.83	33.56	14.06	41	1	41
0.35	0.238	600	95.90	0.23	$3,081.55	1.41	873.99	33.59	14.41	42	1	42
0.35	0.244	600	98.19	0.24	$3,154.92	1.45	896.15	33.62	14.75	43	1	43
0.35	0.25	600	100.47	0.24	$3,228.29	1.48	918.32	33.65	15.09	44	1	44

Figure H-5.4 IGBT auxiliary inverter input filter sizing - Sheet 4 for 600 Hz, variable MVA.

BASIS TRANSFORMER PARAMETERS					
MVA RATING	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
0.15	453.1	0.5947	60	3.00	$3,627.00

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
0.35	0.1	60	334.29	0.44	$2,675.96	2.21	0.10
0.35	0.106	60	349.22	0.46	$2,795.49	2.31	0.11
0.35	0.112	60	363.95	0.48	$2,913.35	2.41	0.11
0.35	0.118	60	378.47	0.50	$3,029.64	2.51	0.12
0.35	0.124	60	392.82	0.52	$3,144.45	2.60	0.12
0.35	0.13	60	406.99	0.53	$3,257.89	2.69	0.13
0.35	0.136	60	421.00	0.55	$3,370.03	2.79	0.14
0.35	0.142	60	434.85	0.57	$3,480.93	2.88	0.14
0.35	0.148	60	448.56	0.59	$3,590.67	2.97	0.15
0.35	0.154	60	462.13	0.61	$3,699.30	3.06	0.15
0.35	0.16	60	475.57	0.62	$3,806.88	3.15	0.16
0.35	0.166	60	488.88	0.64	$3,913.45	3.24	0.17
0.35	0.172	60	502.08	0.66	$4,019.07	3.32	0.17
0.35	0.178	60	515.16	0.68	$4,123.77	3.41	0.18
0.35	0.184	60	528.13	0.69	$4,227.59	3.50	0.18
0.35	0.19	60	540.99	0.71	$4,330.56	3.58	0.19
0.35	0.196	60	553.76	0.73	$4,432.73	3.67	0.20
0.35	0.202	60	566.42	0.74	$4,534.12	3.75	0.20
0.35	0.208	60	578.99	0.76	$4,634.75	3.83	0.21
0.35	0.214	60	591.47	0.78	$4,734.67	3.92	0.21
0.35	0.22	60	603.87	0.79	$4,833.88	4.00	0.22
0.35	0.226	60	616.18	0.81	$4,932.42	4.08	0.23
0.35	0.232	60	628.41	0.82	$5,030.31	4.16	0.23
0.35	0.238	60	640.56	0.84	$5,127.57	4.24	0.24
0.35	0.244	60	652.63	0.86	$5,224.22	4.32	0.24
0.35	0.25	60	664.63	0.87	$5,320.28	4.40	0.25

Figure H-5.5 IGBT auxiliary inverter output transformer sizing - Sheet 5 for 600 Hz switching frequency variable MVA.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$5,900.00	0	0.7967	200	0	0.6	0

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$1,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
0.35	0.2	100	1179.00	2.28	$97,694.86	9.05	7.21	95.67%	92.48%	0.9997	0.38
0.35	0.2	150	1179.15	2.28	$97,705.71	9.11	7.25	95.65%	92.44%	0.9996	0.38
0.35	0.2	200	1179.30	2.28	$97,716.56	9.17	7.30	95.62%	92.39%	0.9994	0.38
0.35	0.2	250	1179.45	2.28	$97,727.41	9.22	7.35	95.59%	92.35%	0.9993	0.37
0.35	0.2	300	1179.60	2.28	$97,738.26	9.28	7.40	95.56%	92.30%	0.9991	0.37
0.35	0.2	350	1179.75	2.28	$97,749.11	9.34	7.44	95.54%	92.26%	0.9990	0.37
0.35	0.2	400	1179.90	2.28	$97,759.96	9.40	7.49	95.51%	92.21%	0.9988	0.37
0.35	0.2	450	1180.05	2.28	$97,770.81	9.46	7.54	95.48%	92.16%	0.9987	0.37
0.35	0.2	500	1180.20	2.28	$97,781.66	9.52	7.59	95.45%	92.12%	0.9985	0.37
0.35	0.2	550	1180.35	2.29	$97,792.51	9.58	7.63	95.43%	92.07%	0.9984	0.37
0.35	0.2	600	1180.50	2.29	$97,803.36	9.64	7.68	95.40%	92.03%	0.9982	0.36
0.35	0.2	650	1180.65	2.29	$97,814.21	9.70	7.73	95.37%	91.98%	0.9981	0.36
0.35	0.2	700	1180.80	2.29	$97,825.06	9.76	7.78	95.35%	91.94%	0.9979	0.36
0.35	0.2	750	1180.95	2.29	$97,835.91	9.82	7.82	95.32%	91.89%	0.9978	0.36
0.35	0.2	800	1181.10	2.29	$97,846.76	9.88	7.87	95.29%	91.85%	0.9976	0.36
0.35	0.2	850	1184.48	2.30	$98,050.60	9.96	7.93	95.26%	91.79%	0.9975	0.36
0.35	0.2	900	1184.63	2.30	$98,061.45	10.02	7.98	95.23%	91.75%	0.9973	0.36
0.35	0.2	950	1184.78	2.30	$98,072.30	10.08	8.03	95.20%	91.70%	0.9972	0.36
0.35	0.2	1000	1184.93	2.30	$98,083.15	10.14	8.07	95.18%	91.66%	0.9970	0.35
0.35	0.2	1050	1185.08	2.30	$98,094.00	10.19	8.12	95.15%	91.61%	0.9969	0.35
0.35	0.2	1100	1185.23	2.30	$98,104.85	10.25	8.17	95.12%	91.57%	0.9967	0.35
0.35	0.2	1150	1185.38	2.30	$98,115.70	10.31	8.22	95.10%	91.52%	0.9966	0.35
0.35	0.2	1200	1185.53	2.30	$98,126.55	10.37	8.26	95.07%	91.48%	0.9964	0.35
0.35	0.2	1250	1185.68	2.30	$98,137.40	10.43	8.31	95.04%	91.43%	0.9963	0.35
0.35	0.2	1300	1185.83	2.30	$98,148.25	10.49	8.36	95.02%	91.39%	0.9961	0.35
0.35	0.2	1350	1185.98	2.30	$98,159.10	10.55	8.41	94.99%	91.34%	0.9960	0.35

Figure H-5.6 IGBT auxiliary inverter summary - Sheet 1 for 0.2 MVA, variable frequency.

IGBT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER IGBT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	IGBTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itqq
1	187.5	0.9	0.0106	0.000346	0	5	3.00E-06	300

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER dv/dt LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER dv/dt LOSS (m^3/kW)
5.27	2	0.004095	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER dv/dt LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$2,448.57	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
0.35	0.2	100	7.49	0.01	$3,833.30	0.69	195.77	780.90	1	1	1
0.35	0.2	150	7.51	0.01	$3,833.99	0.70	195.12	778.26	1	1	1
0.35	0.2	200	7.53	0.01	$3,834.68	0.71	194.48	775.63	1	1	1
0.35	0.2	250	7.54	0.01	$3,835.36	0.72	193.84	773.01	1	1	1
0.35	0.2	300	7.56	0.01	$3,836.05	0.73	193.20	770.40	1	1	1
0.35	0.2	350	7.58	0.01	$3,836.74	0.74	192.56	767.80	1	1	1
0.35	0.2	400	7.60	0.01	$3,837.43	0.75	191.93	765.22	1	1	1
0.35	0.2	450	7.61	0.01	$3,838.11	0.76	191.30	762.64	1	1	1
0.35	0.2	500	7.63	0.01	$3,838.80	0.77	190.67	760.08	1	1	1
0.35	0.2	550	7.65	0.01	$3,839.49	0.78	190.04	757.52	1	1	1
0.35	0.2	600	7.67	0.01	$3,840.18	0.79	189.42	754.98	1	1	1
0.35	0.2	650	7.68	0.01	$3,840.86	0.80	188.80	752.45	1	1	1
0.35	0.2	700	7.70	0.01	$3,841.55	0.81	188.18	749.93	1	1	1
0.35	0.2	750	7.72	0.01	$3,842.24	0.82	187.56	747.42	1	1	1
0.35	0.2	800	7.74	0.01	$3,842.93	0.83	186.95	744.92	1	1	1
0.35	0.2	850	7.76	0.01	$3,843.61	0.84	186.34	742.43	1	1	1
0.35	0.2	900	7.77	0.01	$3,844.30	0.85	185.73	739.95	1	1	1
0.35	0.2	950	7.79	0.01	$3,844.99	0.86	185.12	737.48	1	1	1
0.35	0.2	1000	7.81	0.01	$3,845.68	0.87	184.52	735.03	1	1	1
0.35	0.2	1050	7.83	0.01	$3,846.36	0.88	183.92	732.58	1	1	1
0.35	0.2	1100	7.84	0.01	$3,847.05	0.89	183.32	730.14	1	1	1
0.35	0.2	1150	7.86	0.01	$3,847.74	0.90	182.73	727.72	1	1	1
0.35	0.2	1200	7.88	0.01	$3,848.43	0.91	182.13	725.30	1	1	1
0.35	0.2	1250	7.90	0.01	$3,849.11	0.92	181.54	722.90	1	1	1
0.35	0.2	1300	7.91	0.01	$3,849.80	0.93	180.96	720.50	1	1	1
0.35	0.2	1350	7.93	0.01	$3,850.49	0.94	180.37	718.12	1	1	1

Figure H-5.7 IGBT auxiliary inverter switch quantity characterization - Sheet 2 for 0.2 MVA, variable frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
1	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
1.6	0.00556	34	17

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
0.35	0.2	100	0.69	518.38	0.33	0.01	0.34	0.29	0.01	0.00	0.05
0.35	0.2	150	0.70	518.46	0.33	0.01	0.34	0.29	0.02	0.00	0.05
0.35	0.2	200	0.71	518.54	0.33	0.01	0.34	0.29	0.03	0.00	0.05
0.35	0.2	250	0.72	518.62	0.33	0.01	0.34	0.29	0.03	0.00	0.05
0.35	0.2	300	0.73	518.70	0.33	0.02	0.35	0.29	0.04	0.00	0.05
0.35	0.2	350	0.74	518.77	0.33	0.02	0.35	0.29	0.04	0.01	0.05
0.35	0.2	400	0.75	518.85	0.33	0.02	0.35	0.29	0.05	0.01	0.05
0.35	0.2	450	0.76	518.93	0.33	0.03	0.36	0.29	0.06	0.01	0.05
0.35	0.2	500	0.77	519.01	0.33	0.03	0.36	0.29	0.06	0.01	0.05
0.35	0.2	550	0.78	519.08	0.33	0.03	0.36	0.29	0.07	0.01	0.05
0.35	0.2	600	0.79	519.16	0.33	0.03	0.36	0.29	0.08	0.01	0.05
0.35	0.2	650	0.80	519.24	0.33	0.04	0.37	0.29	0.08	0.01	0.05
0.35	0.2	700	0.81	519.32	0.33	0.04	0.37	0.29	0.09	0.01	0.05
0.35	0.2	750	0.82	519.40	0.33	0.04	0.37	0.29	0.09	0.01	0.05
0.35	0.2	800	0.83	519.48	0.33	0.05	0.38	0.29	0.10	0.01	0.05
0.35	0.2	850	0.84	519.55	0.33	0.05	0.38	0.29	0.11	0.01	0.05
0.35	0.2	900	0.85	519.63	0.33	0.05	0.38	0.29	0.11	0.01	0.05
0.35	0.2	950	0.86	519.71	0.33	0.05	0.38	0.29	0.12	0.01	0.05
0.35	0.2	1000	0.87	519.79	0.33	0.06	0.39	0.29	0.13	0.02	0.05
0.35	0.2	1050	0.88	519.87	0.33	0.06	0.39	0.29	0.13	0.02	0.05
0.35	0.2	1100	0.89	519.94	0.33	0.06	0.39	0.29	0.14	0.02	0.05
0.35	0.2	1150	0.90	520.02	0.33	0.07	0.40	0.29	0.14	0.02	0.05
0.35	0.2	1200	0.91	520.10	0.33	0.07	0.40	0.29	0.15	0.02	0.05
0.35	0.2	1250	0.92	520.18	0.33	0.07	0.40	0.29	0.16	0.02	0.05
0.35	0.2	1300	0.93	520.26	0.33	0.07	0.40	0.29	0.16	0.02	0.05
0.35	0.2	1350	0.94	520.34	0.33	0.08	0.41	0.29	0.17	0.02	0.05

Figure H-5.8 IGBT auxiliary inverter switch loss estimation - Sheet 3 for 0.2 MVA, variable frequency.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
5600	0.45	30	0.875	0.7	2.10E-02	5000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
1.403	2.52E-03

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$60.90	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
0.35	0.2	100	79.92	0.19	$2,567.96	1.18	731.13	33.66	12.01	35	1	35
0.35	0.2	150	79.92	0.19	$2,567.96	1.18	731.40	33.67	12.01	35	1	35
0.35	0.2	200	79.92	0.19	$2,567.96	1.18	731.67	33.68	12.01	35	1	35
0.35	0.2	250	79.92	0.19	$2,567.96	1.18	731.94	33.68	12.01	35	1	35
0.35	0.2	300	79.92	0.19	$2,567.96	1.18	732.20	33.69	12.01	35	1	35
0.35	0.2	350	79.92	0.19	$2,567.96	1.18	732.47	33.70	12.01	35	1	35
0.35	0.2	400	79.92	0.19	$2,567.96	1.18	732.74	33.70	12.01	35	1	35
0.35	0.2	450	79.92	0.19	$2,567.96	1.18	733.01	33.71	12.01	35	1	35
0.35	0.2	500	79.92	0.19	$2,567.96	1.18	733.27	33.72	12.01	35	1	35
0.35	0.2	550	79.92	0.19	$2,567.96	1.18	733.54	33.72	12.01	35	1	35
0.35	0.2	600	79.92	0.19	$2,567.96	1.18	733.81	33.73	12.01	35	1	35
0.35	0.2	650	79.92	0.19	$2,567.96	1.18	734.08	33.74	12.01	35	1	35
0.35	0.2	700	79.92	0.19	$2,567.96	1.18	734.35	33.74	12.01	35	1	35
0.35	0.2	750	79.92	0.19	$2,567.96	1.18	734.62	33.75	12.01	35	1	35
0.35	0.2	800	79.92	0.19	$2,567.96	1.18	734.88	33.76	12.01	35	1	35
0.35	0.2	850	82.20	0.20	$2,641.33	1.20	735.15	33.26	12.36	36	1	36
0.35	0.2	900	82.20	0.20	$2,641.33	1.20	735.42	33.26	12.36	36	1	36
0.35	0.2	950	82.20	0.20	$2,641.33	1.20	735.69	33.27	12.36	36	1	36
0.35	0.2	1000	82.20	0.20	$2,641.33	1.20	735.96	33.28	12.36	36	1	36
0.35	0.2	1050	82.20	0.20	$2,641.33	1.20	736.23	33.28	12.36	36	1	36
0.35	0.2	1100	82.20	0.20	$2,641.33	1.20	736.49	33.29	12.36	36	1	36
0.35	0.2	1150	82.20	0.20	$2,641.33	1.20	736.76	33.30	12.36	36	1	36
0.35	0.2	1200	82.20	0.20	$2,641.33	1.20	737.03	33.30	12.36	36	1	36
0.35	0.2	1250	82.20	0.20	$2,641.33	1.20	737.30	33.31	12.36	36	1	36
0.35	0.2	1300	82.20	0.20	$2,641.33	1.20	737.57	33.31	12.36	36	1	36
0.35	0.2	1350	82.20	0.20	$2,641.33	1.20	737.84	33.32	12.36	36	1	36

Figure H-5.9 IGBT auxiliary inverter input filter sizing - Sheet 4 for 0.2 MVA, variable frequency.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$5,900.00	0	0.7967	200	0	0.6	0

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$1,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
0.35	0.1	600	839.76	1.64	$89,541.01	8.30	6.61	92.34%	87.03%	0.9880	0.26
0.35	0.106	600	864.12	1.68	$90,048.42	8.67	6.90	92.44%	87.19%	0.9880	0.26
0.35	0.112	600	888.17	1.73	$90,551.40	9.04	7.20	92.53%	87.34%	0.9880	0.26
0.35	0.118	600	911.96	1.77	$91,050.26	9.41	7.50	92.61%	87.47%	0.9880	0.26
0.35	0.124	600	935.48	1.81	$91,545.26	9.79	7.80	92.69%	87.58%	0.9880	0.26
0.35	0.13	600	958.75	1.85	$92,036.62	10.16	8.10	92.75%	87.68%	0.9880	0.26
0.35	0.136	600	981.80	1.89	$92,524.56	10.54	8.40	92.81%	87.78%	0.9880	0.26
0.35	0.142	600	1004.63	1.93	$93,009.26	10.92	8.70	92.86%	87.86%	0.9880	0.26
0.35	0.148	600	1027.25	1.97	$93,490.89	11.30	9.01	92.90%	87.93%	0.9880	0.26
0.35	0.154	600	1049.68	2.01	$93,969.62	11.69	9.31	92.95%	88.00%	0.9880	0.26
0.35	0.16	600	1071.92	2.05	$94,445.57	12.08	9.62	92.98%	88.06%	0.9880	0.26
0.35	0.166	600	1093.98	2.09	$94,918.88	12.47	9.93	93.02%	88.11%	0.9880	0.26
0.35	0.172	600	1115.88	2.13	$95,389.67	12.86	10.24	93.05%	88.16%	0.9880	0.26
0.35	0.178	600	1140.84	2.18	$96,051.03	13.27	10.57	93.06%	88.19%	0.9880	0.26
0.35	0.184	600	1162.41	2.22	$96,517.10	13.66	10.88	93.09%	88.23%	0.9880	0.26
0.35	0.19	600	1183.84	2.25	$96,980.94	14.06	11.20	93.11%	88.26%	0.9880	0.26
0.35	0.196	600	1205.13	2.29	$97,442.66	14.46	11.52	93.13%	88.30%	0.9880	0.26
0.35	0.202	600	1226.27	2.33	$97,902.33	14.86	11.84	93.15%	88.32%	0.9880	0.26
0.35	0.208	600	1247.29	2.37	$98,360.02	15.27	12.17	93.16%	88.35%	0.9880	0.26
0.35	0.214	600	1268.18	2.41	$98,815.82	15.68	12.49	93.17%	88.37%	0.9880	0.26
0.35	0.22	600	1288.94	2.44	$99,269.77	16.09	12.82	93.19%	88.39%	0.9880	0.26
0.35	0.226	600	1309.58	2.48	$99,721.96	16.50	13.15	93.20%	88.40%	0.9880	0.26
0.35	0.232	600	1330.11	2.52	$100,172.42	16.92	13.48	93.20%	88.42%	0.9880	0.26
0.35	0.238	600	1350.53	2.55	$100,621.23	17.33	13.81	93.21%	88.43%	0.9880	0.26
0.35	0.244	600	1370.84	2.59	$101,068.43	17.75	14.14	93.22%	88.44%	0.9880	0.26
0.35	0.25	600	1391.04	2.63	$101,514.08	18.18	14.48	93.22%	88.45%	0.9880	0.26

Figure H-6.1 BJT auxiliary inverter summary - Sheet 1 for 600 Hz, variable MVA.

BJT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER BJT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	BJTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itqq
1.2	1350	1.4	0.002	0.006	0	1	2.00E-05	1000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER dv/dt LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER dv/dt LOSS (m^3/kW)
7.55	2	0.0045	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER dv/dt LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$2,402.03	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
0.35	0.1	600	11.60	0.01	$3,816.37	0.91	675.83	535.99	1	1	1
0.35	0.106	600	11.60	0.01	$3,816.37	0.95	675.83	535.99	1	1	1
0.35	0.112	600	11.60	0.01	$3,816.37	0.99	675.83	535.99	1	1	1
0.35	0.118	600	11.60	0.01	$3,816.37	1.03	675.83	535.99	1	1	1
0.35	0.124	600	11.60	0.01	$3,816.37	1.07	675.83	535.99	1	1	1
0.35	0.13	600	11.60	0.01	$3,816.37	1.11	675.83	535.99	1	1	1
0.35	0.136	600	11.60	0.01	$3,816.37	1.15	675.83	535.99	1	1	1
0.35	0.142	600	11.60	0.01	$3,816.37	1.20	675.83	535.99	1	1	1
0.35	0.148	600	11.60	0.01	$3,816.37	1.24	675.83	535.99	1	1	1
0.35	0.154	600	11.60	0.01	$3,816.37	1.28	675.83	535.99	1	1	1
0.35	0.16	600	11.60	0.01	$3,816.37	1.33	675.83	535.99	1	1	1
0.35	0.166	600	11.60	0.01	$3,816.37	1.37	675.83	535.99	1	1	1
0.35	0.172	600	11.60	0.01	$3,816.37	1.41	675.83	535.99	1	1	1
0.35	0.178	600	11.60	0.01	$3,816.37	1.46	675.83	535.99	1	1	1
0.35	0.184	600	11.60	0.01	$3,816.37	1.51	675.83	535.99	1	1	1
0.35	0.19	600	11.60	0.01	$3,816.37	1.55	675.83	535.99	1	1	1
0.35	0.196	600	11.60	0.01	$3,816.37	1.60	675.83	535.99	1	1	1
0.35	0.202	600	11.60	0.01	$3,816.37	1.65	675.83	535.99	1	1	1
0.35	0.208	600	11.60	0.01	$3,816.37	1.69	675.83	535.99	1	1	1
0.35	0.214	600	11.60	0.01	$3,816.37	1.74	675.83	535.99	1	1	1
0.35	0.22	600	11.60	0.01	$3,816.37	1.79	675.83	535.99	1	1	1
0.35	0.226	600	11.60	0.01	$3,816.37	1.84	675.83	535.99	1	1	1
0.35	0.232	600	11.60	0.01	$3,816.37	1.89	675.83	535.99	1	1	1
0.35	0.238	600	11.60	0.01	$3,816.37	1.94	675.83	535.99	1	1	1
0.35	0.244	600	11.60	0.01	$3,816.37	1.99	675.83	535.99	1	1	1
0.35	0.25	600	11.60	0.01	$3,816.37	2.04	675.83	535.99	1	1	1

Figure H-6.2 BJT auxiliary switch quantity characterization - Sheet 2 for 600 Hz, variable MVA.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
3	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
0.82	0.001133	400	1

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
0.35	0.1	600	0.91	262.26	0.16	0.30	0.46	0.09	0.32	0.01	0.02
0.35	0.106	600	0.95	278.00	0.17	0.31	0.49	0.10	0.32	0.01	0.03
0.35	0.112	600	0.99	293.73	0.18	0.33	0.52	0.11	0.32	0.01	0.03
0.35	0.118	600	1.03	309.47	0.20	0.35	0.55	0.11	0.32	0.02	0.03
0.35	0.124	600	1.07	325.20	0.21	0.37	0.58	0.12	0.32	0.02	0.03
0.35	0.13	600	1.11	340.94	0.22	0.39	0.61	0.13	0.32	0.02	0.03
0.35	0.136	600	1.15	356.68	0.24	0.40	0.64	0.14	0.32	0.02	0.03
0.35	0.142	600	1.20	372.41	0.25	0.42	0.67	0.15	0.32	0.02	0.04
0.35	0.148	600	1.24	388.15	0.27	0.44	0.71	0.15	0.32	0.02	0.04
0.35	0.154	600	1.28	403.88	0.28	0.46	0.74	0.16	0.32	0.02	0.04
0.35	0.16	600	1.33	419.62	0.30	0.48	0.77	0.17	0.32	0.02	0.04
0.35	0.166	600	1.37	435.35	0.31	0.49	0.80	0.18	0.32	0.02	0.04
0.35	0.172	600	1.41	451.09	0.33	0.51	0.84	0.19	0.32	0.02	0.04
0.35	0.178	600	1.46	466.83	0.34	0.53	0.87	0.20	0.32	0.02	0.04
0.35	0.184	600	1.51	482.56	0.36	0.55	0.91	0.21	0.32	0.02	0.05
0.35	0.19	600	1.55	498.30	0.38	0.56	0.94	0.22	0.32	0.02	0.05
0.35	0.196	600	1.60	514.03	0.39	0.58	0.97	0.23	0.32	0.03	0.05
0.35	0.202	600	1.65	529.77	0.41	0.60	1.01	0.24	0.32	0.03	0.05
0.35	0.208	600	1.69	545.50	0.43	0.62	1.04	0.25	0.32	0.03	0.05
0.35	0.214	600	1.74	561.24	0.45	0.64	1.08	0.26	0.32	0.03	0.05
0.35	0.22	600	1.79	576.97	0.46	0.65	1.12	0.27	0.32	0.03	0.05
0.35	0.226	600	1.84	592.71	0.48	0.67	1.15	0.28	0.32	0.03	0.06
0.35	0.232	600	1.89	608.45	0.50	0.69	1.19	0.29	0.32	0.03	0.06
0.35	0.238	600	1.94	624.18	0.52	0.71	1.23	0.30	0.32	0.03	0.06
0.35	0.244	600	1.99	639.92	0.54	0.72	1.26	0.31	0.32	0.03	0.06
0.35	0.25	600	2.04	655.65	0.56	0.74	1.30	0.32	0.32	0.03	0.06

Figure H-6.3 BJT auxiliary switch loss estimation - Sheet 3 for 600 Hz, variable MVA.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
5600	0.45	30	0.875	0.7	2.10E-02	5000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
1.403	2.52E-03

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$60.90	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
0.35	0.1	600	43.38	0.10	$1,394.03	0.63	379.92	32.90	6.52	19	1	19
0.35	0.106	600	45.67	0.11	$1,467.40	0.66	402.39	33.00	6.86	20	1	20
0.35	0.112	600	47.95	0.11	$1,540.77	0.70	424.86	33.10	7.20	21	1	21
0.35	0.118	600	50.23	0.12	$1,614.14	0.73	447.35	33.18	7.55	22	1	22
0.35	0.124	600	52.52	0.13	$1,687.51	0.77	469.85	33.26	7.89	23	1	23
0.35	0.13	600	54.80	0.13	$1,760.88	0.80	492.35	33.34	8.23	24	1	24
0.35	0.136	600	57.08	0.14	$1,834.25	0.84	514.87	33.41	8.58	25	1	25
0.35	0.142	600	59.37	0.14	$1,907.62	0.87	537.40	33.47	8.92	26	1	26
0.35	0.148	600	61.65	0.15	$1,980.99	0.91	559.94	33.53	9.26	27	1	27
0.35	0.154	600	63.93	0.15	$2,054.36	0.94	582.50	33.59	9.60	28	1	28
0.35	0.16	600	66.22	0.16	$2,127.73	0.98	605.06	33.64	9.95	29	1	29
0.35	0.166	600	68.50	0.16	$2,201.10	1.01	627.63	33.69	10.29	30	1	30
0.35	0.172	600	70.78	0.17	$2,274.47	1.05	650.22	33.74	10.63	31	1	31
0.35	0.178	600	75.35	0.18	$2,421.21	1.10	672.81	33.23	11.32	33	1	33
0.35	0.184	600	77.64	0.19	$2,494.58	1.13	695.42	33.29	11.66	34	1	34
0.35	0.19	600	79.92	0.19	$2,567.95	1.17	718.04	33.34	12.01	35	1	35
0.35	0.196	600	82.20	0.20	$2,641.33	1.20	740.66	33.39	12.35	36	1	36
0.35	0.202	600	84.49	0.20	$2,714.70	1.24	763.30	33.44	12.69	37	1	37
0.35	0.208	600	86.77	0.21	$2,788.07	1.27	785.95	33.48	13.03	38	1	38
0.35	0.214	600	89.05	0.21	$2,861.44	1.31	808.61	33.53	13.38	39	1	39
0.35	0.22	600	91.34	0.22	$2,934.81	1.34	831.28	33.57	13.72	40	1	40
0.35	0.226	600	93.62	0.22	$3,008.18	1.38	853.97	33.61	14.06	41	1	41
0.35	0.232	600	95.90	0.23	$3,081.55	1.41	876.66	33.65	14.41	42	1	42
0.35	0.238	600	98.19	0.24	$3,154.92	1.45	899.36	33.69	14.75	43	1	43
0.35	0.244	600	100.47	0.24	$3,228.29	1.48	922.08	33.72	15.09	44	1	44
0.35	0.25	600	102.75	0.25	$3,301.66	1.52	944.80	33.76	15.44	45	1	45

Figure H-6.4 BJT auxiliary input filter sizing - Sheet 4 for 600 Hz, variable MVA.

BASIS TRANSFORMER PARAMETERS					
MVA RATING	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
0.15	453.1	0.5947	60	3.00	$3,627.00

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
0.35	0.1	60	334.29	0.44	$2,675.96	2.21	0.10
0.35	0.106	60	349.22	0.46	$2,795.49	2.31	0.11
0.35	0.112	60	363.95	0.48	$2,913.35	2.41	0.11
0.35	0.118	60	378.47	0.50	$3,029.64	2.51	0.12
0.35	0.124	60	392.82	0.52	$3,144.45	2.60	0.12
0.35	0.13	60	406.99	0.53	$3,257.89	2.69	0.13
0.35	0.136	60	421.00	0.55	$3,370.03	2.79	0.14
0.35	0.142	60	434.85	0.57	$3,480.93	2.88	0.14
0.35	0.148	60	448.56	0.59	$3,590.67	2.97	0.15
0.35	0.154	60	462.13	0.61	$3,699.30	3.06	0.15
0.35	0.16	60	475.57	0.62	$3,806.88	3.15	0.16
0.35	0.166	60	488.88	0.64	$3,913.45	3.24	0.17
0.35	0.172	60	502.08	0.66	$4,019.07	3.32	0.17
0.35	0.178	60	515.16	0.68	$4,123.77	3.41	0.18
0.35	0.184	60	528.13	0.69	$4,227.59	3.50	0.18
0.35	0.19	60	540.99	0.71	$4,330.56	3.58	0.19
0.35	0.196	60	553.76	0.73	$4,432.73	3.67	0.20
0.35	0.202	60	566.42	0.74	$4,534.12	3.75	0.20
0.35	0.208	60	578.99	0.76	$4,634.75	3.83	0.21
0.35	0.214	60	591.47	0.78	$4,734.67	3.92	0.21
0.35	0.22	60	603.87	0.79	$4,833.88	4.00	0.22
0.35	0.226	60	616.18	0.81	$4,932.42	4.08	0.23
0.35	0.232	60	628.41	0.82	$5,030.31	4.16	0.23
0.35	0.238	60	640.56	0.84	$5,127.57	4.24	0.24
0.35	0.244	60	652.63	0.86	$5,224.22	4.32	0.24
0.35	0.25	60	664.63	0.87	$5,320.28	4.40	0.25

Figure H-6.5 BJT auxiliary inverter output transformer sizing - Sheet 5 for 600 Hz switching frequency, variable MVA.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$5,900.00	0	0.7967	200	0	0.6	0

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$1,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MVA
0.35	0.2	100	1207.37	2.29	$96,958.96	9.95	7.93	95.26%	91.79%	0.9980	0.39
0.35	0.2	150	1211.25	2.30	$97,198.82	10.44	8.32	95.04%	91.42%	0.9970	0.38
0.35	0.2	200	1211.90	2.30	$97,245.69	10.92	8.70	94.82%	91.07%	0.9960	0.36
0.35	0.2	250	1212.55	2.30	$97,292.57	11.39	9.08	94.61%	90.72%	0.9950	0.35
0.35	0.2	300	1213.20	2.31	$97,339.44	11.87	9.45	94.40%	90.37%	0.9940	0.33
0.35	0.2	350	1213.85	2.31	$97,386.31	12.34	9.83	94.19%	90.02%	0.9930	0.32
0.35	0.2	400	1214.49	2.31	$97,433.18	12.82	10.21	93.98%	89.67%	0.9920	0.30
0.35	0.2	450	1215.14	2.31	$97,480.06	13.29	10.59	93.77%	89.33%	0.9910	0.29
0.35	0.2	500	1215.79	2.31	$97,526.93	13.77	10.97	93.56%	88.99%	0.9900	0.28
0.35	0.2	550	1216.44	2.31	$97,573.80	14.24	11.35	93.35%	88.66%	0.9890	0.27
0.35	0.2	600	1217.09	2.31	$97,620.67	14.72	11.73	93.14%	88.32%	0.9880	0.26
0.35	0.2	650	1220.97	2.32	$97,860.53	15.21	12.12	92.93%	87.98%	0.9870	0.25
0.35	0.2	700	1221.61	2.32	$97,907.40	15.69	12.50	92.73%	87.65%	0.9860	0.24
0.35	0.2	750	1222.26	2.32	$97,954.28	16.16	12.88	92.52%	87.32%	0.9850	0.23
0.35	0.2	800	1222.91	2.33	$98,001.15	16.64	13.25	92.32%	87.00%	0.9840	0.22
0.35	0.2	850	1223.56	2.33	$98,048.02	17.11	13.63	92.12%	86.68%	0.9830	0.21
0.35	0.2	900	1224.21	2.33	$98,094.89	17.59	14.01	91.92%	86.36%	0.9820	0.21
0.35	0.2	950	1224.86	2.33	$98,141.77	18.06	14.39	91.72%	86.04%	0.9810	0.20
0.35	0.2	1000	1332.35	2.44	$141,626.19	20.99	16.72	90.50%	84.14%	0.9800	0.39
0.35	0.2	1050	1333.65	2.44	$141,719.94	21.63	17.23	90.24%	83.73%	0.9790	0.38
0.35	0.2	1100	1334.94	2.44	$141,813.68	22.26	17.74	89.98%	83.33%	0.9780	0.37
0.35	0.2	1150	1336.24	2.45	$141,907.43	22.90	18.25	89.73%	82.94%	0.9770	0.35
0.35	0.2	1200	1337.54	2.45	$142,001.17	23.54	18.75	89.47%	82.55%	0.9760	0.34
0.35	0.2	1250	1338.83	2.45	$142,094.91	24.18	19.26	89.22%	82.16%	0.9750	0.33
0.35	0.2	1300	1340.13	2.45	$142,188.66	24.81	19.77	88.96%	81.77%	0.9740	0.33
0.35	0.2	1350	1344.66	2.46	$142,475.39	25.47	20.29	88.70%	81.38%	0.9730	0.32

Figure H-6.6 BJT auxiliary inverter summary - Sheet 1 for 0.2 MVA, variable frequency.

BJT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER BJT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	BJTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itgq
1.2	1350	1.4	0.002	0.006	0	1	2.00E-05	1000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER dv/dt LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER dv/dt LOSS (m^3/kW)
7.55	2	0.0045	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER dv/dt LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$2,402.03	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
0.35	0.2	100	10.83	0.01	$3,786.67	0.84	1000.00	797.09	1	1	1
0.35	0.2	150	10.91	0.01	$3,789.64	0.92	992.67	790.85	1	1	1
0.35	0.2	200	10.99	0.01	$3,792.61	1.00	947.37	754.38	1	1	1
0.35	0.2	250	11.06	0.01	$3,795.58	1.08	904.99	720.27	1	1	1
0.35	0.2	300	11.14	0.01	$3,798.55	1.16	865.35	688.37	1	1	1
0.35	0.2	350	11.21	0.01	$3,801.52	1.24	828.28	658.55	1	1	1
0.35	0.2	400	11.29	0.01	$3,804.49	1.31	793.61	630.67	1	1	1
0.35	0.2	450	11.37	0.01	$3,807.46	1.39	761.19	604.60	1	1	1
0.35	0.2	500	11.44	0.01	$3,810.43	1.47	730.85	580.21	1	1	1
0.35	0.2	550	11.52	0.01	$3,813.40	1.55	702.44	557.38	1	1	1
0.35	0.2	600	11.60	0.01	$3,816.37	1.63	675.83	535.99	1	1	1
0.35	0.2	650	11.67	0.01	$3,819.34	1.71	650.89	515.95	1	1	1
0.35	0.2	700	11.75	0.01	$3,822.31	1.79	627.48	497.14	1	1	1
0.35	0.2	750	11.83	0.01	$3,825.28	1.87	605.50	479.48	1	1	1
0.35	0.2	800	11.90	0.01	$3,828.25	1.95	584.84	462.89	1	1	1
0.35	0.2	850	11.98	0.01	$3,831.22	2.02	565.40	447.28	1	1	1
0.35	0.2	900	12.06	0.01	$3,834.19	2.10	547.10	432.57	1	1	1
0.35	0.2	950	12.13	0.01	$3,837.16	2.18	529.84	418.71	1	1	1
0.35	0.2	1000	24.42	0.02	$6,580.27	2.67	513.55	405.63	2	1	2
0.35	0.2	1050	24.57	0.02	$6,586.21	2.77	498.16	393.28	2	1	2
0.35	0.2	1100	24.72	0.02	$6,592.15	2.88	483.60	381.59	2	1	2
0.35	0.2	1150	24.87	0.02	$6,598.09	2.98	469.82	370.53	2	1	2
0.35	0.2	1200	25.03	0.02	$6,604.03	3.09	456.76	360.05	2	1	2
0.35	0.2	1250	25.18	0.02	$6,609.97	3.20	444.38	350.10	2	1	2
0.35	0.2	1300	25.33	0.02	$6,615.91	3.30	432.61	340.66	2	1	2
0.35	0.2	1350	25.49	0.02	$6,621.85	3.41	421.43	331.69	2	1	2

Figure H-6.7 BJT auxiliary switch quantity characterization - Sheet 2 for 0.2 MVA, variable frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
3	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
0.82	0.001133	400	1

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
0.35	0.2	100	0.84	519.27	0.40	0.10	0.50	0.23	0.05	0.00	0.05
0.35	0.2	150	0.92	519.79	0.40	0.15	0.55	0.23	0.08	0.01	0.05
0.35	0.2	200	1.00	520.31	0.40	0.20	0.60	0.23	0.11	0.01	0.05
0.35	0.2	250	1.08	520.83	0.40	0.25	0.65	0.23	0.14	0.01	0.05
0.35	0.2	300	1.16	521.36	0.40	0.30	0.70	0.23	0.16	0.01	0.05
0.35	0.2	350	1.24	521.88	0.40	0.35	0.75	0.23	0.19	0.01	0.05
0.35	0.2	400	1.31	522.41	0.40	0.40	0.80	0.23	0.22	0.02	0.05
0.35	0.2	450	1.39	522.93	0.40	0.45	0.85	0.23	0.24	0.02	0.05
0.35	0.2	500	1.47	523.46	0.40	0.49	0.90	0.23	0.27	0.02	0.05
0.35	0.2	550	1.55	523.99	0.40	0.54	0.95	0.23	0.30	0.02	0.05
0.35	0.2	600	1.63	524.52	0.40	0.59	1.00	0.23	0.32	0.03	0.05
0.35	0.2	650	1.71	525.05	0.40	0.64	1.05	0.23	0.35	0.03	0.05
0.35	0.2	700	1.79	525.59	0.40	0.69	1.10	0.23	0.38	0.03	0.05
0.35	0.2	750	1.87	526.12	0.40	0.74	1.15	0.23	0.41	0.03	0.05
0.35	0.2	800	1.95	526.65	0.40	0.79	1.20	0.23	0.43	0.03	0.05
0.35	0.2	850	2.02	527.19	0.40	0.84	1.25	0.23	0.46	0.04	0.05
0.35	0.2	900	2.10	527.73	0.41	0.89	1.30	0.23	0.49	0.04	0.05
0.35	0.2	950	2.18	528.27	0.41	0.94	1.35	0.23	0.51	0.04	0.05
0.35	0.2	1000	1.33	264.40	0.16	0.49	0.65	0.09	0.54	0.02	0.02
0.35	0.2	1050	1.39	264.67	0.16	0.52	0.68	0.09	0.57	0.02	0.02
0.35	0.2	1100	1.44	264.94	0.16	0.54	0.70	0.09	0.59	0.02	0.02
0.35	0.2	1150	1.49	265.21	0.16	0.57	0.73	0.09	0.62	0.03	0.02
0.35	0.2	1200	1.54	265.49	0.16	0.59	0.75	0.09	0.65	0.03	0.02
0.35	0.2	1250	1.60	265.76	0.16	0.62	0.78	0.09	0.68	0.03	0.02
0.35	0.2	1300	1.65	266.03	0.16	0.64	0.80	0.09	0.70	0.03	0.02
0.35	0.2	1350	1.70	266.30	0.16	0.67	0.83	0.09	0.73	0.03	0.02

Figure H-6.8 BJT auxiliary switch loss estimation - Sheet 3 for 0.2 MVA, variable frequency.

CAPACITOR PARAMETERS						
CAPACITANCE (uF)	VOLTAGE (kV)	RMS RIPPLE CURRENT (A)	VOLTAGE DE-RATING	CURRENT DE-RATING	MAX ESR (OHMS)	BLEEDER RES (OHMS)
5600	0.45	30	0.875	0.7	2.10E-02	5000

CAPACITOR PARAMETERS	
MASS (kg)	VOLUME (m^3)
1.403	2.52E-03

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
62.75%	117.00%

COST ESTIMATES		
CAP & BLEEDER COST PER CAP	DUMP COST PER kJ	BUS & FRAME % INC IN COST
$60.90	$16.91	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	OUTPUT MVA (MVA)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	RMS CURRENT (A)	LOSS PER CAPACITOR (W)	TOTAL STORED ENERGY (kJ)	PARALLEL CAPS REQ	SERIES CAPS REQ	TOTAL CAPS REQ
0.35	0.2	100	79.92	0.19	$2,567.96	1.18	734.99	33.76	12.01	35	1	35
0.35	0.2	150	82.20	0.20	$2,641.33	1.20	737.06	33.30	12.35	36	1	36
0.35	0.2	200	82.20	0.20	$2,641.33	1.20	739.12	33.35	12.35	36	1	36
0.35	0.2	250	82.20	0.20	$2,641.33	1.20	741.19	33.40	12.35	36	1	36
0.35	0.2	300	82.20	0.20	$2,641.33	1.20	743.27	33.45	12.35	36	1	36
0.35	0.2	350	82.20	0.20	$2,641.33	1.21	745.34	33.50	12.35	36	1	36
0.35	0.2	400	82.20	0.20	$2,641.33	1.21	747.42	33.55	12.35	36	1	36
0.35	0.2	450	82.20	0.20	$2,641.33	1.21	749.50	33.60	12.35	36	1	36
0.35	0.2	500	82.20	0.20	$2,641.33	1.21	751.58	33.65	12.35	36	1	36
0.35	0.2	550	82.20	0.20	$2,641.33	1.21	753.67	33.70	12.35	36	1	36
0.35	0.2	600	82.20	0.20	$2,641.33	1.22	755.75	33.75	12.35	36	1	36
0.35	0.2	650	84.49	0.20	$2,714.70	1.23	757.84	33.31	12.69	37	1	37
0.35	0.2	700	84.49	0.20	$2,714.70	1.23	759.94	33.36	12.69	37	1	37
0.35	0.2	750	84.49	0.20	$2,714.70	1.24	762.03	33.41	12.69	37	1	37
0.35	0.2	800	84.49	0.20	$2,714.70	1.24	764.13	33.46	12.69	37	1	37
0.35	0.2	850	84.49	0.20	$2,714.70	1.24	766.23	33.51	12.69	37	1	37
0.35	0.2	900	84.49	0.20	$2,714.70	1.24	768.33	33.56	12.69	37	1	37
0.35	0.2	950	84.49	0.20	$2,714.70	1.24	770.43	33.61	12.69	37	1	37
0.35	0.2	1000	86.77	0.21	$2,788.07	1.27	781.32	33.38	13.03	38	1	38
0.35	0.2	1050	86.77	0.21	$2,788.07	1.27	784.01	33.44	13.03	38	1	38
0.35	0.2	1100	86.77	0.21	$2,788.07	1.27	786.72	33.50	13.03	38	1	38
0.35	0.2	1150	86.77	0.21	$2,788.07	1.28	789.42	33.56	13.03	38	1	38
0.35	0.2	1200	86.77	0.21	$2,788.07	1.28	792.13	33.63	13.03	38	1	38
0.35	0.2	1250	86.77	0.21	$2,788.07	1.28	794.84	33.69	13.03	38	1	38
0.35	0.2	1300	86.77	0.21	$2,788.07	1.28	797.55	33.75	13.03	38	1	38
0.35	0.2	1350	89.05	0.21	$2,861.44	1.30	800.27	33.34	13.38	39	1	39

Figure H-6.9 BJT auxiliary input filter sizing - Sheet 4 for 0.2 MVA, variable frequency.

BASIS TRANSFORMER PARAMETERS					
MVA RATING	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
0.15	453.1	0.5947	60	3.00	$3,627.00

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20
0.35	0.2	60	562.21	0.74	$4,500.41	3.72	0.20

Figure H-6.10 BJT auxiliary inverter output transformer sizing - Sheet 5 for 0.2 MVA, variable switching frequency.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
1	4

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	10	100	20711.01	45.52	$1,215,097.60	209.73	167.09	97.95%	96.37%	0.98	17.78
7	10	150	21102.50	46.34	$1,241,503.37	247.99	197.57	97.58%	95.73%	0.97	17.22
7	10	200	21494.99	47.17	$1,267,978.21	286.34	228.13	97.22%	95.11%	0.96	16.68
7	10	250	21888.51	47.99	$1,294,524.77	324.80	258.77	96.85%	94.49%	0.96	16.15
7	10	300	22283.11	48.82	$1,321,145.85	363.37	289.50	96.49%	93.87%	0.95	15.65
7	10	350	22678.84	49.65	$1,347,844.36	402.05	320.32	96.13%	93.26%	0.94	15.16
7	10	400	23075.73	50.48	$1,374,623.37	440.85	351.23	95.78%	92.66%	0.93	14.68
7	10	450	23473.85	51.31	$1,401,486.08	479.77	382.24	95.42%	92.06%	0.92	14.23
7	10	500	23873.23	52.15	$1,428,435.87	518.82	413.34	95.07%	91.47%	0.91	13.79
7	10	550	24273.93	52.99	$1,455,476.27	558.00	444.56	94.71%	90.89%	0.90	13.36
7	10	600	24676.00	53.83	$1,482,610.99	597.32	475.88	94.36%	90.31%	0.89	12.95
7	10	650	25079.51	54.68	$1,509,843.95	636.77	507.32	94.01%	89.73%	0.88	12.55
7	10	700	25484.52	55.52	$1,537,179.24	676.38	538.87	93.66%	89.16%	0.88	12.17
7	10	750	25891.08	56.38	$1,564,621.17	716.14	570.55	93.32%	88.60%	0.87	11.80
7	10	800	26299.27	57.23	$1,592,174.30	756.06	602.36	92.97%	88.04%	0.86	11.44
7	10	850	26709.16	58.09	$1,619,843.39	796.16	634.30	92.63%	87.49%	0.85	11.10
7	10	900	27120.83	58.95	$1,647,633.50	836.42	666.38	92.28%	86.94%	0.84	10.76
7	10	950	27534.34	59.82	$1,675,549.93	876.87	698.60	91.94%	86.39%	0.83	10.44
7	10	1000	27949.80	60.69	$1,703,598.29	917.51	730.98	91.60%	85.85%	0.82	10.13
7	10	1050	32907.71	70.16	$2,283,543.86	1278.54	1018.61	88.66%	81.32%	0.81	14.74
7	10	1100	33487.91	71.37	$2,322,550.38	1334.79	1063.42	88.22%	80.66%	0.81	14.30
7	10	1150	34069.68	72.58	$2,361,665.98	1391.19	1108.36	87.79%	80.00%	0.80	13.88
7	10	1200	34653.09	73.80	$2,400,895.64	1447.77	1153.44	87.35%	79.36%	0.79	13.47
7	10	1250	35238.23	75.02	$2,440,244.63	1504.51	1198.65	86.92%	78.72%	0.78	13.07
7	10	1300	35825.18	76.24	$2,479,718.51	1561.44	1244.00	86.49%	78.09%	0.77	12.69
7	10	1350	36414.02	77.46	$2,519,323.15	1618.56	1289.51	86.07%	77.47%	0.76	12.31

Figure H-7.1 Single phase GTO input converter summary - Sheet 1 for 10 MW output power and variable switching frequency.

GTO PARAMETERS							
VOLTAGE RATING (kV)	POWER DISS PER GTO (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS PER AMP (J/A)	FIXED SW LOSS (J)	MINIMUM OFF TIME (s)	MAXIMUM Itgq (A)
6	2900	1.77	0.00118	0.003167	1.05	1.77E-04	3000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
21.15	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$9,304.40	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL(Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	10	100	487.91	0.54	$64,705.56	39.27	2031.19	1606.25	2	3	6
7	10	150	541.72	0.57	$65,692.08	48.80	1984.87	1562.53	2	3	6
7	10	200	595.68	0.60	$66,681.25	58.35	1939.91	1520.18	2	3	6
7	10	250	649.78	0.64	$67,673.16	67.93	1896.29	1479.17	2	3	6
7	10	300	704.04	0.67	$68,667.91	77.54	1853.98	1439.45	2	3	6
7	10	350	758.46	0.71	$69,665.63	87.17	1812.95	1401.00	2	3	6
7	10	400	813.05	0.74	$70,666.41	96.83	1773.16	1363.78	2	3	6
7	10	450	867.81	0.78	$71,670.40	106.52	1734.59	1327.74	2	3	6
7	10	500	922.75	0.81	$72,677.70	116.25	1697.19	1292.85	2	3	6
7	10	550	977.89	0.85	$73,688.47	126.01	1660.93	1259.08	2	3	6
7	10	600	1033.22	0.88	$74,702.84	135.80	1625.79	1226.38	2	3	6
7	10	650	1088.75	0.92	$75,720.96	145.62	1591.72	1194.72	2	3	6
7	10	700	1144.50	0.96	$76,742.98	155.49	1558.70	1164.07	2	3	6
7	10	750	1200.47	0.99	$77,769.08	165.39	1526.69	1134.39	2	3	6
7	10	800	1256.67	1.03	$78,799.42	175.33	1495.66	1105.65	2	3	6
7	10	850	1313.11	1.06	$79,834.18	185.32	1465.57	1077.81	2	3	6
7	10	900	1369.80	1.10	$80,873.56	195.34	1436.41	1050.84	2	3	6
7	10	950	1426.76	1.14	$81,917.77	205.42	1408.12	1024.72	2	3	6
7	10	1000	1483.99	1.17	$82,967.01	215.54	1380.70	999.40	2	3	6
7	10	1050	2216.72	1.75	$123,730.61	305.45	1354.10	974.86	3	3	9
7	10	1100	2296.96	1.81	$125,201.70	319.46	1328.29	951.07	3	3	9
7	10	1150	2377.43	1.86	$126,677.02	333.51	1303.26	928.01	3	3	9
7	10	1200	2458.14	1.91	$128,156.74	347.60	1278.97	905.64	3	3	9
7	10	1250	2539.10	1.96	$129,641.06	361.74	1255.40	883.94	3	3	9
7	10	1300	2620.33	2.01	$131,130.21	375.91	1232.52	862.88	3	3	9
7	10	1350	2701.83	2.07	$132,624.40	390.14	1210.31	842.45	3	3	9

Figure H-7.2 Single phase GTO input converter switch quantity characterization - Sheet 2 for 10 MW output power and variable switching frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
6	2.4

ANTI-PARALLEL DIODE PARAMETERS		
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)
1.1	0.001583	380

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	10	100	6.55	1142.21	1.11	0.17	1.28	1.04	2.70	0.28	1.25
7	10	150	8.13	1152.60	1.12	0.25	1.37	1.04	4.05	0.42	1.25
7	10	200	9.73	1163.17	1.12	0.33	1.45	1.05	5.40	0.57	1.25
7	10	250	11.32	1173.94	1.13	0.41	1.54	1.06	6.75	0.72	1.25
7	10	300	12.92	1184.92	1.13	0.50	1.63	1.06	8.10	0.88	1.25
7	10	350	14.53	1196.10	1.14	0.58	1.72	1.07	9.45	1.04	1.25
7	10	400	16.14	1207.49	1.14	0.66	1.80	1.08	10.80	1.21	1.25
7	10	450	17.75	1219.10	1.15	0.75	1.89	1.08	12.15	1.38	1.25
7	10	500	19.37	1230.94	1.15	0.83	1.98	1.09	13.50	1.56	1.25
7	10	550	21.00	1243.00	1.16	0.91	2.07	1.10	14.85	1.74	1.25
7	10	600	22.63	1255.31	1.16	0.99	2.15	1.10	16.20	1.93	1.25
7	10	650	24.27	1267.87	1.17	1.08	2.24	1.11	17.55	2.12	1.25
7	10	700	25.91	1280.67	1.17	1.16	2.33	1.12	18.90	2.32	1.25
7	10	750	27.56	1293.74	1.18	1.24	2.42	1.12	20.25	2.52	1.25
7	10	800	29.22	1307.08	1.18	1.32	2.51	1.13	21.60	2.73	1.25
7	10	850	30.89	1320.70	1.19	1.41	2.60	1.14	22.95	2.95	1.25
7	10	900	32.56	1334.60	1.19	1.49	2.69	1.15	24.30	3.18	1.25
7	10	950	34.24	1348.80	1.20	1.57	2.77	1.16	25.65	3.41	1.25
7	10	1000	35.92	1363.30	1.21	1.66	2.86	1.16	27.00	3.65	1.25
7	10	1050	33.94	918.75	0.68	1.34	2.02	0.61	28.35	2.13	0.83
7	10	1100	35.50	928.84	0.68	1.41	2.09	0.61	29.70	2.26	0.83
7	10	1150	37.06	939.17	0.69	1.47	2.16	0.62	31.05	2.40	0.83
7	10	1200	38.62	949.72	0.69	1.53	2.22	0.62	32.40	2.55	0.83
7	10	1250	40.19	960.51	0.69	1.60	2.29	0.62	33.75	2.70	0.83
7	10	1300	41.77	971.55	0.69	1.66	2.36	0.63	35.10	2.85	0.83
7	10	1350	43.35	982.85	0.70	1.73	2.42	0.63	36.45	3.01	0.83

Figure H-7.3 Single phase GTO input converter switch loss estimation - Sheet 3 for 10 MW output power and variable switching frequency.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '50% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
6	6984	9.748	60	30.00	$75,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	10	60	12253.23	17.10	$132,276.63	52.63	12.70
7	10	60	12287.69	17.15	$132,648.66	52.78	12.74
7	10	60	12322.21	17.20	$133,021.32	52.93	12.79
7	10	60	12356.79	17.25	$133,394.64	53.08	12.84
7	10	60	12391.44	17.30	$133,768.68	53.23	12.89
7	10	60	12426.16	17.34	$134,143.46	53.38	12.94
7	10	60	12460.95	17.39	$134,519.02	53.53	12.98
7	10	60	12495.82	17.44	$134,895.42	53.68	13.03
7	10	60	12530.76	17.49	$135,272.69	53.83	13.08
7	10	60	12565.80	17.54	$135,650.88	53.98	13.13
7	10	60	12600.92	17.59	$136,030.04	54.13	13.18
7	10	60	12636.14	17.64	$136,410.22	54.28	13.23
7	10	60	12671.46	17.69	$136,791.48	54.43	13.28
7	10	60	12706.88	17.74	$137,173.87	54.58	13.33
7	10	60	12742.41	17.79	$137,557.46	54.74	13.38
7	10	60	12778.06	17.84	$137,942.31	54.89	13.43
7	10	60	12813.83	17.89	$138,328.48	55.04	13.48
7	10	60	12849.73	17.94	$138,716.04	55.20	13.53
7	10	60	12885.77	17.99	$139,105.07	55.35	13.58
7	10	60	13204.46	18.43	$142,545.42	56.72	14.03
7	10	60	13253.88	18.50	$143,078.93	56.93	14.10
7	10	60	13303.38	18.57	$143,613.29	57.15	14.17
7	10	60	13352.97	18.64	$144,148.56	57.36	14.24
7	10	60	13402.64	18.71	$144,684.81	57.57	14.31
7	10	60	13452.41	18.78	$145,222.12	57.79	14.38
7	10	60	13502.29	18.85	$145,760.55	58.00	14.45

Figure H-7.4 Single phase GTO input transformer sizing - Sheet 4 for 10 MW output power and variable switching frequency.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
1	4

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	25	600	49005.44	98.89	$2,895,405.25	1301.25	1036.71	95.05%	91.45%	0.89	25.90
7	26	600	53036.96	106.19	$3,371,183.70	1489.05	1186.33	94.58%	90.67%	0.89	32.38
7	27	600	54138.84	108.27	$3,403,103.84	1512.95	1205.36	94.69%	90.85%	0.89	32.38
7	28	600	55234.37	110.34	$3,435,082.59	1537.27	1224.74	94.80%	91.02%	0.89	32.38
7	29	600	56323.91	112.40	$3,467,128.07	1562.03	1244.47	94.89%	91.18%	0.89	32.38
7	30	600	57407.84	114.46	$3,499,247.77	1587.21	1264.53	94.98%	91.32%	0.89	32.38
7	31	600	58486.48	116.51	$3,531,448.63	1612.83	1284.94	95.05%	91.45%	0.89	32.38
7	32	600	59560.12	118.56	$3,563,737.13	1638.88	1305.70	95.13%	91.57%	0.89	32.38
7	33	600	63506.36	125.69	$4,036,619.44	1823.90	1453.10	94.76%	90.97%	0.89	38.85
7	34	600	64554.53	127.68	$4,067,674.62	1848.27	1472.51	94.84%	91.10%	0.89	38.85
7	35	600	65598.12	129.67	$4,098,793.97	1872.99	1492.21	94.92%	91.23%	0.89	38.85
7	36	600	66637.36	131.65	$4,129,982.37	1898.08	1512.20	94.99%	91.35%	0.89	38.85
7	37	600	67672.48	133.62	$4,161,244.41	1923.53	1532.48	95.06%	91.46%	0.89	38.85
7	38	600	68703.67	135.60	$4,192,584.38	1949.34	1553.04	95.12%	91.56%	0.89	38.85
7	39	600	72602.90	142.65	$4,664,430.80	2134.13	1700.26	94.81%	91.05%	0.89	45.33
7	40	600	73613.16	144.57	$4,694,739.77	2158.51	1719.69	94.88%	91.16%	0.89	45.33
7	41	600	74619.76	146.50	$4,725,109.38	2183.21	1739.36	94.94%	91.27%	0.89	45.33
7	42	600	75622.86	148.41	$4,755,543.04	2208.22	1759.28	95.00%	91.37%	0.89	45.33
7	43	600	76622.62	150.33	$4,786,043.98	2233.53	1779.45	95.06%	91.46%	0.89	45.33
7	44	600	77619.19	152.24	$4,816,615.25	2259.16	1799.87	95.12%	91.55%	0.89	45.33
7	45	600	78612.69	154.15	$4,847,259.77	2285.10	1820.54	95.17%	91.64%	0.89	45.33
7	46	600	82458.65	161.10	$5,317,297.47	2468.14	1966.37	94.91%	91.21%	0.89	51.81
7	47	600	83434.50	162.97	$5,347,041.00	2492.80	1986.02	94.96%	91.30%	0.89	51.81
7	48	600	84407.46	164.83	$5,376,844.05	2517.74	2005.88	95.02%	91.39%	0.89	51.81
7	49	600	85377.63	166.70	$5,406,709.01	2542.95	2025.96	95.07%	91.47%	0.89	51.81
7	50	600	86345.14	168.56	$5,436,638.16	2568.42	2046.26	95.11%	91.55%	0.89	51.81

Figure H-7.5 Single phase GTO input converter summary - Sheet 1 for 600 Hz switching frequency and variable power.

GTO PARAMETERS							
VOLTAGE RATING (kV)	POWER DISS PER GTO (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS PER AMP (J/A)	FIXED SW LOSS (J)	MINIMUM OFF TIME (s)	MAXIMUM Itgq (A)
6	2900	1.77	0.00118	0.003167	1.05	1.77E-04	3000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
21.15	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$9,304.40	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL(Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	25	600	2124.75	1.81	$149,374.79	298.54	1625.79	1226.38	4	3	12
7	26	600	2593.85	2.22	$185,305.20	344.58	1625.79	1226.38	5	3	15
7	27	600	2604.98	2.23	$185,509.28	349.78	1625.79	1226.38	5	3	15
7	28	600	2616.44	2.23	$185,719.36	355.10	1625.79	1226.38	5	3	15
7	29	600	2628.22	2.24	$185,935.43	360.53	1625.79	1226.38	5	3	15
7	30	600	2640.33	2.25	$186,157.49	366.08	1625.79	1226.38	5	3	15
7	31	600	2652.77	2.26	$186,385.53	371.74	1625.79	1226.38	5	3	15
7	32	600	2665.54	2.26	$186,619.57	377.51	1625.79	1226.38	5	3	15
7	33	600	3132.80	2.68	$222,516.29	422.91	1625.79	1226.38	6	3	18
7	34	600	3144.39	2.68	$222,728.86	428.28	1625.79	1226.38	6	3	18
7	35	600	3156.26	2.69	$222,946.43	433.74	1625.79	1226.38	6	3	18
7	36	600	3168.40	2.70	$223,168.98	439.29	1625.79	1226.38	6	3	18
7	37	600	3180.81	2.71	$223,396.53	444.94	1625.79	1226.38	6	3	18
7	38	600	3193.50	2.71	$223,629.07	450.69	1625.79	1226.38	6	3	18
7	39	600	3660.69	3.13	$259,524.58	496.07	1625.79	1226.38	7	3	21
7	40	600	3672.38	3.13	$259,738.93	501.47	1625.79	1226.38	7	3	21
7	41	600	3684.31	3.14	$259,957.57	506.95	1625.79	1226.38	7	3	21
7	42	600	3696.47	3.15	$260,180.48	512.51	1625.79	1226.38	7	3	21
7	43	600	3708.86	3.16	$260,407.67	518.15	1625.79	1226.38	7	3	21
7	44	600	3721.49	3.16	$260,639.15	523.88	1625.79	1226.38	7	3	21
7	45	600	3734.35	3.17	$260,874.90	529.68	1625.79	1226.38	7	3	21
7	46	600	4200.39	3.58	$296,749.36	574.66	1625.79	1226.38	8	3	24
7	47	600	4212.36	3.59	$296,968.80	580.16	1625.79	1226.38	8	3	24
7	48	600	4224.54	3.60	$297,191.98	585.72	1625.79	1226.38	8	3	24
7	49	600	4236.91	3.61	$297,418.90	591.36	1625.79	1226.38	8	3	24
7	50	600	4249.50	3.61	$297,649.57	597.07	1625.79	1226.38	8	3	24

Figure H-7.10 Single phase GTO input converter switch quantity characterization - Sheet 2 for 600 Hz switching frequency and variable power.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
6	2.4

ANTI-PARALLEL DIODE PARAMETERS		
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)
1.1	0.001583	380

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	25	600	24.88	1569.14	1.62	1:16	2.78	1.60	16.20	2.74	1.56
7	26	600	22.97	1305.52	1.23	1.02	2.25	1.18	16.20	2.05	1.30
7	27	600	23.32	1355.74	1.30	1.05	2.35	1.25	16.20	2.17	1.35
7	28	600	23.67	1405.95	1.37	1.08	2.45	1.33	16.20	2.30	1.40
7	29	600	24.04	1456.16	1.45	1.10	2.55	1.41	16.20	2.43	1.45
7	30	600	24.41	1506.37	1.52	1.13	2.65	1.49	16.20	2.56	1.50
7	31	600	24.78	1556.59	1.60	1.16	2.75	1.58	16.20	2.70	1.55
7	32	600	25.17	1606.80	1.68	1.18	2.86	1.67	16.20	2.84	1.60
7	33	600	23.50	1380.84	1.34	1.06	2.40	1.29	16.20	2.23	1.37
7	34	600	23.79	1422.69	1.40	1.08	2.48	1.36	16.20	2.34	1.42
7	35	600	24.10	1464.53	1.46	1.11	2.56	1.42	16.20	2.45	1.46
7	36	600	24.41	1506.37	1.52	1.13	2.65	1.49	16.20	2.56	1.50
7	37	600	24.72	1548.22	1.58	1.15	2.74	1.56	16.20	2.68	1.54
7	38	600	25.04	1590.06	1.65	1.17	2.82	1.64	16.20	2.79	1.58
7	39	600	23.62	1398.78	1.36	1.07	2.43	1.32	16.20	2.28	1.39
7	40	600	23.88	1434.64	1.41	1.09	2.50	1.38	16.20	2.37	1.43
7	41	600	24.14	1470.51	1.47	1.11	2.58	1.43	16.20	2.47	1.46
7	42	600	24.41	1506.37	1.52	1.13	2.65	1.49	16.20	2.56	1.50
7	43	600	24.67	1542.24	1.58	1.15	2.72	1.55	16.20	2.66	1.54
7	44	600	24.95	1578.11	1.63	1.17	2.80	1.62	16.20	2.76	1.57
7	45	600	25.22	1613.97	1.69	1.19	2.87	1.68	16.20	2.86	1.61
7	46	600	23.94	1443.61	1.43	1.10	2.52	1.39	16.20	2.39	1.44
7	47	600	24.17	1474.99	1.47	1.11	2.59	1.44	16.20	2.48	1.47
7	48	600	24.41	1506.37	1.52	1.13	2.65	1.49	16.20	2.56	1.50
7	49	600	24.64	1537.76	1.57	1.15	2.71	1.55	16.20	2.65	1.53
7	50	600	24.88	1569.14	1.62	1.16	2.78	1.60	16.20	2.74	1.56

Figure H-7.7 Single phase GTO input converter switch loss estimation - Sheet 3 for 600 Hz switching frequency and variable power.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '50% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
6	6984	9.748	60	30.00	$75,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	25	60	24935.98	34.80	$269,190.04	107.11	32.74
7	26	60	25776.77	35.98	$278,266.57	110.72	34.22
7	27	60	26494.28	36.98	$286,012.32	113.81	35.50
7	28	60	27205.69	37.97	$293,692.17	116.86	36.78
7	29	60	27911.27	38.96	$301,309.03	119.89	38.05
7	30	60	28611.26	39.93	$308,865.59	122.90	39.33
7	31	60	29305.89	40.90	$316,364.34	125.88	40.61
7	32	60	29995.39	41.87	$323,807.60	128.85	41.89
7	33	60	30785.21	42.97	$332,333.91	132.24	43.36
7	34	60	31462.57	43.91	$339,646.14	135.15	44.64
7	35	60	32135.34	44.85	$346,908.94	138.04	45.92
7	36	60	32803.71	45.79	$354,124.08	140.91	47.20
7	37	60	33467.81	46.71	$361,293.20	143.76	48.47
7	38	60	34127.78	47.63	$368,417.84	146.60	49.75
7	39	60	34884.80	48.69	$376,590.03	149.85	51.23
7	40	60	35534.96	49.60	$383,608.62	152.64	52.51
7	41	60	36181.38	50.50	$390,586.87	155.42	53.78
7	42	60	36824.17	51.40	$397,526.01	158.18	55.06
7	43	60	37463.45	52.29	$404,427.20	160.93	56.34
7	44	60	38099.32	53.18	$411,291.53	163.66	57.62
7	45	60	38731.87	54.06	$418,120.05	166.37	58.90
7	46	60	39457.05	55.07	$425,948.52	169.49	60.37
7	47	60	40081.58	55.94	$432,690.48	172.17	61.65
7	48	60	40703.05	56.81	$439,399.46	174.84	62.93
7	49	60	41321.55	57.68	$446,076.32	177.50	64.21
7	50	60	41937.15	58.53	$452,721.87	180.14	65.49

Figure H-7.8 Single phase GTO input transformer sizing - Sheet 4 for 600 Hz switching frequency and variable power.

CONVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
1	4

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS									
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	10	100	22839.22	46.29	$2,291,517.23	272.04	216.73	97.35%	95.34%	0.9997	17.44
7	10	150	22856.15	46.33	$2,292,876.72	274.33	218.56	97.33%	95.30%	0.9996	17.38
7	10	200	22873.09	46.38	$2,294,236.40	276.62	220.38	97.31%	95.27%	0.9994	17.32
7	10	250	22890.03	46.42	$2,295,596.28	278.91	222.21	97.29%	95.23%	0.9993	17.26
7	10	300	22906.97	46.46	$2,296,956.36	281.20	224.04	97.26%	95.19%	0.9991	17.20
7	10	350	22923.92	46.51	$2,298,316.64	283.50	225.86	97.24%	95.15%	0.9990	17.14
7	10	400	22940.87	46.55	$2,299,677.11	285.79	227.69	97.22%	95.12%	0.9988	17.09
7	10	450	22957.82	46.60	$2,301,037.78	288.08	229.52	97.20%	95.08%	0.9987	17.03
7	10	500	22974.78	46.64	$2,302,398.65	290.38	231.34	97.18%	95.04%	0.9985	16.97
7	10	550	22991.74	46.68	$2,303,759.72	292.67	233.17	97.16%	95.00%	0.9984	16.91
7	10	600	23008.70	46.73	$2,305,120.98	294.96	235.00	97.13%	94.97%	0.9982	16.85
7	10	650	23025.66	46.77	$2,306,482.45	297.26	236.82	97.11%	94.93%	0.9981	16.79
7	10	700	23042.63	46.82	$2,307,844.11	299.55	238.65	97.09%	94.89%	0.9979	16.74
7	10	750	23059.60	46.86	$2,309,205.97	301.84	240.48	97.07%	94.86%	0.9978	16.68
7	10	800	23076.57	46.91	$2,310,568.03	304.14	242.31	97.05%	94.82%	0.9976	16.62
7	10	850	23093.55	46.95	$2,311,930.29	306.43	244.14	97.03%	94.78%	0.9975	16.57
7	10	900	23110.52	46.99	$2,313,292.75	308.73	245.96	97.01%	94.74%	0.9973	16.51
7	10	950	23127.51	47.04	$2,314,655.40	311.02	247.79	96.98%	94.71%	0.9972	16.45
7	10	1000	23144.49	47.08	$2,316,018.26	313.32	249.62	96.96%	94.67%	0.9970	16.40
7	10	1050	23161.48	47.13	$2,317,381.31	315.62	251.45	96.94%	94.63%	0.9969	16.34
7	10	1100	23178.47	47.17	$2,318,744.57	317.91	253.28	96.92%	94.60%	0.9967	16.29
7	10	1150	23195.46	47.21	$2,320,108.02	320.21	255.11	96.90%	94.56%	0.9966	16.23
7	10	1200	23212.46	47.26	$2,321,471.68	322.51	256.94	96.88%	94.52%	0.9964	16.17
7	10	1250	23229.46	47.30	$2,322,835.53	324.80	258.77	96.85%	94.49%	0.9963	16.12
7	10	1300	23246.46	47.35	$2,324,199.59	327.10	260.60	96.83%	94.45%	0.9961	16.07
7	10	1350	23263.46	47.39	$2,325,563.84	329.40	262.43	96.81%	94.41%	0.9960	16.01

Figure H-8.1 Single phase IGBT input converter summary - Sheet 1 for 10 MW output power and variable switching frequency.

IGBT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER IGBT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	IGBTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itgq
1	187.5	0.9	0.0106	0.000346	0	10	3.00E-06	300

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
7.73	2	0.00819	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$4,090.19	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	10	100	838.98	0.51	$164,533.50	54.79	195.77	1561.79	2	18	36
7	10	150	841.06	0.51	$164,571.50	55.36	195.12	1556.51	2	18	36
7	10	200	843.13	0.51	$164,609.50	55.93	194.48	1551.25	2	18	36
7	10	250	845.20	0.51	$164,647.52	56.50	193.84	1546.01	2	18	36
7	10	300	847.28	0.51	$164,685.54	57.07	193.20	1540.80	2	18	36
7	10	350	849.35	0.51	$164,723.57	57.64	192.56	1535.61	2	18	36
7	10	400	851.43	0.52	$164,761.61	58.22	191.93	1530.43	2	18	36
7	10	450	853.50	0.52	$164,799.65	58.79	191.30	1525.28	2	18	36
7	10	500	855.58	0.52	$164,837.71	59.36	190.67	1520.16	2	18	36
7	10	550	857.65	0.52	$164,875.77	59.93	190.04	1515.05	2	18	36
7	10	600	859.73	0.52	$164,913.84	60.50	189.42	1509.96	2	18	36
7	10	650	861.81	0.52	$164,951.91	61.07	188.80	1504.90	2	18	36
7	10	700	863.88	0.52	$164,990.00	61.64	188.18	1499.86	2	18	36
7	10	750	865.96	0.53	$165,028.09	62.21	187.56	1494.84	2	18	36
7	10	800	868.04	0.53	$165,066.19	62.78	186.95	1489.84	2	18	36
7	10	850	870.12	0.53	$165,104.30	63.36	186.34	1484.86	2	18	36
7	10	900	872.20	0.53	$165,142.41	63.93	185.73	1479.90	2	18	36
7	10	950	874.28	0.53	$165,180.53	64.50	185.12	1474.97	2	18	36
7	10	1000	876.36	0.53	$165,218.67	65.07	184.52	1470.05	2	18	36
7	10	1050	878.44	0.53	$165,256.80	65.64	183.92	1465.16	2	18	36
7	10	1100	880.52	0.53	$165,294.95	66.22	183.32	1460.29	2	18	36
7	10	1150	882.60	0.54	$165,333.10	66.79	182.73	1455.44	2	18	36
7	10	1200	884.68	0.54	$165,371.27	67.36	182.13	1450.60	2	18	36
7	10	1250	886.76	0.54	$165,409.44	67.93	181.54	1445.80	2	18	36
7	10	1300	888.84	0.54	$165,447.61	68.50	180.96	1441.01	2	18	36
7	10	1350	890.93	0.54	$165,485.80	69.08	180.37	1436.24	2	18	36

Figure H-8.2 Single phase IGBT input converter switch quantity characterization - Sheet 2 for 10 MW output power and variable switching frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
1	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
1.6	0.00556	34	34

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	10	100	1.52	1122.33	0.75	0.01	0.76	0.64	0.01	0.01	0.11
7	10	150	1.54	1122.50	0.75	0.02	0.76	0.64	0.02	0.01	0.11
7	10	200	1.55	1122.67	0.75	0.02	0.77	0.64	0.03	0.01	0.11
7	10	250	1.57	1122.84	0.75	0.03	0.78	0.64	0.03	0.02	0.11
7	10	300	1.59	1123.01	0.75	0.04	0.78	0.64	0.04	0.02	0.11
7	10	350	1.60	1123.18	0.75	0.04	0.79	0.64	0.04	0.02	0.11
7	10	400	1.62	1123.35	0.75	0.05	0.80	0.64	0.05	0.03	0.11
7	10	450	1.63	1123.51	0.75	0.06	0.80	0.64	0.06	0.03	0.11
7	10	500	1.65	1123.68	0.75	0.06	0.81	0.64	0.06	0.03	0.11
7	10	550	1.66	1123.85	0.75	0.07	0.81	0.64	0.07	0.04	0.11
7	10	600	1.68	1124.02	0.75	0.07	0.82	0.64	0.08	0.04	0.11
7	10	650	1.70	1124.19	0.75	0.08	0.83	0.64	0.08	0.04	0.11
7	10	700	1.71	1124.36	0.75	0.09	0.83	0.64	0.09	0.05	0.11
7	10	750	1.73	1124.53	0.75	0.09	0.84	0.64	0.09	0.05	0.11
7	10	800	1.74	1124.70	0.75	0.10	0.85	0.64	0.10	0.05	0.11
7	10	850	1.76	1124.87	0.75	0.11	0.85	0.64	0.11	0.06	0.11
7	10	900	1.78	1125.03	0.75	0.11	0.86	0.64	0.11	0.06	0.11
7	10	950	1.79	1125.20	0.75	0.12	0.86	0.64	0.12	0.06	0.11
7	10	1000	1.81	1125.37	0.75	0.12	0.87	0.64	0.13	0.07	0.11
7	10	1050	1.82	1125.54	0.75	0.13	0.88	0.64	0.13	0.07	0.11
7	10	1100	1.84	1125.71	0.75	0.14	0.88	0.64	0.14	0.07	0.11
7	10	1150	1.86	1125.88	0.75	0.14	0.89	0.64	0.14	0.08	0.11
7	10	1200	1.87	1126.05	0.75	0.15	0.90	0.64	0.15	0.08	0.11
7	10	1250	1.89	1126.22	0.75	0.15	0.90	0.64	0.16	0.08	0.11
7	10	1300	1.90	1126.39	0.75	0.16	0.91	0.64	0.16	0.09	0.11
7	10	1350	1.92	1126.56	0.75	0.17	0.91	0.64	0.17	0.09	0.11

Figure H-8.3 Single phase IGBT input converter switch loss estimation - Sheet 3 for 10 MW output power and variable switching frequency.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '50% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
6	6984	9.748	60	30.00	$75,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	10	60	12309.34	17.18	$132,882.38	52.88	12.77
7	10	60	12311.40	17.18	$132,904.63	52.88	12.78
7	10	60	12313.47	17.19	$132,926.89	52.89	12.78
7	10	60	12315.53	17.19	$132,949.15	52.90	12.78
7	10	60	12317.59	17.19	$132,971.41	52.91	12.79
7	10	60	12319.65	17.20	$132,993.67	52.92	12.79
7	10	60	12321.71	17.20	$133,015.93	52.93	12.79
7	10	60	12323.78	17.20	$133,038.20	52.94	12.79
7	10	60	12325.84	17.20	$133,060.46	52.95	12.80
7	10	60	12327.90	17.21	$133,082.73	52.96	12.80
7	10	60	12329.96	17.21	$133,105.00	52.96	12.80
7	10	60	12332.03	17.21	$133,127.27	52.97	12.81
7	10	60	12334.09	17.22	$133,149.54	52.98	12.81
7	10	60	12336.15	17.22	$133,171.82	52.99	12.81
7	10	60	12338.22	17.22	$133,194.09	53.00	12.81
7	10	60	12340.28	17.22	$133,216.37	53.01	12.82
7	10	60	12342.34	17.23	$133,238.65	53.02	12.82
7	10	60	12344.41	17.23	$133,260.93	53.03	12.82
7	10	60	12346.47	17.23	$133,283.21	53.03	12.83
7	10	60	12348.54	17.24	$133,305.49	53.04	12.83
7	10	60	12350.60	17.24	$133,327.78	53.05	12.83
7	10	60	12352.67	17.24	$133,350.06	53.06	12.83
7	10	60	12354.73	17.24	$133,372.35	53.07	12.84
7	10	60	12356.79	17.25	$133,394.64	53.08	12.84
7	10	60	12358.86	17.25	$133,416.93	53.09	12.84
7	10	60	12360.92	17.25	$133,439.22	53.10	12.85

Figure H-8.4 Single phase IGBT input transformer sizing - Sheet 4 for 10 MW output power and variable switching frequency.

CONVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
1	4

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	25	600	43452.93	84.94	$3,728,740.48	826.83	658.73	96.80%	94.39%	0.9982	25.28
7	26	600	46758.98	87.85	$4,593,723.80	790.74	629.99	97.05%	94.82%	0.9982	33.70
7	27	600	47846.63	90.12	$4,630,228.74	829.58	660.93	97.02%	94.77%	0.9982	33.70
7	28	600	48926.58	92.38	$4,666,860.18	869.15	692.45	96.99%	94.72%	0.9982	33.70
7	29	600	49999.26	94.64	$4,703,626.88	909.46	724.57	96.96%	94.67%	0.9982	33.70
7	30	600	51065.05	96.90	$4,740,536.94	950.50	757.27	96.93%	94.61%	0.9982	33.70
7	31	600	52124.30	99.16	$4,777,597.84	992.29	790.56	96.90%	94.56%	0.9982	33.70
7	32	600	53177.33	101.41	$4,814,816.50	1034.81	824.43	96.87%	94.51%	0.9982	33.70
7	33	600	54224.46	103.66	$4,852,199.39	1078.07	858.90	96.84%	94.46%	0.9982	33.70
7	34	600	57459.60	106.42	$5,714,685.16	1039.17	827.91	97.03%	94.79%	0.9982	42.13
7	35	600	58482.94	108.59	$5,750,145.11	1078.65	859.36	97.01%	94.75%	0.9982	42.13
7	36	600	59500.83	110.76	$5,785,721.12	1118.71	891.28	96.99%	94.71%	0.9982	42.13
7	37	600	60513.50	112.92	$5,821,418.11	1159.37	923.67	96.96%	94.67%	0.9982	42.13
7	38	600	61521.17	115.08	$5,857,240.72	1200.62	956.53	96.94%	94.63%	0.9982	42.13
7	39	600	62524.05	117.24	$5,893,193.30	1242.46	989.87	96.91%	94.59%	0.9982	42.13
7	40	600	63522.33	119.40	$5,929,279.96	1284.89	1023.67	96.89%	94.54%	0.9982	42.13
7	41	600	64516.20	121.56	$5,965,504.56	1327.92	1057.95	96.86%	94.50%	0.9982	42.13
7	42	600	65505.82	123.72	$6,001,870.79	1371.54	1092.70	96.84%	94.46%	0.9982	42.13
7	43	600	68674.86	126.30	$6,860,880.37	1327.00	1057.22	97.01%	94.75%	0.9982	50.56
7	44	600	69645.92	128.39	$6,895,637.17	1367.38	1089.39	96.99%	94.71%	0.9982	50.56
7	45	600	70612.98	130.48	$6,930,502.15	1408.26	1121.96	96.97%	94.68%	0.9982	50.56
7	46	600	71576.18	132.57	$6,965,478.28	1449.62	1154.91	96.94%	94.64%	0.9982	50.56
7	47	600	72535.65	134.66	$7,000,568.39	1491.48	1188.26	96.92%	94.61%	0.9982	50.56
7	48	600	73491.52	136.74	$7,035,775.15	1533.84	1222.01	96.90%	94.57%	0.9982	50.56
7	49	600	74443.91	138.83	$7,071,101.12	1576.69	1256.15	96.88%	94.53%	0.9982	50.56
7	50	600	75392.94	140.92	$7,106,548.75	1620.03	1290.68	96.86%	94.50%	0.9982	50.56

Figure H-8.5 Single phase IGBT input converter summary - Sheet 1 for 600 Hz switching frequency and variable power.

IGBT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER IGBT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	IGBTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itgq
1	187.5	0.9	0.0106	0.000346	0	10	3.00E-06	300

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
7.73	2	0.00819	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$4,090.19	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	25	600	1311.92	0.80	$247,230.09	180.29	189.42	1509.96	3	18	54
7	26	600	1731.05	1.05	$328,940.25	170.53	189.42	1509.96	4	18	72
7	27	600	1733.27	1.05	$328,980.93	179.46	189.42	1509.96	4	18	72
7	28	600	1735.57	1.05	$329,023.12	188.57	189.42	1509.96	4	18	72
7	29	600	1737.96	1.05	$329,066.80	197.87	189.42	1509.96	4	18	72
7	30	600	1740.42	1.06	$329,111.99	207.37	189.42	1509.96	4	18	72
7	31	600	1742.97	1.06	$329,158.68	217.05	189.42	1509.96	4	18	72
7	32	600	1745.60	1.06	$329,206.86	226.93	189.42	1509.96	4	18	72
7	33	600	1748.31	1.06	$329,256.55	236.99	189.42	1509.96	4	18	72
7	34	600	2167.16	1.31	$410,961.56	226.58	189.42	1509.96	5	18	90
7	35	600	2169.47	1.32	$411,003.90	235.71	189.42	1509.96	5	18	90
7	36	600	2171.84	1.32	$411,047.43	245.00	189.42	1509.96	5	18	90
7	37	600	2174.28	1.32	$411,092.17	254.43	189.42	1509.96	5	18	90
7	38	600	2176.79	1.32	$411,138.10	264.02	189.42	1509.96	5	18	90
7	39	600	2179.36	1.32	$411,185.24	273.76	189.42	1509.96	5	18	90
7	40	600	2182.00	1.32	$411,233.58	283.66	189.42	1509.96	5	18	90
7	41	600	2184.70	1.33	$411,283.12	293.70	189.42	1509.96	5	18	90
7	42	600	2187.47	1.33	$411,333.86	303.90	189.42	1509.96	5	18	90
7	43	600	2605.73	1.58	$493,028.11	292.13	189.42	1509.96	6	18	108
7	44	600	2608.16	1.58	$493,072.55	301.53	189.42	1509.96	6	18	108
7	45	600	2610.63	1.58	$493,117.98	311.05	189.42	1509.96	6	18	108
7	46	600	2613.17	1.59	$493,164.42	320.70	189.42	1509.96	6	18	108
7	47	600	2615.75	1.59	$493,211.86	330.48	189.42	1509.96	6	18	108
7	48	600	2618.40	1.59	$493,260.30	340.39	189.42	1509.96	6	18	108
7	49	600	2621.09	1.59	$493,309.73	350.42	189.42	1509.96	6	18	108
7	50	600	2623.84	1.59	$493,360.17	360.58	189.42	1509.96	6	18	108

Figure H-8.6 Single phase IGBT input converter switch quantity characterization - Sheet 2 for 600 Hz switching frequency and variable power.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
1	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
1.6	0.00556	34	34

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	25	600	3.34	1873.37	1.72	0.12	1.84	1.13	0.08	0.11	0.18
7	26	600	2.37	1461.23	1.14	0.10	1.23	0.85	0.08	0.07	0.14
7	27	600	2.49	1517.43	1.21	0.10	1.31	0.89	0.08	0.07	0.14
7	28	600	2.62	1573.63	1.28	0.10	1.39	0.93	0.08	0.08	0.15
7	29	600	2.75	1629.83	1.36	0.11	1.47	0.97	0.08	0.08	0.16
7	30	600	2.88	1686.03	1.44	0.11	1.55	1.00	0.08	0.09	0.16
7	31	600	3.01	1742.23	1.52	0.11	1.64	1.04	0.08	0.09	0.17
7	32	600	3.15	1798.43	1.60	0.12	1.72	1.08	0.08	0.10	0.17
7	33	600	3.29	1854.63	1.69	0.12	1.81	1.12	0.08	0.11	0.18
7	34	600	2.52	1528.67	1.22	0.10	1.33	0.90	0.08	0.07	0.15
7	35	600	2.62	1573.63	1.28	0.10	1.39	0.93	0.08	0.08	0.15
7	36	600	2.72	1618.59	1.35	0.11	1.45	0.96	0.08	0.08	0.15
7	37	600	2.83	1663.55	1.41	0.11	1.52	0.99	0.08	0.09	0.16
7	38	600	2.93	1708.51	1.47	0.11	1.58	1.02	0.08	0.09	0.16
7	39	600	3.04	1753.47	1.54	0.12	1.65	1.05	0.08	0.10	0.17
7	40	600	3.15	1798.43	1.60	0.12	1.72	1.08	0.08	0.10	0.17
7	41	600	3.26	1843.39	1.67	0.12	1.79	1.11	0.08	0.11	0.18
7	42	600	3.38	1888.35	1.74	0.12	1.87	1.15	0.08	0.11	0.18
7	43	600	2.70	1611.10	1.33	0.11	1.44	0.95	0.08	0.08	0.15
7	44	600	2.79	1648.56	1.39	0.11	1.50	0.98	0.08	0.08	0.16
7	45	600	2.88	1686.03	1.44	0.11	1.55	1.00	0.08	0.09	0.16
7	46	600	2.97	1723.50	1.49	0.11	1.61	1.03	0.08	0.09	0.16
7	47	600	3.06	1760.97	1.55	0.12	1.66	1.06	0.08	0.10	0.17
7	48	600	3.15	1798.43	1.60	0.12	1.72	1.08	0.08	0.10	0.17
7	49	600	3.24	1835.90	1.66	0.12	1.78	1.11	0.08	0.10	0.18
7	50	600	3.34	1873.37	1.72	0.12	1.84	1.13	0.08	0.11	0.18

Figure H-8.7 Single phase IGBT input converter switch loss estimation - Sheet 3 for 600 Hz switching frequency and variable power.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '60% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
6	6984	9.748	60	30.00	$75,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	25	60	24597.52	34.33	$265,536.28	105.66	32.15
7	26	60	25283.59	35.29	$272,942.60	108.61	33.35
7	27	60	26016.13	36.31	$280,850.53	111.75	34.66
7	28	60	26742.39	37.33	$288,690.65	114.87	35.94
7	29	60	27462.66	38.33	$296,466.11	117.97	37.24
7	30	60	28177.20	39.33	$304,179.81	121.04	38.54
7	31	60	28886.27	40.32	$311,834.43	124.08	39.84
7	32	60	29590.10	41.30	$319,432.47	127.11	41.13
7	33	60	30288.91	42.28	$326,976.23	130.11	42.43
7	34	60	30982.97	43.17	$333,876.01	132.85	43.63
7	35	60	31614.23	44.13	$341,283.45	135.80	44.93
7	36	60	32295.97	45.08	$348,642.97	138.73	46.22
7	37	60	32973.34	46.02	$355,955.35	141.64	47.52
7	38	60	33646.50	46.96	$363,222.24	144.53	48.82
7	39	60	34315.59	47.90	$370,445.20	147.40	50.12
7	40	60	34980.74	48.82	$377,625.72	150.26	51.42
7	41	60	35642.09	49.75	$384,765.18	153.10	52.72
7	42	60	36299.76	50.67	$391,864.89	155.93	54.02
7	43	60	36898.43	51.50	$398,327.59	158.50	55.21
7	44	60	37546.64	52.41	$405,325.23	161.28	56.51
7	45	60	38191.46	53.31	$412,286.23	164.05	57.81
7	46	60	38832.99	54.20	$419,211.65	166.81	59.10
7	47	60	39471.31	55.09	$426,102.49	169.55	60.40
7	48	60	40106.52	55.98	$432,959.73	172.28	61.70
7	49	60	40738.70	56.86	$439,784.27	174.99	63.00
7	50	60	41367.93	57.74	$446,577.01	177.70	64.30

Figure H-8.8 Single phase IGBT input transformer sizing - Sheet 4 for 600 Hz switching frequency and variable power.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
1	4

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	10	100	41105.71	78.92	$4,603,199.89	400.93	319.42	96.15%	93.28%	0.9990	17.81
7	10	150	41157.82	79.16	$4,610,048.45	415.78	331.25	96.01%	93.05%	0.9985	17.80
7	10	200	41209.95	79.40	$4,616,898.15	430.63	343.09	95.87%	92.82%	0.9980	17.79
7	10	250	41262.10	79.64	$4,623,748.99	445.49	354.92	95.74%	92.59%	0.9975	17.78
7	10	300	41314.25	79.88	$4,630,600.97	460.35	366.76	95.60%	92.36%	0.9970	17.77
7	10	350	41366.42	80.12	$4,637,454.08	475.21	378.60	95.46%	92.13%	0.9965	17.76
7	10	400	41418.60	80.36	$4,644,308.35	490.07	390.44	95.33%	91.91%	0.9960	17.75
7	10	450	41470.79	80.60	$4,651,163.76	504.93	402.28	95.19%	91.68%	0.9955	17.75
7	10	500	41523.00	80.84	$4,658,020.32	519.80	414.12	95.06%	91.46%	0.9950	17.74
7	10	550	41575.22	81.08	$4,664,878.04	534.67	425.97	94.92%	91.24%	0.9945	17.73
7	10	600	41627.45	81.33	$4,671,736.92	549.54	437.82	94.79%	91.01%	0.9940	17.72
7	10	650	41679.69	81.57	$4,678,596.95	564.41	449.66	94.66%	90.79%	0.9935	17.71
7	10	700	41731.95	81.81	$4,685,458.15	579.28	461.51	94.52%	90.57%	0.9930	17.65
7	10	750	41784.22	82.05	$4,692,320.52	594.16	473.36	94.39%	90.35%	0.9925	17.29
7	10	800	41836.50	82.29	$4,699,184.06	609.03	485.22	94.26%	90.14%	0.9920	16.93
7	10	850	41888.79	82.53	$4,706,048.77	623.91	497.07	94.13%	89.92%	0.9915	16.59
7	10	900	41941.10	82.77	$4,712,914.66	638.79	508.92	94.00%	89.70%	0.9910	16.26
7	10	950	41993.43	83.01	$4,719,781.72	653.67	520.78	93.86%	89.49%	0.9905	15.94
7	10	1000	42045.76	83.25	$4,726,649.97	668.56	532.64	93.73%	89.28%	0.9900	15.62
7	10	1050	42098.11	83.50	$4,733,519.40	683.44	544.50	93.60%	89.06%	0.9895	15.32
7	10	1100	42150.47	83.74	$4,740,390.02	698.33	556.36	93.47%	88.85%	0.9890	15.02
7	10	1150	42202.85	83.98	$4,747,261.83	713.22	568.22	93.34%	88.64%	0.9885	14.74
7	10	1200	42255.23	84.22	$4,754,134.84	728.11	580.09	93.21%	88.43%	0.9880	14.46
7	10	1250	42307.64	84.46	$4,761,009.05	743.01	591.95	93.08%	88.22%	0.9875	14.19
7	10	1300	42360.05	84.70	$4,767,884.45	757.90	603.82	92.95%	88.01%	0.9870	13.93
7	10	1350	42412.48	84.94	$4,774,761.06	772.80	615.69	92.83%	87.81%	0.9865	13.68

Figure H-9.1 Single phase BJT input converter summary - Sheet 1 for 10 MW output power and variable switching frequency.

BJT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER BJT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	BJTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itqq
0.55	1500	1	0.001838	0.00275	0	2	1.00E-05	1000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
20.88	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$5,332.87	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	10	100	4015.46	4.98	$379,117.26	86.89	1000.00	1594.97	2	32	64
7	10	150	4018.72	4.98	$379,176.94	90.59	1000.00	1594.57	2	32	64
7	10	200	4021.98	4.98	$379,236.66	94.29	1000.00	1594.17	2	32	64
7	10	250	4025.24	4.99	$379,296.44	97.99	1000.00	1593.77	2	32	64
7	10	300	4028.50	4.99	$379,356.26	101.69	1000.00	1593.37	2	32	64
7	10	350	4031.76	4.99	$379,416.13	105.39	1000.00	1592.97	2	32	64
7	10	400	4035.03	4.99	$379,476.05	109.09	1000.00	1592.57	2	32	64
7	10	450	4038.30	4.99	$379,536.03	112.79	1000.00	1592.17	2	32	64
7	10	500	4041.58	5.00	$379,596.05	116.49	1000.00	1591.77	2	32	64
7	10	550	4044.85	5.00	$379,656.11	120.20	1000.00	1591.37	2	32	64
7	10	600	4048.13	5.00	$379,716.23	123.90	1000.00	1590.97	2	32	64
7	10	650	4051.42	5.00	$379,776.40	127.60	1000.00	1590.57	2	32	64
7	10	700	4054.70	5.00	$379,836.62	131.31	997.36	1585.98	2	32	64
7	10	750	4057.99	5.01	$379,896.89	135.01	977.23	1553.57	2	32	64
7	10	800	4061.28	5.01	$379,957.21	138.71	957.69	1522.13	2	32	64
7	10	850	4064.57	5.01	$380,017.57	142.42	938.75	1491.64	2	32	64
7	10	900	4067.87	5.01	$380,077.99	146.13	920.36	1462.07	2	32	64
7	10	950	4071.16	5.02	$380,138.46	149.83	902.53	1433.38	2	32	64
7	10	1000	4074.47	5.02	$380,198.98	153.54	885.24	1405.56	2	32	64
7	10	1050	4077.77	5.02	$380,259.55	157.25	868.46	1378.57	2	32	64
7	10	1100	4081.08	5.02	$380,320.16	160.95	852.18	1352.38	2	32	64
7	10	1150	4084.38	5.02	$380,380.83	164.66	836.39	1326.98	2	32	64
7	10	1200	4087.70	5.03	$380,441.56	168.37	821.06	1302.34	2	32	64
7	10	1250	4091.01	5.03	$380,502.33	172.08	806.19	1278.42	2	32	64
7	10	1300	4094.33	5.03	$380,563.15	175.79	791.75	1255.21	2	32	64
7	10	1350	4097.65	5.03	$380,624.02	179.50	777.74	1232.69	2	32	64

Figure H-9.2 Single phase BJT input converter switch quantity characterization - Sheet 2 for 10 MW output power and variable switching frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
2.5	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
0.998	0.000265	100	2

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	10	100	1.36	1123.12	0.73	0.10	0.82	0.41	0.01	0.01	0.11
7	10	150	1.42	1123.68	0.73	0.15	0.87	0.41	0.01	0.01	0.11
7	10	200	1.47	1124.25	0.73	0.20	0.92	0.41	0.02	0.01	0.11
7	10	250	1.53	1124.81	0.73	0.25	0.97	0.41	0.02	0.02	0.11
7	10	300	1.59	1125.37	0.73	0.29	1.02	0.41	0.03	0.02	0.11
7	10	350	1.65	1125.94	0.73	0.34	1.07	0.41	0.03	0.03	0.11
7	10	400	1.70	1126.50	0.73	0.39	1.12	0.41	0.04	0.03	0.11
7	10	450	1.76	1127.07	0.73	0.44	1.17	0.41	0.04	0.03	0.11
7	10	500	1.82	1127.64	0.73	0.49	1.22	0.41	0.05	0.04	0.11
7	10	550	1.88	1128.20	0.73	0.54	1.27	0.41	0.05	0.04	0.11
7	10	600	1.94	1128.77	0.73	0.59	1.32	0.41	0.06	0.05	0.11
7	10	650	1.99	1129.34	0.73	0.64	1.37	0.41	0.06	0.05	0.11
7	10	700	2.05	1129.91	0.73	0.69	1.42	0.41	0.07	0.05	0.11
7	10	750	2.11	1130.48	0.73	0.74	1.46	0.41	0.07	0.06	0.11
7	10	800	2.17	1131.05	0.73	0.79	1.51	0.41	0.08	0.06	0.11
7	10	850	2.23	1131.62	0.73	0.83	1.56	0.41	0.08	0.06	0.11
7	10	900	2.28	1132.19	0.73	0.88	1.61	0.41	0.09	0.07	0.11
7	10	950	2.34	1132.76	0.73	0.93	1.66	0.41	0.09	0.07	0.11
7	10	1000	2.40	1133.33	0.73	0.98	1.71	0.41	0.09	0.08	0.11
7	10	1050	2.46	1133.90	0.73	1.03	1.76	0.41	0.10	0.08	0.11
7	10	1100	2.51	1134.48	0.73	1.08	1.81	0.41	0.10	0.08	0.11
7	10	1150	2.57	1135.05	0.73	1.13	1.86	0.41	0.11	0.09	0.11
7	10	1200	2.63	1135.62	0.73	1.18	1.91	0.41	0.11	0.09	0.11
7	10	1250	2.69	1136.20	0.73	1.23	1.96	0.41	0.12	0.10	0.11
7	10	1300	2.75	1136.78	0.73	1.28	2.01	0.41	0.12	0.10	0.11
7	10	1350	2.80	1137.35	0.73	1.33	2.06	0.41	0.13	0.10	0.11

Figure H-9.3 Single phase BJT input converter switch loss estimation - Sheet 3 for 10 MW output power and variable switching frequency.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '50% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
6	6984	9.748	60	30.00	$75,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	10	60	12425.15	17.34	$134,132.54	53.37	12.93
7	10	60	12438.47	17.36	$134,276.36	53.43	12.95
7	10	60	12451.79	17.38	$134,420.14	53.49	12.97
7	10	60	12465.11	17.40	$134,563.89	53.54	12.99
7	10	60	12478.42	17.42	$134,707.61	53.60	13.01
7	10	60	12491.73	17.44	$134,851.29	53.66	13.03
7	10	60	12505.04	17.45	$134,994.94	53.72	13.05
7	10	60	12518.34	17.47	$135,138.56	53.77	13.06
7	10	60	12531.64	17.49	$135,282.14	53.83	13.08
7	10	60	12544.94	17.51	$135,425.70	53.89	13.10
7	10	60	12558.23	17.53	$135,569.21	53.94	13.12
7	10	60	12571.52	17.55	$135,712.70	54.00	13.14
7	10	60	12584.81	17.57	$135,856.15	54.06	13.16
7	10	60	12598.10	17.58	$135,999.58	54.12	13.18
7	10	60	12611.38	17.60	$136,142.97	54.17	13.19
7	10	60	12624.66	17.62	$136,286.32	54.23	13.21
7	10	60	12637.94	17.64	$136,429.65	54.29	13.23
7	10	60	12651.21	17.66	$136,572.94	54.34	13.25
7	10	60	12664.48	17.68	$136,716.20	54.40	13.27
7	10	60	12677.75	17.70	$136,859.43	54.46	13.29
7	10	60	12691.01	17.71	$137,002.63	54.51	13.30
7	10	60	12704.28	17.73	$137,145.79	54.57	13.32
7	10	60	12717.54	17.75	$137,288.93	54.63	13.34
7	10	60	12730.79	17.77	$137,432.03	54.69	13.36
7	10	60	12744.04	17.79	$137,575.10	54.74	13.38
7	10	60	12757.30	17.81	$137,718.14	54.80	13.40

Figure H-9.4 Single phase BJT input transformer sizing - Sheet 4 for 10 MW output power and variable switching frequency.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
1	4

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS									
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	25	600	72035.44	141.50	$7,413,041.17	1529.36	1218.44	94.24%	90.10%	0.9940	26.58
7	26	600	73224.39	144.39	$7,467,099.52	1609.13	1282.00	94.17%	89.99%	0.9940	26.58
7	27	600	85438.45	162.30	$9,451,745.54	1553.61	1237.76	94.56%	90.63%	0.9940	35.44
7	28	600	86587.38	165.04	$9,502,024.16	1625.61	1295.12	94.51%	90.55%	0.9940	35.44
7	29	600	87729.96	167.78	$9,552,619.04	1698.76	1353.40	94.47%	90.48%	0.9940	35.44
7	30	600	88866.57	170.53	$9,603,538.34	1773.08	1412.61	94.42%	90.40%	0.9940	35.44
7	31	600	89997.56	173.28	$9,654,789.60	1848.55	1472.74	94.37%	90.32%	0.9940	35.44
7	32	600	91123.27	176.03	$9,706,379.80	1925.19	1533.80	94.33%	90.25%	0.9940	35.44
7	33	600	92244.01	178.79	$9,758,315.46	2002.99	1595.78	94.28%	90.17%	0.9940	35.44
7	34	600	93360.05	181.55	$9,810,602.63	2081.95	1658.69	94.23%	90.09%	0.9940	35.44
7	35	600	94471.67	184.32	$9,863,246.95	2162.07	1722.52	94.18%	90.01%	0.9940	35.44
7	36	600	106594.79	201.97	$11,842,386.96	2096.93	1670.63	94.50%	90.53%	0.9940	44.30
7	37	600	107676.61	204.62	$11,892,009.46	2170.73	1729.42	94.46%	90.46%	0.9940	44.30
7	38	600	108754.18	207.27	$11,941,902.33	2245.45	1788.95	94.42%	90.40%	0.9940	44.30
7	39	600	109827.68	209.92	$11,992,069.96	2321.11	1849.23	94.38%	90.34%	0.9940	44.30
7	40	600	110897.33	212.58	$12,042,516.49	2397.69	1910.24	94.34%	90.28%	0.9940	44.30
7	41	600	111963.29	215.24	$12,093,245.82	2475.21	1972.00	94.31%	90.21%	0.9940	44.30
7	42	600	113025.76	217.91	$12,144,261.64	2553.65	2034.49	94.27%	90.15%	0.9940	44.30
7	43	600	114084.88	220.58	$12,195,567.45	2633.03	2097.73	94.23%	90.09%	0.9940	44.30
7	44	600	115140.83	223.25	$12,247,166.55	2713.34	2161.72	94.19%	90.03%	0.9940	44.30
7	45	600	127200.28	240.73	$14,222,566.62	2641.77	2104.69	94.45%	90.46%	0.9940	53.16
7	46	600	128232.59	243.30	$14,271,650.36	2716.75	2164.43	94.42%	90.41%	0.9940	53.16
7	47	600	129261.79	245.88	$14,320,968.66	2792.50	2224.79	94.39%	90.35%	0.9940	53.16
7	48	600	130287.99	248.47	$14,370,524.22	2869.03	2285.76	94.36%	90.30%	0.9940	53.16
7	49	600	131311.33	251.05	$14,420,319.61	2946.34	2347.35	94.33%	90.25%	0.9940	53.16
7	50	600	132331.92	253.64	$14,470,357.30	3024.42	2409.56	94.30%	90.20%	0.9940	53.16

Figure H-9.5 Single phase BJT input converter summary - Sheet 1 for 600 Hz switching frequency and variable power.

BJT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER BJT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	BJTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itgg
0.55	1500	1	0.001838	0.00275	0	2	1.00E-05	1000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
20.88	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$5,332.87	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	25	600	6113.94	7.53	$569,789.62	355.39	1000.00	1590.97	3	32	96
7	26	600	6119.19	7.53	$569,885.88	374.51	1000.00	1590.97	3	32	96
7	27	600	8122.23	10.02	$758,808.50	359.92	1000.00	1590.97	4	32	128
7	28	600	8126.53	10.02	$758,887.27	377.12	1000.00	1590.97	4	32	128
7	29	600	8130.97	10.02	$758,968.73	394.62	1000.00	1590.97	4	32	128
7	30	600	8135.56	10.03	$759,052.88	412.41	1000.00	1590.97	4	32	128
7	31	600	8140.30	10.03	$759,139.72	430.50	1000.00	1590.97	4	32	128
7	32	600	8145.18	10.03	$759,229.26	448.88	1000.00	1590.97	4	32	128
7	33	600	8150.21	10.04	$759,321.48	467.56	1000.00	1590.97	4	32	128
7	34	600	8155.39	10.04	$759,416.40	486.53	1000.00	1590.97	4	32	128
7	35	600	8160.71	10.04	$759,514.00	505.81	1000.00	1590.97	4	32	128
7	36	600	10162.59	12.53	$948,415.28	488.87	1000.00	1590.97	5	32	160
7	37	600	10167.14	12.53	$948,498.62	506.57	1000.00	1590.97	5	32	160
7	38	600	10171.80	12.53	$948,584.12	524.51	1000.00	1590.97	5	32	160
7	39	600	10176.58	12.54	$948,671.77	542.69	1000.00	1590.97	5	32	160
7	40	600	10181.48	12.54	$948,761.57	561.10	1000.00	1590.97	5	32	160
7	41	600	10186.49	12.54	$948,853.53	579.75	1000.00	1590.97	5	32	160
7	42	600	10191.63	12.55	$948,947.63	598.64	1000.00	1590.97	5	32	160
7	43	600	10196.88	12.55	$949,043.89	617.76	1000.00	1590.97	5	32	160
7	44	600	10202.25	12.55	$949,142.31	637.12	1000.00	1590.97	5	32	160
7	45	600	12203.34	15.04	$1,138,029.32	618.61	1000.00	1590.97	6	32	192
7	46	600	12208.06	15.04	$1,138,115.72	636.65	1000.00	1590.97	6	32	192
7	47	600	12212.87	15.05	$1,138,203.90	654.89	1000.00	1590.97	6	32	192
7	48	600	12217.78	15.05	$1,138,293.89	673.32	1000.00	1590.97	6	32	192
7	49	600	12222.78	15.05	$1,138,385.66	691.95	1000.00	1590.97	6	32	192
7	50	600	12227.88	15.06	$1,138,479.23	710.78	1000.00	1590.97	6	32	192

Figure H-9.6 Single phase BJT input converter swith quantity characterization - Sheet 2 for 600 Hz switching frequency and variable power.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
2.5	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
0.998	0.000265	100	2

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	25	600	3.70	1881.28	1.62	0.98	2.61	0.74	0.06	0.12	0.18
7	26	600	3.90	1956.53	1.73	1.02	2.75	0.78	0.06	0.13	0.19
7	27	600	2.81	1523.84	1.16	0.80	1.95	0.58	0.06	0.08	0.14
7	28	600	2.95	1580.28	1.23	0.83	2.05	0.60	0.06	0.08	0.15
7	29	600	3.08	1636.72	1.30	0.85	2.15	0.63	0.06	0.09	0.16
7	30	600	3.22	1693.15	1.37	0.88	2.25	0.65	0.06	0.10	0.16
7	31	600	3.36	1749.59	1.44	0.91	2.36	0.68	0.06	0.10	0.17
7	32	600	3.51	1806.03	1.52	0.94	2.46	0.71	0.06	0.11	0.17
7	33	600	3.65	1862.47	1.60	0.97	2.57	0.73	0.06	0.12	0.18
7	34	600	3.80	1918.91	1.68	1.00	2.68	0.76	0.06	0.12	0.18
7	35	600	3.95	1975.35	1.76	1.03	2.79	0.79	0.06	0.13	0.19
7	36	600	3.06	1625.43	1.28	0.85	2.13	0.62	0.06	0.09	0.15
7	37	600	3.17	1670.58	1.34	0.87	2.21	0.64	0.06	0.09	0.16
7	38	600	3.28	1715.73	1.40	0.90	2.29	0.67	0.06	0.10	0.16
7	39	600	3.39	1760.88	1.46	0.92	2.38	0.69	0.06	0.10	0.17
7	40	600	3.51	1806.03	1.52	0.94	2.46	0.71	0.06	0.11	0.17
7	41	600	3.62	1851.18	1.58	0.97	2.55	0.73	0.06	0.11	0.18
7	42	600	3.74	1896.33	1.65	0.99	2.64	0.75	0.06	0.12	0.18
7	43	600	3.86	1941.48	1.71	1.01	2.72	0.77	0.06	0.13	0.18
7	44	600	3.98	1986.64	1.78	1.04	2.81	0.79	0.06	0.13	0.19
7	45	600	3.22	1693.15	1.37	0.88	2.25	0.65	0.06	0.10	0.16
7	46	600	3.32	1730.78	1.42	0.90	2.32	0.67	0.06	0.10	0.16
7	47	600	3.41	1768.41	1.47	0.92	2.39	0.69	0.06	0.10	0.17
7	48	600	3.51	1806.03	1.52	0.94	2.46	0.71	0.06	0.11	0.17
7	49	600	3.60	1843.66	1.57	0.96	2.53	0.72	0.06	0.11	0.18
7	50	600	3.70	1881.28	1.62	0.98	2.61	0.74	0.06	0.12	0.18

Figure H-9.7 Single phase BJT input converter switch loss estimation - Sheet 3 for 600 Hz switching frequency and variable power.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '50% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
5	5984	9.748	60	30.00	$75,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	25	60	25098.17	35.03	$270,940.94	107.81	33.03
7	26	60	25861.26	36.10	$278,178.67	111.09	34.37
7	27	60	26622.64	37.02	$286,318.47	113.93	35.56
7	28	60	27266.75	38.06	$294,351.32	117.13	36.89
7	29	60	28004.87	39.08	$302,320.52	120.30	38.22
7	30	60	28737.56	40.11	$310,228.99	123.44	39.56
7	31	60	29464.77	41.13	$318,079.44	126.57	40.90
7	32	60	30186.84	42.13	$325,874.37	129.67	42.24
7	33	60	30903.98	43.13	$333,616.13	132.75	43.59
7	34	60	31616.40	44.13	$341,306.87	135.81	44.93
7	35	60	32324.29	45.12	$348,948.64	138.85	46.28
7	36	60	32932.83	45.97	$356,518.02	141.46	47.44
7	37	60	33627.24	46.94	$363,014.30	144.45	48.78
7	38	60	34317.50	47.90	$370,465.88	147.41	50.12
7	39	60	35003.77	48.86	$377,874.36	150.36	51.46
7	40	60	35686.19	49.81	$385,241.19	153.29	52.81
7	41	60	36364.88	50.76	$392,567.79	156.21	54.15
7	42	60	37039.96	51.70	$399,855.49	159.11	55.49
7	43	60	37711.56	52.64	$407,105.53	161.99	56.84
7	44	60	38379.77	53.57	$414,319.10	164.86	58.19
7	45	60	38950.97	54.37	$420,485.30	167.32	59.34
7	46	60	39608.87	55.28	$427,587.51	170.14	60.68
7	47	60	40263.63	56.20	$434,655.78	172.95	62.02
7	48	60	40915.33	57.11	$441,691.10	175.76	63.37
7	49	60	41564.07	58.01	$448,694.39	178.54	64.71
7	50	60	42209.92	58.91	$455,666.53	181.31	66.05

Figure H-9.8 Single phase BJT input transformer sizing - Sheet 4 for 600 Hz switching frequency and variable power.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	10	100	19974.99	44.24	$1,043,761.15	185.00	147.39	98.18%	96.78%	0.98	15.40
7	10	150	20276.07	44.87	$1,064,115.59	214.56	170.94	97.90%	96.29%	0.97	14.91
7	10	200	20578.13	45.50	$1,084,537.25	244.22	194.57	97.62%	95.80%	0.96	14.44
7	10	250	20881.22	46.14	$1,105,028.73	273.98	218.28	97.33%	95.31%	0.96	13.99
7	10	300	21185.37	46.78	$1,125,592.74	303.84	242.07	97.05%	94.82%	0.95	13.55
7	10	350	21490.63	47.42	$1,146,232.14	333.81	265.95	96.77%	94.34%	0.94	13.13
7	10	400	21797.03	48.07	$1,166,949.92	363.89	289.91	96.49%	93.86%	0.93	12.72
7	10	450	22104.63	48.71	$1,187,749.22	394.10	313.98	96.21%	93.39%	0.92	12.32
7	10	500	22413.47	49.36	$1,208,633.33	424.42	338.14	95.93%	92.91%	0.91	11.94
7	10	550	22723.62	50.01	$1,229,605.72	454.88	362.40	95.65%	92.44%	0.90	11.57
7	10	600	23035.11	50.67	$1,250,670.01	485.47	386.77	95.37%	91.98%	0.89	11.22
7	10	650	23348.01	51.32	$1,271,830.02	516.19	411.25	95.09%	91.51%	0.88	10.87
7	10	700	23662.38	51.98	$1,293,089.78	547.06	435.84	94.81%	91.05%	0.88	10.54
7	10	750	23978.28	52.65	$1,314,453.50	578.08	460.56	94.54%	90.59%	0.87	10.22
7	10	800	29889.68	63.72	$2,082,670.00	974.35	776.26	91.12%	85.10%	0.86	19.82
7	10	850	30454.12	64.90	$2,120,544.50	1028.88	819.71	90.67%	84.40%	0.85	19.22
7	10	900	31019.53	66.07	$2,158,487.41	1083.50	863.23	90.22%	83.70%	0.84	18.64
7	10	950	31585.95	67.25	$2,196,501.66	1138.24	906.83	89.78%	83.02%	0.83	18.08
7	10	1000	32153.42	68.43	$2,234,590.39	1193.08	950.53	89.34%	82.35%	0.82	17.54
7	10	1050	32722.00	69.61	$2,272,756.85	1248.03	994.31	88.90%	81.68%	0.81	17.02
7	10	1100	33291.73	70.79	$2,311,004.52	1303.11	1038.19	88.47%	81.03%	0.81	16.51
7	10	1150	33862.67	71.98	$2,349,337.03	1358.31	1082.16	88.04%	80.38%	0.80	16.02
7	10	1200	34434.89	73.17	$2,387,758.24	1413.63	1126.24	87.61%	79.75%	0.79	15.55
7	10	1250	35008.43	74.36	$2,426,272.23	1469.10	1170.43	87.19%	79.12%	0.78	15.09
7	10	1300	35583.37	75.56	$2,464,883.28	1524.70	1214.73	86.77%	78.50%	0.77	14.65
7	10	1350	36159.77	76.75	$2,503,595.95	1580.45	1259.15	86.35%	77.88%	0.76	14.22

Figure H-10.1 Three phase GTO input converter summary - Sheet 1 for 10 MW output power and variable switching frequency.

GTO PARAMETERS							
VOLTAGE RATING (kV)	POWER DISS PER GTO (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS PER AMP (J/A)	FIXED SW LOSS (J)	MINIMUM OFF TIME (s)	MAXIMUM Itgq (A)
6	2900	1.77	0.00118	0.003167	1.05	1.77E-04	3000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
21.15	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$9,304.40	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	10	100	245.18	0.27	$32,925.32	22.08	2031.19	1606.25	1	3	3
7	10	150	272.73	0.29	$33,430.40	26.98	1984.87	1562.53	1	3	3
7	10	200	300.38	0.30	$33,937.18	31.91	1939.91	1520.18	1	3	3
7	10	250	328.12	0.32	$34,445.72	36.85	1896.29	1479.17	1	3	3
7	10	300	355.95	0.34	$34,956.11	41.81	1853.98	1439.45	1	3	3
7	10	350	383.90	0.36	$35,468.40	46.78	1812.95	1401.00	1	3	3
7	10	400	411.95	0.38	$35,982.68	51.78	1773.16	1363.78	1	3	3
7	10	450	440.11	0.39	$36,499.02	56.79	1734.59	1327.74	1	3	3
7	10	500	468.39	0.41	$37,017.51	61.83	1697.19	1292.85	1	3	3
7	10	550	496.80	0.43	$37,538.24	66.88	1660.93	1259.08	1	3	3
7	10	600	525.33	0.45	$38,061.29	71.96	1625.79	1226.38	1	3	3
7	10	650	553.99	0.47	$38,586.77	77.06	1591.72	1194.72	1	3	3
7	10	700	582.79	0.48	$39,114.78	82.19	1558.70	1164.07	1	3	3
7	10	750	611.74	0.50	$39,645.42	87.34	1526.69	1134.39	1	3	3
7	10	800	1202.79	0.99	$77,811.75	153.13	1495.66	1105.65	2	3	6
7	10	850	1254.83	1.03	$78,765.78	162.18	1465.57	1077.81	2	3	6
7	10	900	1306.97	1.06	$79,721.59	171.25	1436.41	1050.84	2	3	6
7	10	950	1359.20	1.09	$80,679.25	180.34	1408.12	1024.72	2	3	6
7	10	1000	1411.54	1.13	$81,638.85	189.45	1380.70	999.40	2	3	6
7	10	1050	1464.00	1.16	$82,600.46	198.57	1354.10	974.86	2	3	6
7	10	1100	1516.56	1.19	$83,564.17	207.72	1328.29	951.07	2	3	6
7	10	1150	1569.25	1.23	$84,530.08	216.88	1303.26	928.01	2	3	6
7	10	1200	1622.06	1.26	$85,498.28	226.07	1278.97	905.64	2	3	6
7	10	1250	1675.00	1.30	$86,468.88	235.28	1255.40	883.94	2	3	6
7	10	1300	1728.08	1.33	$87,441.99	244.51	1232.52	862.88	2	3	6
7	10	1350	1781.30	1.36	$88,417.72	253.77	1210.31	842.45	2	3	6

Figure H-10.2 Three phase GTO input converter switch quantity characterization - Sheet 2 for 10 MW output power and variable switching frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
6	2.4

ANTI-PARALLEL DIODE PARAMETERS		
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)
1.1	0.001583	380

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	10	100	7.36	1318.92	1.37	0.18	1.55	1.31	2.70	0.35	1.44
7	10	150	8.99	1330.91	1.38	0.27	1.65	1.32	4.05	0.53	1.44
7	10	200	10.64	1343.12	1.38	0.37	1.75	1.33	5.40	0.71	1.44
7	10	250	12.28	1355.55	1.39	0.46	1.85	1.34	6.75	0.90	1.44
7	10	300	13.94	1368.22	1.40	0.55	1.95	1.35	8.10	1.10	1.44
7	10	350	15.59	1381.13	1.40	0.64	2.04	1.36	9.45	1.30	1.44
7	10	400	17.26	1394.29	1.41	0.73	2.14	1.36	10.80	1.51	1.44
7	10	450	18.93	1407.69	1.41	0.82	2.24	1.37	12.15	1.73	1.44
7	10	500	20.61	1421.36	1.42	0.92	2.34	1.38	13.50	1.95	1.44
7	10	550	22.29	1435.30	1.43	1.01	2.44	1.39	14.85	2.17	1.44
7	10	600	23.99	1449.51	1.44	1.10	2.53	1.40	16.20	2.41	1.44
7	10	650	25.69	1464.00	1.44	1.19	2.63	1.41	17.55	2.65	1.44
7	10	700	27.40	1478.79	1.45	1.28	2.73	1.42	18.90	2.90	1.44
7	10	750	29.11	1493.88	1.46	1.37	2.83	1.43	20.25	3.16	1.44
7	10	800	25.52	754.64	0.55	0.94	1.49	0.47	21.60	1.24	0.72
7	10	850	27.03	762.50	0.55	1.00	1.55	0.48	22.95	1.33	0.72
7	10	900	28.54	770.53	0.55	1.06	1.61	0.48	24.30	1.43	0.72
7	10	950	30.06	778.73	0.55	1.12	1.67	0.48	25.65	1.53	0.72
7	10	1000	31.57	787.10	0.56	1.18	1.73	0.48	27.00	1.63	0.72
7	10	1050	33.10	795.66	0.56	1.24	1.80	0.49	28.35	1.74	0.72
7	10	1100	34.62	804.40	0.56	1.30	1.86	0.49	29.70	1.85	0.72
7	10	1150	36.15	813.34	0.56	1.35	1.92	0.49	31.05	1.97	0.72
7	10	1200	37.68	822.48	0.57	1.41	1.98	0.50	32.40	2.08	0.72
7	10	1250	39.21	831.83	0.57	1.47	2.04	0.50	33.75	2.20	0.72
7	10	1300	40.75	841.39	0.57	1.53	2.10	0.50	35.10	2.33	0.72
7	10	1350	42.29	851.17	0.57	1.59	2.16	0.50	36.45	2.46	0.72

Figure H-10.3 Three phase GTO input converter switch loss estimation - Sheet 3 for 10 MW output power and variable switching frequency.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '50% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
6	6984	9.748	60	30.00	$75,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	10	60	12230.94	17.07	$132,035.96	52.54	12.67
7	10	60	12257.58	17.11	$132,323.62	52.65	12.70
7	10	60	12284.30	17.15	$132,612.01	52.77	12.74
7	10	60	12311.08	17.18	$132,901.18	52.88	12.78
7	10	60	12337.95	17.22	$133,191.17	53.00	12.81
7	10	60	12364.89	17.26	$133,482.01	53.11	12.85
7	10	60	12391.91	17.30	$133,773.74	53.23	12.89
7	10	60	12419.02	17.33	$134,066.40	53.35	12.93
7	10	60	12446.22	17.37	$134,360.04	53.46	12.96
7	10	60	12473.52	17.41	$134,654.70	53.58	13.00
7	10	60	12500.91	17.45	$134,950.44	53.70	13.04
7	10	60	12528.41	17.49	$135,247.30	53.82	13.08
7	10	60	12556.02	17.53	$135,545.33	53.93	13.12
7	10	60	12583.74	17.56	$135,844.60	54.05	13.16
7	10	60	12936.12	18.06	$139,648.58	55.57	13.65
7	10	60	12984.36	18.12	$140,169.31	55.77	13.72
7	10	60	13032.62	18.19	$140,690.36	55.98	13.78
7	10	60	13080.92	18.26	$141,211.76	56.19	13.85
7	10	60	13129.26	18.33	$141,733.56	56.40	13.92
7	10	60	13177.63	18.39	$142,255.81	56.60	13.99
7	10	60	13226.06	18.46	$142,778.54	56.81	14.06
7	10	60	13274.53	18.53	$143,301.82	57.02	14.13
7	10	60	13323.06	18.60	$143,825.69	57.23	14.20
7	10	60	13371.65	18.66	$144,350.20	57.44	14.26
7	10	60	13420.30	18.73	$144,875.42	57.65	14.33
7	10	60	13469.02	18.80	$145,401.40	57.86	14.40

Figure H-10.4 Three phase GTO input transformer sizing - Sheet 4 for 10 MW output power and variable switching frequency.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS									
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	25	600	50109.03	100.28	$3,086,620.10	1312.41	1045.59	95.01%	91.38%	0.89	33.65
7	26	600	51203.19	102.31	$3,116,901.36	1332.76	1061.81	95.12%	91.57%	0.89	33.65
7	27	600	52290.11	104.34	$3,147,190.29	1353.47	1078.31	95.23%	91.74%	0.89	33.65
7	28	600	53370.21	106.36	$3,177,495.73	1374.53	1095.08	95.32%	91.89%	0.89	33.65
7	29	600	54443.87	108.37	$3,207,825.85	1395.94	1112.15	95.41%	92.04%	0.89	33.65
7	30	600	55511.44	110.37	$3,238,188.22	1417.71	1129.49	95.49%	92.17%	0.89	33.65
7	31	600	56573.27	112.36	$3,268,589.84	1439.84	1147.12	95.56%	92.30%	0.89	33.65
7	32	600	57629.66	114.35	$3,299,037.21	1462.32	1165.03	95.63%	92.41%	0.89	33.65
7	33	600	58680.89	116.33	$3,329,536.41	1485.16	1183.23	95.69%	92.52%	0.89	33.65
7	34	600	64084.69	126.06	$4,024,761.64	1753.33	1396.88	95.10%	91.52%	0.89	44.86
7	35	600	65105.16	127.97	$4,053,540.77	1773.60	1413.03	95.18%	91.66%	0.89	44.86
7	36	600	66120.74	129.88	$4,082,337.36	1794.14	1429.39	95.25%	91.78%	0.89	44.86
7	37	600	67131.67	131.78	$4,111,156.00	1814.94	1445.96	95.32%	91.90%	0.89	44.86
7	38	600	68138.13	133.67	$4,140,001.02	1836.01	1462.75	95.39%	92.01%	0.89	44.86
7	39	600	69140.34	135.55	$4,168,876.48	1857.35	1479.75	95.45%	92.12%	0.89	44.86
7	40	600	70138.45	137.44	$4,197,786.21	1878.95	1496.96	95.51%	92.22%	0.89	44.86
7	41	600	71132.66	139.31	$4,226,733.86	1900.83	1514.39	95.57%	92.31%	0.89	44.86
7	42	600	72123.11	141.19	$4,255,722.86	1922.97	1532.03	95.62%	92.40%	0.89	44.86
7	43	600	73109.97	143.06	$4,284,756.47	1945.39	1549.89	95.67%	92.48%	0.89	44.86
7	44	600	74093.38	144.92	$4,313,837.78	1968.07	1567.96	95.72%	92.56%	0.89	44.86
7	45	600	79398.84	154.46	$5,005,769.06	2233.13	1779.14	95.27%	91.81%	0.89	56.08
7	46	600	80359.25	156.27	$5,033,504.68	2253.75	1795.57	95.33%	91.91%	0.89	56.08
7	47	600	81316.33	158.08	$5,061,266.19	2274.59	1812.17	95.38%	92.00%	0.89	56.08
7	48	600	82270.18	159.88	$5,089,056.10	2295.64	1828.94	95.44%	92.09%	0.89	56.08
7	49	600	83220.93	161.68	$5,116,876.79	2316.91	1845.88	95.49%	92.17%	0.89	56.08
7	50	600	84168.68	163.48	$5,144,730.57	2338.39	1863.00	95.53%	92.25%	0.89	56.08

Figure H-10.5 Three phase GTO input converter summary - Sheet 1 for 600 Hz switching frequency and variable power.

GTO PARAMETERS							
VOLTAGE RATING (kV)	POWER DISS PER GTO (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS PER AMP (J/A)	FIXED SW LOSS (J)	MINIMUM OFF TIME (s)	MAXIMUM Itgq (A)
6	2900	1.77	0.00118	0.003167	1.05	1.77E-04	3000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
21.15	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$9,304.40	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL(Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	25	600	1543.89	1.32	$111,395.39	200.88	1625.79	1226.38	3	3	9
7	26	600	1549.94	1.33	$111,506.43	203.75	1625.79	1226.38	3	3	9
7	27	600	1556.18	1.33	$111,620.80	206.69	1625.79	1226.38	3	3	9
7	28	600	1562.60	1.34	$111,738.50	209.69	1625.79	1226.38	3	3	9
7	29	600	1569.20	1.34	$111,859.52	212.76	1625.79	1226.38	3	3	9
7	30	600	1575.99	1.34	$111,983.87	215.88	1625.79	1226.38	3	3	9
7	31	600	1582.95	1.35	$112,111.56	219.08	1625.79	1226.38	3	3	9
7	32	600	1590.10	1.35	$112,242.57	222.33	1625.79	1226.38	3	3	9
7	33	600	1597.42	1.36	$112,376.90	225.65	1625.79	1226.38	3	3	9
7	34	600	2062.52	1.77	$148,233.99	269.74	1625.79	1226.38	4	3	12
7	35	600	2068.65	1.77	$148,346.28	272.64	1625.79	1226.38	4	3	12
7	36	600	2074.91	1.78	$148,461.06	275.59	1625.79	1226.38	4	3	12
7	37	600	2081.31	1.78	$148,578.35	278.58	1625.79	1226.38	4	3	12
7	38	600	2087.84	1.78	$148,698.12	281.62	1625.79	1226.38	4	3	12
7	39	600	2094.51	1.79	$148,820.40	284.71	1625.79	1226.38	4	3	12
7	40	600	2101.31	1.79	$148,945.17	287.85	1625.79	1226.38	4	3	12
7	41	600	2108.26	1.80	$149,072.43	291.03	1625.79	1226.38	4	3	12
7	42	600	2115.33	1.80	$149,202.19	294.26	1625.79	1226.38	4	3	12
7	43	600	2122.55	1.81	$149,334.45	297.54	1625.79	1226.38	4	3	12
7	44	600	2129.90	1.81	$149,469.21	300.86	1625.79	1226.38	4	3	12
7	45	600	2593.64	2.22	$185,301.33	344.48	1625.79	1226.38	5	3	15
7	46	600	2600.02	2.22	$185,418.36	347.47	1625.79	1226.38	5	3	15
7	47	600	2606.51	2.23	$185,537.39	350.50	1625.79	1226.38	5	3	15
7	48	600	2613.11	2.23	$185,658.42	353.56	1625.79	1226.38	5	3	15
7	49	600	2619.82	2.24	$185,781.44	356.67	1625.79	1226.38	5	3	15
7	50	600	2626.64	2.24	$185,906.46	359.81	1625.79	1226.38	5	3	15

Figure H-10.6 Three phase GTO input converter switch quantity characterization - Sheet 2 for 600 Hz switching frequency and variable power.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dl/dt SNUBBER INDUCTOR (uH)
6	2.4

ANTI-PARALLEL DIODE PARAMETERS		
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)
1.1	0.001583	380

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	25	600	22.32	1207.92	1.10	0.97	2.07	1.04	16.20	1.82	1.20
7	26	600	22.64	1256.24	1.16	0.99	2.16	1.10	16.20	1.93	1.25
7	27	600	22.97	1304.56	1.23	1.02	2.25	1.17	16.20	2.04	1.30
7	28	600	23.30	1352.87	1.30	1.05	2.34	1.25	16.20	2.16	1.35
7	29	600	23.64	1401.19	1.36	1.07	2.44	1.32	16.20	2.28	1.40
7	30	600	23.99	1449.51	1.44	1.10	2.53	1.40	16.20	2.41	1.44
7	31	600	24.34	1497.83	1.51	1.12	2.63	1.48	16.20	2.54	1.49
7	32	600	24.70	1546.14	1.58	1.15	2.73	1.56	16.20	2.67	1.54
7	33	600	25.07	1594.46	1.66	1.18	2.83	1.64	16.20	2.81	1.59
7	34	600	22.48	1232.08	1.13	0.98	2.11	1.07	16.20	1.87	1.23
7	35	600	22.72	1268.32	1.18	1.00	2.18	1.12	16.20	1.96	1.26
7	36	600	22.97	1304.56	1.23	1.02	2.25	1.17	16.20	2.04	1.30
7	37	600	23.21	1340.80	1.28	1.04	2.32	1.23	16.20	2.13	1.34
7	38	600	23.47	1377.03	1.33	1.06	2.39	1.28	16.20	2.22	1.37
7	39	600	23.73	1413.27	1.38	1.08	2.46	1.34	16.20	2.32	1.41
7	40	600	23.99	1449.51	1.44	1.10	2.53	1.40	16.20	2.41	1.44
7	41	600	24.25	1485.75	1.49	1.12	2.61	1.46	16.20	2.51	1.48
7	42	600	24.52	1521.98	1.54	1.14	2.68	1.52	16.20	2.60	1.52
7	43	600	24.79	1558.22	1.60	1.16	2.76	1.58	16.20	2.70	1.55
7	44	600	25.07	1594.46	1.66	1.18	2.83	1.64	16.20	2.81	1.59
7	45	600	22.97	1304.56	1.23	1.02	2.25	1.17	16.20	2.04	1.30
7	46	600	23.16	1333.55	1.27	1.04	2.30	1.22	16.20	2.11	1.33
7	47	600	23.37	1362.54	1.31	1.05	2.36	1.26	16.20	2.19	1.36
7	48	600	23.57	1391.53	1.35	1.07	2.42	1.31	16.20	2.26	1.39
7	49	600	23.78	1420.52	1.39	1.08	2.48	1.35	16.20	2.33	1.41
7	50	600	23.99	1449.51	1.44	1.10	2.53	1.40	16.20	2.41	1.44

Figure H-10.7 Three phase GTO input converter switch loss estimation - Sheet 3 for 600 Hz switching frequency and variable power.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '50% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
6	6984	9.748	60	30.00	$75,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	25	60	24943.92	34.82	$269,275.71	107.15	32.78
7	26	60	25666.66	35.82	$277,077.94	110.25	34.03
7	27	60	26382.95	36.82	$284,810.48	113.33	35.30
7	28	60	27093.08	37.82	$292,476.49	116.38	36.57
7	29	60	27797.32	38.80	$300,078.92	119.40	37.85
7	30	60	28495.92	39.77	$307,620.48	122.41	39.12
7	31	60	29189.11	40.74	$315,103.67	125.38	40.39
7	32	60	29877.12	41.70	$322,530.84	128.34	41.67
7	33	60	30560.13	42.65	$329,904.16	131.27	42.94
7	34	60	31399.99	43.83	$338,970.65	134.88	44.52
7	35	60	32070.29	44.76	$346,206.70	137.76	45.79
7	36	60	32736.14	45.69	$353,394.68	140.62	47.07
7	37	60	33397.69	46.62	$360,536.25	143.46	48.34
7	38	60	34055.08	47.53	$367,632.95	146.28	49.61
7	39	60	34708.45	48.44	$374,686.23	149.09	50.89
7	40	60	35357.92	49.35	$381,697.48	151.88	52.16
7	41	60	36003.63	50.25	$388,668.00	154.65	53.43
7	42	60	36645.67	51.15	$395,599.03	157.41	54.71
7	43	60	37284.16	52.04	$402,491.73	160.16	55.98
7	44	60	37919.21	52.93	$409,347.22	162.88	57.26
7	45	60	38699.91	54.02	$417,775.07	166.24	58.83
7	46	60	39325.96	54.89	$424,533.45	168.93	60.11
7	47	60	39948.85	55.76	$431,257.65	171.60	61.38
7	48	60	40568.65	56.62	$437,948.57	174.26	62.66
7	49	60	41185.45	57.49	$444,607.08	176.91	63.92
7	50	60	41799.32	58.34	$451,233.99	179.55	65.20

Figure H-10.8 Three phase GTO input transformer sizing - Sheet 4 for 600 Hz switching frequency and variable power.

CONVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	10	100	21608.75	45.11	$1,859,267.20	251.97	200.75	97.54%	95.67%	0.9997	15.11
7	10	150	21622.95	45.15	$1,860,414.18	253.92	202.29	97.52%	95.64%	0.9996	15.05
7	10	200	21637.15	45.19	$1,861,561.36	255.86	203.84	97.51%	95.61%	0.9994	15.00
7	10	250	21651.36	45.22	$1,862,708.73	257.80	205.39	97.49%	95.57%	0.9993	14.95
7	10	300	21665.57	45.26	$1,863,856.30	259.74	206.94	97.47%	95.54%	0.9991	14.90
7	10	350	21679.78	45.30	$1,865,004.07	261.68	208.48	97.45%	95.51%	0.9990	14.85
7	10	400	21694.00	45.34	$1,866,152.03	263.63	210.03	97.43%	95.48%	0.9988	14.80
7	10	450	21708.22	45.37	$1,867,300.20	265.57	211.58	97.41%	95.45%	0.9987	14.75
7	10	500	21722.44	45.41	$1,868,448.56	267.51	213.13	97.39%	95.41%	0.9985	14.69
7	10	550	21736.66	45.45	$1,869,597.12	269.46	214.68	97.38%	95.38%	0.9984	14.64
7	10	600	21750.89	45.49	$1,870,745.88	271.40	216.23	97.36%	95.35%	0.9982	14.59
7	10	650	21765.12	45.52	$1,871,894.83	273.35	217.78	97.34%	95.32%	0.9981	14.54
7	10	700	21779.35	45.56	$1,873,043.99	275.29	219.32	97.32%	95.29%	0.9979	14.49
7	10	750	21793.59	45.60	$1,874,193.34	277.24	220.87	97.30%	95.26%	0.9978	14.44
7	10	800	21807.82	45.63	$1,875,342.90	279.18	222.42	97.28%	95.22%	0.9976	14.40
7	10	850	21822.07	45.67	$1,876,492.65	281.13	223.97	97.27%	95.19%	0.9975	14.35
7	10	900	21836.31	45.71	$1,877,642.60	283.07	225.52	97.25%	95.16%	0.9973	14.30
7	10	950	21850.56	45.75	$1,878,792.75	285.02	227.08	97.23%	95.13%	0.9972	14.25
7	10	1000	21864.81	45.78	$1,879,943.10	286.97	228.63	97.21%	95.10%	0.9970	14.20
7	10	1050	21879.06	45.82	$1,881,093.65	288.91	230.18	97.19%	95.07%	0.9969	14.15
7	10	1100	21893.32	45.86	$1,882,244.40	290.86	231.73	97.17%	95.03%	0.9967	14.10
7	10	1150	21907.58	45.90	$1,883,395.35	292.81	233.28	97.16%	95.00%	0.9966	14.06
7	10	1200	21921.84	45.93	$1,884,546.50	294.75	234.83	97.14%	94.97%	0.9964	14.01
7	10	1250	21936.10	45.97	$1,885,697.85	296.70	236.38	97.12%	94.94%	0.9963	13.96
7	10	1300	21950.37	46.01	$1,886,849.40	298.65	237.94	97.10%	94.91%	0.9961	13.91
7	10	1350	21964.64	46.05	$1,888,001.15	300.60	239.49	97.08%	94.88%	0.9960	13.87

Figure H-11.1 Three phase IGBT input converter summary - Sheet 1 for 10 MW output power and variable switching frequency.

IGBT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER IGBT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	IGBTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itgq
1	187.5	0.9	0.0106	0.000346	0	10	3.00E-06	300

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
7.73	2	0.00819	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$4,090.19	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	10	100	419.73	0.25	$82,821.02	33.20	195.77	1561.79	1	18	18
7	10	150	420.88	0.25	$82,842.16	33.52	195.12	1556.51	1	18	18
7	10	200	422.03	0.26	$82,863.30	33.84	194.48	1551.25	1	18	18
7	10	250	423.18	0.26	$82,884.45	34.16	193.84	1546.01	1	18	18
7	10	300	424.34	0.26	$82,905.61	34.49	193.20	1540.80	1	18	18
7	10	350	425.49	0.26	$82,926.77	34.81	192.56	1535.61	1	18	18
7	10	400	426.65	0.26	$82,947.93	35.13	191.93	1530.43	1	18	18
7	10	450	427.80	0.26	$82,969.10	35.45	191.30	1525.28	1	18	18
7	10	500	428.96	0.26	$82,990.27	35.78	190.67	1520.16	1	18	18
7	10	550	430.11	0.26	$83,011.45	36.10	190.04	1515.05	1	18	18
7	10	600	431.27	0.26	$83,032.64	36.42	189.42	1509.96	1	18	18
7	10	650	432.42	0.26	$83,053.83	36.74	188.80	1504.90	1	18	18
7	10	700	433.58	0.26	$83,075.02	37.07	188.18	1499.86	1	18	18
7	10	750	434.74	0.26	$83,096.22	37.39	187.56	1494.84	1	18	18
7	10	800	435.89	0.26	$83,117.43	37.71	186.95	1489.84	1	18	18
7	10	850	437.05	0.27	$83,138.64	38.04	186.34	1484.86	1	18	18
7	10	900	438.21	0.27	$83,159.85	38.36	185.73	1479.90	1	18	18
7	10	950	439.36	0.27	$83,181.07	38.68	185.12	1474.97	1	18	18
7	10	1000	440.52	0.27	$83,202.30	39.01	184.52	1470.05	1	18	18
7	10	1050	441.68	0.27	$83,223.53	39.33	183.92	1465.16	1	18	18
7	10	1100	442.84	0.27	$83,244.77	39.65	183.32	1460.29	1	18	18
7	10	1150	444.00	0.27	$83,266.01	39.98	182.73	1455.44	1	18	18
7	10	1200	445.16	0.27	$83,287.25	40.30	182.13	1450.60	1	18	18
7	10	1250	446.32	0.27	$83,308.50	40.62	181.54	1445.80	1	18	18
7	10	1300	447.47	0.27	$83,329.76	40.95	180.96	1441.01	1	18	18
7	10	1350	448.63	0.27	$83,351.02	41.27	180.37	1436.24	1	18	18

Figure H-11.2 Three phase IGBT input converter switch quantity characterization - Sheet 2 for 10 MW output power and variable switching frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
1	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
1.6	0.00556	34	34

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	10	100	1.84	1295.96	0.94	0.01	0.95	0.75	0.01	0.01	0.12
7	10	150	1.86	1296.15	0.94	0.02	0.96	0.75	0.02	0.01	0.12
7	10	200	1.88	1296.35	0.94	0.03	0.97	0.75	0.03	0.02	0.12
7	10	250	1.90	1296.54	0.94	0.04	0.97	0.75	0.03	0.02	0.12
7	10	300	1.92	1296.74	0.94	0.04	0.98	0.75	0.04	0.03	0.12
7	10	350	1.93	1296.93	0.94	0.05	0.99	0.75	0.04	0.03	0.12
7	10	400	1.95	1297.13	0.94	0.06	1.00	0.75	0.05	0.04	0.12
7	10	450	1.97	1297.32	0.94	0.06	1.00	0.75	0.06	0.04	0.12
7	10	500	1.99	1297.52	0.94	0.07	1.01	0.75	0.06	0.04	0.12
7	10	550	2.01	1297.71	0.94	0.08	1.02	0.75	0.07	0.05	0.12
7	10	600	2.02	1297.91	0.94	0.09	1.02	0.75	0.08	0.05	0.12
7	10	650	2.04	1298.10	0.94	0.09	1.03	0.75	0.08	0.06	0.12
7	10	700	2.06	1298.30	0.94	0.10	1.04	0.75	0.09	0.06	0.12
7	10	750	2.08	1298.49	0.94	0.11	1.05	0.75	0.09	0.07	0.12
7	10	800	2.10	1298.69	0.94	0.11	1.05	0.75	0.10	0.07	0.12
7	10	850	2.11	1298.88	0.94	0.12	1.06	0.75	0.11	0.08	0.12
7	10	900	2.13	1299.08	0.94	0.13	1.07	0.75	0.11	0.08	0.12
7	10	950	2.15	1299.27	0.94	0.14	1.07	0.75	0.12	0.08	0.12
7	10	1000	2.17	1299.47	0.94	0.14	1.08	0.75	0.13	0.09	0.12
7	10	1050	2.18	1299.66	0.94	0.15	1.09	0.75	0.13	0.09	0.12
7	10	1100	2.20	1299.86	0.94	0.16	1.10	0.75	0.14	0.10	0.12
7	10	1150	2.22	1300.06	0.94	0.16	1.10	0.75	0.14	0.10	0.12
7	10	1200	2.24	1300.25	0.94	0.17	1.11	0.75	0.15	0.11	0.12
7	10	1250	2.26	1300.45	0.94	0.18	1.12	0.75	0.16	0.11	0.12
7	10	1300	2.27	1300.64	0.94	0.19	1.13	0.75	0.16	0.12	0.12
7	10	1350	2.29	1300.84	0.94	0.19	1.13	0.75	0.17	0.12	0.12

Figure H-11.3 Three phase IGBT input converter switch loss estimation - Sheet 3 for 10 MW output power and variable switching frequency.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '50% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
6	6984	9.748	60	30.00	$75,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	10	60	12291.28	17.16	$132,687.40	52.80	12.75
7	10	60	12293.03	17.16	$132,706.27	52.81	12.75
7	10	60	12294.78	17.16	$132,725.14	52.81	12.75
7	10	60	12296.52	17.16	$132,744.01	52.82	12.76
7	10	60	12298.27	17.17	$132,762.89	52.83	12.76
7	10	60	12300.02	17.17	$132,781.77	52.84	12.76
7	10	60	12301.77	17.17	$132,800.65	52.84	12.76
7	10	60	12303.52	17.17	$132,819.53	52.85	12.77
7	10	60	12305.27	17.18	$132,838.42	52.86	12.77
7	10	60	12307.02	17.18	$132,857.30	52.87	12.77
7	10	60	12308.77	17.18	$132,876.19	52.87	12.77
7	10	60	12310.52	17.18	$132,895.08	52.88	12.78
7	10	60	12312.27	17.18	$132,913.97	52.89	12.78
7	10	60	12314.02	17.19	$132,932.87	52.90	12.78
7	10	60	12315.77	17.19	$132,951.76	52.90	12.78
7	10	60	12317.52	17.19	$132,970.66	52.91	12.79
7	10	60	12319.27	17.19	$132,989.56	52.92	12.79
7	10	60	12321.02	17.20	$133,008.46	52.93	12.79
7	10	60	12322.77	17.20	$133,027.36	52.93	12.79
7	10	60	12324.52	17.20	$133,046.27	52.94	12.79
7	10	60	12326.27	17.20	$133,065.17	52.95	12.80
7	10	60	12328.03	17.21	$133,084.08	52.96	12.80
7	10	60	12329.78	17.21	$133,102.99	52.96	12.80
7	10	60	12331.53	17.21	$133,121.90	52.97	12.80
7	10	60	12333.28	17.21	$133,140.82	52.98	12.81
7	10	60	12335.03	17.22	$133,159.74	52.99	12.81

Figure H-11.4 Three phase IGBT input transformer sizing - Sheet 4 for 10 MW output power and variable switching frequency.

CONVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	25	600	43138.77	82.95	$3,678,561.25	695.14	553.82	97.29%	95.24%	0.9982	29.19
7	26	600	44230.92	85.19	$3,714,098.85	731.17	582.52	97.26%	95.19%	0.9982	29.19
7	27	600	45314.94	87.44	$3,749,753.68	767.92	611.80	97.23%	95.14%	0.9982	29.19
7	28	600	46391.28	89.67	$3,785,535.27	805.41	641.67	97.20%	95.09%	0.9982	29.19
7	29	600	47460.37	91.90	$3,821,452.38	843.64	672.13	97.17%	95.03%	0.9982	29.19
7	30	600	51855.21	95.16	$5,102,580.70	776.11	618.33	97.48%	95.56%	0.9982	43.78
7	31	600	52891.80	97.27	$5,135,444.66	808.05	643.77	97.46%	95.53%	0.9982	43.78
7	32	600	53921.62	99.37	$5,168,358.12	840.47	669.60	97.44%	95.49%	0.9982	43.78
7	33	600	54944.98	101.47	$5,201,327.55	873.38	695.82	97.42%	95.46%	0.9982	43.78
7	34	600	55962.17	103.56	$5,234,358.97	906.77	722.43	97.40%	95.43%	0.9982	43.78
7	35	600	56973.43	105.65	$5,267,458.01	940.65	749.42	97.38%	95.39%	0.9982	43.78
7	36	600	57979.04	107.73	$5,300,629.94	975.02	776.80	97.36%	95.36%	0.9982	43.78
7	37	600	58979.21	109.81	$5,333,879.68	1009.88	804.57	97.34%	95.33%	0.9982	43.78
7	38	600	59974.17	111.89	$5,367,211.88	1045.23	832.74	97.32%	95.29%	0.9982	43.78
7	39	600	60964.12	113.96	$5,400,630.89	1081.07	861.29	97.30%	95.26%	0.9982	43.78
7	40	600	61949.25	116.03	$5,434,140.83	1117.40	890.23	97.28%	95.22%	0.9982	43.78
7	41	600	62929.76	118.10	$5,467,745.56	1154.22	919.57	97.26%	95.19%	0.9982	43.78
7	42	600	63905.80	120.16	$5,501,448.76	1191.53	949.30	97.24%	95.15%	0.9982	43.78
7	43	600	64877.55	122.22	$5,535,253.88	1229.34	979.42	97.22%	95.11%	0.9982	43.78
7	44	600	69165.73	125.20	$6,810,694.76	1152.52	918.21	97.45%	95.51%	0.9982	58.38
7	45	600	70115.86	127.17	$6,842,280.47	1185.65	944.61	97.43%	95.48%	0.9982	58.38
7	46	600	71061.87	129.15	$6,873,923.37	1219.14	971.29	97.42%	95.45%	0.9982	58.38
7	47	600	72003.87	131.12	$6,905,626.29	1253.00	998.27	97.40%	95.43%	0.9982	58.38
7	48	600	72942.01	133.08	$6,937,391.92	1287.23	1025.54	97.39%	95.40%	0.9982	58.38
7	49	600	73876.41	135.05	$6,969,222.82	1321.83	1053.10	97.37%	95.38%	0.9982	58.38
7	50	600	74807.16	137.01	$7,001,121.42	1356.79	1080.96	97.36%	95.35%	0.9982	58.38

Figure H-11.5 Three phase IGBT input converter summary - Sheet 1 for 600 Hz switching frequency and variable power.

IGBT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER IGBT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	IGBTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itqq
1	187.5	0.9	0.0106	0.000346	0	10	3.00E-06	300

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
7.73	2	0.00819	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$4,090.19	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	25	600	868.82	0.53	$165,080.46	98.31	189.42	1509.96	2	18	36
7	26	600	870.24	0.53	$165,106.50	103.79	189.42	1509.96	2	18	36
7	27	600	871.71	0.53	$165,133.55	109.39	189.42	1509.96	2	18	36
7	28	600	873.24	0.53	$165,161.59	115.12	189.42	1509.96	2	18	36
7	29	600	874.83	0.53	$165,190.63	120.98	189.42	1509.96	2	18	36
7	30	600	1293.80	0.78	$246,897.91	109.26	189.42	1509.96	3	18	54
7	31	600	1294.94	0.79	$246,918.78	114.08	189.42	1509.96	3	18	54
7	32	600	1296.12	0.79	$246,940.32	118.99	189.42	1509.96	3	18	54
7	33	600	1297.33	0.79	$246,962.52	123.98	189.42	1509.96	3	18	54
7	34	600	1298.57	0.79	$246,985.39	129.05	189.42	1509.96	3	18	54
7	35	600	1299.86	0.79	$247,008.93	134.21	189.42	1509.96	3	18	54
7	36	600	1301.18	0.79	$247,033.14	139.45	189.42	1509.96	3	18	54
7	37	600	1302.54	0.79	$247,058.01	144.78	189.42	1509.96	3	18	54
7	38	600	1303.93	0.79	$247,083.55	150.19	189.42	1509.96	3	18	54
7	39	600	1305.36	0.79	$247,109.76	155.69	189.42	1509.96	3	18	54
7	40	600	1306.82	0.79	$247,136.63	161.27	189.42	1509.96	3	18	54
7	41	600	1308.33	0.79	$247,164.17	166.93	189.42	1509.96	3	18	54
7	42	600	1309.87	0.80	$247,192.38	172.68	189.42	1509.96	3	18	54
7	43	600	1311.44	0.80	$247,221.26	178.52	189.42	1509.96	3	18	54
7	44	600	1729.77	1.05	$328,916.69	165.30	189.42	1509.96	4	18	72
7	45	600	1731.01	1.05	$328,939.48	170.36	189.42	1509.96	4	18	72
7	46	600	1732.28	1.05	$328,962.77	175.49	189.42	1509.96	4	18	72
7	47	600	1733.58	1.05	$328,986.56	180.68	189.42	1509.96	4	18	72
7	48	600	1734.91	1.05	$329,010.85	185.93	189.42	1509.96	4	18	72
7	49	600	1736.26	1.05	$329,035.64	191.25	189.42	1509.96	4	18	72
7	50	600	1737.64	1.05	$329,060.93	196.63	189.42	1509.96	4	18	72

Figure H-11.6 Three phase IGBT input switch quantity characterization - Sheet 2 for 600 Hz switching frequency and variable power.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	di/dt SNUBBER INDUCTOR (uH)
1	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
1.6	0.00556	34	34

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	25	600	2.73	1622.38	1.35	0.11	1.46	0.96	0.08	0.08	0.15
7	26	600	2.88	1687.28	1.44	0.11	1.55	1.01	0.08	0.09	0.16
7	27	600	3.04	1752.17	1.54	0.12	1.65	1.05	0.08	0.10	0.17
7	28	600	3.20	1817.07	1.63	0.12	1.75	1.10	0.08	0.10	0.17
7	29	600	3.36	1881.97	1.73	0.12	1.86	1.14	0.08	0.11	0.18
7	30	600	2.02	1297.91	0.94	0.09	1.02	0.75	0.08	0.05	0.12
7	31	600	2.11	1341.17	0.99	0.09	1.08	0.78	0.08	0.06	0.13
7	32	600	2.20	1384.43	1.04	0.09	1.13	0.80	0.08	0.06	0.13
7	33	600	2.30	1427.70	1.09	0.09	1.19	0.83	0.08	0.06	0.14
7	34	600	2.39	1470.96	1.15	0.10	1.25	0.86	0.08	0.07	0.14
7	35	600	2.49	1514.23	1.21	0.10	1.31	0.89	0.08	0.07	0.14
7	36	600	2.58	1557.49	1.26	0.10	1.37	0.92	0.08	0.08	0.15
7	37	600	2.68	1600.75	1.32	0.11	1.43	0.95	0.08	0.08	0.15
7	38	600	2.78	1644.02	1.38	0.11	1.49	0.98	0.08	0.08	0.16
7	39	600	2.88	1687.28	1.44	0.11	1.55	1.01	0.08	0.09	0.16
7	40	600	2.99	1730.54	1.50	0.11	1.62	1.04	0.08	0.09	0.16
7	41	600	3.09	1773.81	1.57	0.12	1.68	1.07	0.08	0.10	0.17
7	42	600	3.20	1817.07	1.63	0.12	1.75	1.10	0.08	0.10	0.17
7	43	600	3.31	1860.33	1.70	0.12	1.82	1.13	0.08	0.11	0.18
7	44	600	2.30	1427.70	1.09	0.09	1.19	0.83	0.08	0.06	0.14
7	45	600	2.37	1460.15	1.14	0.10	1.23	0.85	0.08	0.07	0.14
7	46	600	2.44	1492.59	1.18	0.10	1.28	0.87	0.08	0.07	0.14
7	47	600	2.51	1525.04	1.22	0.10	1.32	0.90	0.08	0.07	0.15
7	48	600	2.58	1557.49	1.26	0.10	1.37	0.92	0.08	0.08	0.15
7	49	600	2.66	1589.94	1.31	0.10	1.41	0.94	0.08	0.08	0.15
7	50	600	2.73	1622.38	1.35	0.11	1.46	0.96	0.08	0.08	0.15

Figure H-11.7 Three phase IGBT input converter switch loss estimation - Sheet 3 for 600 Hz switching frequency and variable power.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '60% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
6	6984	9.748	60	30.00	$76,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	25	60	24503.30	34.20	$264,519.18	105.25	31.99
7	26	60	25241.37	35.23	$272,486.77	108.43	33.28
7	27	60	25972.84	36.25	$280,383.24	111.57	34.57
7	28	60	26698.05	37.26	$288,211.89	114.68	35.86
7	29	60	27417.27	38.27	$295,976.17	117.77	37.16
7	30	60	28057.93	39.16	$302,892.21	120.52	38.32
7	31	60	28761.30	40.14	$310,485.30	123.55	39.61
7	32	60	29459.33	41.12	$318,020.69	126.54	40.89
7	33	60	30152.22	42.09	$325,500.69	129.52	42.18
7	34	60	30840.19	43.05	$332,927.47	132.48	43.47
7	35	60	31523.42	44.00	$340,303.05	135.41	44.76
7	36	60	32202.07	44.95	$347,629.31	138.33	46.05
7	37	60	32876.33	45.89	$354,908.03	141.22	47.34
7	38	60	33546.33	46.82	$362,140.87	144.10	48.63
7	39	60	34212.22	47.75	$369,329.39	146.96	49.92
7	40	60	34874.15	48.68	$376,475.07	149.80	51.21
7	41	60	35532.24	49.59	$383,579.30	152.63	52.50
7	42	60	36186.61	50.51	$390,643.40	155.44	53.80
7	43	60	36837.38	51.42	$397,668.60	158.24	55.09
7	44	60	37413.08	52.22	$403,883.37	160.71	56.24
7	45	60	38053.86	53.11	$410,800.82	163.46	57.53
7	46	60	38691.31	54.00	$417,682.19	166.20	58.82
7	47	60	39326.50	54.89	$424,528.49	168.92	60.11
7	48	60	39956.54	55.77	$431,340.70	171.63	61.39
7	49	60	40584.51	56.65	$438,119.73	174.33	62.68
7	50	60	41209.48	57.52	$444,866.45	177.02	63.97

Figure H-11.8 Three phase IGBT input transformer sizing - Sheet 4 for 600 Hz switching frequency and variable power.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	10	100	35355.86	69.89	$3,601,467.21	368.64	293.69	96.44%	93.79%	0.9990	15.42
7	10	150	35400.68	70.10	$3,607,378.39	381.48	303.92	96.33%	93.59%	0.9985	15.41
7	10	200	35445.50	70.31	$3,613,290.73	394.32	314.15	96.21%	93.38%	0.9980	15.41
7	10	250	35490.34	70.51	$3,619,204.22	407.16	324.38	96.09%	93.18%	0.9975	15.40
7	10	300	35535.20	70.72	$3,625,118.88	420.00	334.61	95.97%	92.98%	0.9970	15.39
7	10	350	35580.07	70.93	$3,631,034.70	432.84	344.85	95.85%	92.78%	0.9965	15.38
7	10	400	35624.95	71.14	$3,636,951.69	445.69	355.08	95.73%	92.59%	0.9960	15.38
7	10	450	35669.85	71.35	$3,642,869.84	458.54	365.32	95.62%	92.39%	0.9955	15.37
7	10	500	35714.76	71.55	$3,648,789.18	471.39	375.56	95.50%	92.19%	0.9950	15.36
7	10	550	35759.69	71.76	$3,654,709.68	484.24	385.79	95.38%	92.00%	0.9945	15.35
7	10	600	35804.63	71.97	$3,660,631.37	497.09	396.04	95.26%	91.80%	0.9940	15.34
7	10	650	35849.58	72.18	$3,666,554.24	509.95	406.28	95.15%	91.61%	0.9935	15.34
7	10	700	35894.55	72.39	$3,672,478.29	522.81	416.52	95.03%	91.41%	0.9930	15.29
7	10	750	35939.53	72.60	$3,678,403.53	535.67	426.77	94.92%	91.22%	0.9925	14.97
7	10	800	35984.53	72.80	$3,684,329.96	548.53	437.01	94.80%	91.03%	0.9920	14.67
7	10	850	36029.54	73.01	$3,690,257.58	561.39	447.26	94.68%	90.84%	0.9915	14.37
7	10	900	36074.57	73.22	$3,696,186.40	574.26	457.51	94.57%	90.65%	0.9910	14.08
7	10	950	36119.61	73.43	$3,702,116.42	587.12	467.76	94.45%	90.46%	0.9905	13.80
7	10	1000	36164.66	73.64	$3,708,047.65	599.99	478.01	94.34%	90.27%	0.9900	13.53
7	10	1050	36209.73	73.85	$3,713,980.08	612.86	488.27	94.23%	90.08%	0.9895	13.27
7	10	1100	36254.82	74.05	$3,719,913.71	625.73	498.52	94.11%	89.89%	0.9890	13.01
7	10	1150	36299.92	74.26	$3,725,848.56	638.61	508.78	94.00%	89.71%	0.9885	12.76
7	10	1200	36345.03	74.47	$3,731,784.63	651.48	519.04	93.88%	89.52%	0.9880	12.52
7	10	1250	36390.16	74.68	$3,737,721.91	664.36	529.30	93.77%	89.34%	0.9875	12.29
7	10	1300	36435.31	74.89	$3,743,660.41	677.24	539.56	93.66%	89.15%	0.9870	12.06
7	10	1350	36480.46	75.10	$3,749,600.14	690.12	549.82	93.54%	88.97%	0.9865	11.84

Figure H-12.1 Three phase BJT input converter summary - Sheet 1 for 10 MW output power and variable switching frequency.

BJT PARAMETERS								
VOLTAGE RATING (kV)	POWER DISS PER BJT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	BJTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itgq
0.55	1500	1	0.001838	0.00275	0	2	1.00E-05	1000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
20.88	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$5,332.87	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	10	100	2008.17	2.49	$190,116.64	52.57	1000.00	1594.97	1	32	32
7	10	150	2010.01	2.49	$190,150.50	54.70	1000.00	1594.57	1	32	32
7	10	200	2011.86	2.49	$190,184.39	56.83	1000.00	1594.17	1	32	32
7	10	250	2013.71	2.49	$190,218.31	58.96	1000.00	1593.77	1	32	32
7	10	300	2015.57	2.49	$190,252.26	61.09	1000.00	1593.37	1	32	32
7	10	350	2017.42	2.50	$190,286.24	63.22	1000.00	1592.97	1	32	32
7	10	400	2019.27	2.50	$190,320.26	65.36	1000.00	1592.57	1	32	32
7	10	450	2021.13	2.50	$190,354.31	67.49	1000.00	1592.17	1	32	32
7	10	500	2022.99	2.50	$190,388.39	69.62	1000.00	1591.77	1	32	32
7	10	550	2024.85	2.50	$190,422.51	71.76	1000.00	1591.37	1	32	32
7	10	600	2026.71	2.50	$190,456.65	73.89	1000.00	1590.97	1	32	32
7	10	650	2028.58	2.50	$190,490.83	76.03	1000.00	1590.57	1	32	32
7	10	700	2030.44	2.50	$190,525.05	78.16	997.36	1585.98	1	32	32
7	10	750	2032.31	2.51	$190,559.29	80.30	977.23	1553.57	1	32	32
7	10	800	2034.18	2.51	$190,593.57	82.43	957.69	1522.13	1	32	32
7	10	850	2036.05	2.51	$190,627.88	84.57	938.75	1491.64	1	32	32
7	10	900	2037.93	2.51	$190,662.23	86.70	920.36	1462.07	1	32	32
7	10	950	2039.80	2.51	$190,696.60	88.84	902.53	1433.38	1	32	32
7	10	1000	2041.68	2.51	$190,731.01	90.98	885.24	1405.56	1	32	32
7	10	1050	2043.56	2.51	$190,765.46	93.11	868.46	1378.57	1	32	32
7	10	1100	2045.44	2.51	$190,799.93	95.25	852.18	1352.38	1	32	32
7	10	1150	2047.32	2.52	$190,834.45	97.39	836.39	1326.98	1	32	32
7	10	1200	2049.21	2.52	$190,868.99	99.52	821.06	1302.34	1	32	32
7	10	1250	2051.09	2.52	$190,903.57	101.66	806.19	1278.42	1	32	32
7	10	1300	2052.98	2.52	$190,938.18	103.80	791.75	1255.21	1	32	32
7	10	1350	2054.87	2.52	$190,972.82	105.94	777.74	1232.69	1	32	32

Figure H-12.2 Three phase BJT input converter switch quantity characterization - Sheet 2 for 10 MW output power and variable switching frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	di/dt SNUBBER INDUCTOR (uH)
2.5	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
0.998	0.000265	100	2

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	10	100	1.64	1296.87	0.90	0.11	1.02	0.48	0.01	0.01	0.12
7	10	150	1.71	1297.52	0.90	0.17	1.07	0.48	0.01	0.01	0.12
7	10	200	1.78	1298.17	0.90	0.23	1.13	0.48	0.02	0.02	0.12
7	10	250	1.84	1298.82	0.90	0.28	1.19	0.48	0.02	0.02	0.12
7	10	300	1.91	1299.47	0.90	0.34	1.25	0.48	0.03	0.03	0.12
7	10	350	1.98	1300.12	0.91	0.40	1.30	0.48	0.03	0.03	0.12
7	10	400	2.04	1300.77	0.91	0.45	1.36	0.48	0.04	0.04	0.12
7	10	450	2.11	1301.43	0.91	0.51	1.42	0.48	0.04	0.04	0.12
7	10	500	2.18	1302.08	0.91	0.57	1.47	0.48	0.05	0.05	0.12
7	10	550	2.24	1302.74	0.91	0.62	1.53	0.48	0.05	0.05	0.12
7	10	600	2.31	1303.39	0.91	0.68	1.59	0.48	0.06	0.06	0.12
7	10	650	2.38	1304.05	0.91	0.74	1.64	0.48	0.06	0.06	0.12
7	10	700	2.44	1304.70	0.91	0.79	1.70	0.48	0.07	0.07	0.12
7	10	750	2.51	1305.36	0.91	0.85	1.76	0.48	0.07	0.07	0.12
7	10	800	2.58	1306.02	0.91	0.91	1.81	0.48	0.08	0.08	0.12
7	10	850	2.64	1306.68	0.91	0.96	1.87	0.48	0.08	0.08	0.12
7	10	900	2.71	1307.34	0.91	1.02	1.93	0.48	0.09	0.09	0.12
7	10	950	2.78	1308.00	0.91	1.08	1.99	0.48	0.09	0.09	0.12
7	10	1000	2.84	1308.66	0.91	1.13	2.04	0.48	0.09	0.10	0.12
7	10	1050	2.91	1309.32	0.91	1.19	2.10	0.48	0.10	0.10	0.12
7	10	1100	2.98	1309.98	0.91	1.25	2.16	0.48	0.10	0.11	0.12
7	10	1150	3.04	1310.64	0.91	1.30	2.21	0.48	0.11	0.11	0.12
7	10	1200	3.11	1311.31	0.91	1.36	2.27	0.48	0.11	0.12	0.12
7	10	1250	3.18	1311.97	0.91	1.42	2.33	0.48	0.12	0.12	0.12
7	10	1300	3.24	1312.64	0.91	1.47	2.38	0.48	0.12	0.13	0.12
7	10	1350	3.31	1313.30	0.91	1.53	2.44	0.48	0.13	0.13	0.12

Figure H-12.3 Three phase BJT input converter switch loss estimation - Sheet 3 for 10 MW output power and variable switching frequency.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '50% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
6	6984	9.748	60	30.00	$75,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS					
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	10	60	12396.17	17.30	$133,819.72	53.25	12.89
7	10	60	12407.69	17.32	$133,944.12	53.30	12.91
7	10	60	12419.22	17.33	$134,068.50	53.35	12.93
7	10	60	12430.74	17.35	$134,192.86	53.40	12.94
7	10	60	12442.25	17.37	$134,317.20	53.45	12.96
7	10	60	12453.77	17.38	$134,441.52	53.50	12.97
7	10	60	12465.29	17.40	$134,565.82	53.55	12.99
7	10	60	12476.80	17.41	$134,690.10	53.59	13.01
7	10	60	12488.31	17.43	$134,814.36	53.64	13.02
7	10	60	12499.82	17.45	$134,938.59	53.69	13.04
7	10	60	12511.32	17.46	$135,062.81	53.74	13.06
7	10	60	12522.83	17.48	$135,187.01	53.79	13.07
7	10	60	12534.33	17.49	$135,311.18	53.84	13.09
7	10	60	12545.83	17.51	$135,435.34	53.89	13.10
7	10	60	12557.33	17.53	$135,559.48	53.94	13.12
7	10	60	12568.83	17.54	$135,683.59	53.99	13.13
7	10	60	12580.32	17.56	$135,807.69	54.04	13.15
7	10	60	12591.82	17.58	$135,931.76	54.09	13.17
7	10	60	12603.31	17.59	$136,055.82	54.14	13.18
7	10	60	12614.80	17.61	$136,179.86	54.19	13.20
7	10	60	12626.29	17.62	$136,303.88	54.24	13.21
7	10	60	12637.77	17.64	$136,427.87	54.29	13.23
7	10	60	12649.26	17.66	$136,551.85	54.34	13.25
7	10	60	12660.74	17.67	$136,675.81	54.38	13.26
7	10	60	12672.22	17.69	$136,799.75	54.43	13.28
7	10	60	12683.70	17.70	$136,923.67	54.48	13.29

Figure H-12.4 Three phase BJT input transformer sizing - Sheet 4 for 10 MW output power and variable switching frequency.

INVERTER PARAMETERS	
NUMBER OF PHASES	NUMBER OF SWITCHES
3	6

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES		
CONTROLLER FIXED COST	CONTROLLER COST/SWITCH	BUS & FRAME % INC IN COST
$3,500.00	$35.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	CONVERTER LOSS (kW)	HEAT EX POWER (kVA)	CONVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	25	600	71451.63	137.79	$7,314,386.21	1283.90	1022.89	95.12%	91.55%	0.9940	30.69
7	26	600	72605.91	140.46	$7,362,065.58	1348.72	1074.53	95.07%	91.47%	0.9940	30.69
7	27	600	73753.01	143.13	$7,410,043.43	1414.69	1127.09	95.02%	91.40%	0.9940	30.69
7	28	600	74893.36	145.81	$7,458,329.37	1481.82	1180.57	94.97%	91.32%	0.9940	30.69
7	29	600	76027.39	148.48	$7,506,932.20	1550.11	1234.97	94.93%	91.24%	0.9940	30.69
7	30	600	77155.48	151.16	$7,555,860.07	1619.56	1290.30	94.88%	91.16%	0.9940	30.69
7	31	600	94901.17	176.76	$10,511,871.70	1511.11	1203.90	95.35%	91.95%	0.9940	46.03
7	32	600	95986.83	179.26	$10,556,066.55	1570.42	1251.16	95.32%	91.90%	0.9940	46.03
7	33	600	97066.62	181.75	$10,600,437.74	1630.50	1299.02	95.29%	91.85%	0.9940	46.03
7	34	600	98140.83	184.24	$10,644,991.35	1691.35	1347.50	95.26%	91.80%	0.9940	46.03
7	35	600	99209.74	186.74	$10,689,733.05	1752.97	1396.59	95.23%	91.74%	0.9940	46.03
7	36	600	100273.58	189.23	$10,734,668.13	1815.35	1446.29	95.20%	91.69%	0.9940	46.03
7	37	600	101332.61	191.72	$10,779,801.57	1878.51	1496.61	95.17%	91.64%	0.9940	46.03
7	38	600	102387.03	194.21	$10,825,138.04	1942.44	1547.54	95.14%	91.59%	0.9940	46.03
7	39	600	103437.05	196.71	$10,870,681.94	2007.13	1599.08	95.11%	91.54%	0.9940	46.03
7	40	600	104482.87	199.20	$10,916,437.40	2072.60	1651.24	95.07%	91.48%	0.9940	46.03
7	41	600	105524.67	201.70	$10,962,408.32	2138.84	1704.02	95.04%	91.43%	0.9940	46.03
7	42	600	106562.63	204.20	$11,008,598.39	2205.86	1757.41	95.01%	91.38%	0.9940	46.03
7	43	600	107596.92	206.70	$11,055,011.11	2273.65	1811.42	94.98%	91.32%	0.9940	46.03
7	44	600	108627.68	209.20	$11,101,649.78	2342.21	1866.04	94.95%	91.27%	0.9940	46.03
7	45	600	109655.06	211.70	$11,148,517.54	2411.55	1921.28	94.91%	91.22%	0.9940	46.03
7	46	600	110679.21	214.21	$11,195,617.37	2481.66	1977.14	94.88%	91.16%	0.9940	46.03
7	47	600	128267.78	239.25	$14,137,737.56	2345.18	1868.40	95.25%	91.77%	0.9940	61.38
7	48	600	129262.81	241.62	$14,181,251.13	2407.45	1918.02	95.22%	91.73%	0.9940	61.38
7	49	600	130254.55	244.00	$14,224,920.28	2470.31	1968.09	95.20%	91.69%	0.9940	61.38
7	50	600	131243.10	246.37	$14,268,747.49	2533.74	2018.63	95.18%	91.66%	0.9940	61.38

Figure H-12.5 Three phase BJT input converter summary - Sheet 1 for 600 Hz switching frequency and variable power.

BJT PARAMETERS									
VOLTAGE RATING (kV)	POWER DISS PER BJT (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS LOSS PER AMP	FIXED SW LOSS	BJTs PER MODULE	MINIMUM OFF TIME	MAXIMUM Itqq
0.55	1500	1	0.001838	0.00275	0	2	1.00E-05	1000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
20.88	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$5,332.87	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX PHASE CUR PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	25	600	4065.19	5.01	$380,028.89	196.14	1000.00	1590.97	2	32	64
7	26	600	4067.83	5.01	$380,077.39	206.40	1000.00	1590.97	2	32	64
7	27	600	4070.58	5.02	$380,127.68	216.86	1000.00	1590.97	2	32	64
7	28	600	4073.42	5.02	$380,179.77	227.52	1000.00	1590.97	2	32	64
7	29	600	4076.36	5.02	$380,233.65	238.38	1000.00	1590.97	2	32	64
7	30	600	4079.39	5.02	$380,289.33	249.43	1000.00	1590.97	2	32	64
7	31	600	6082.28	7.51	$569,209.19	230.92	1000.00	1590.97	3	32	96
7	32	600	6084.49	7.51	$569,249.62	240.30	1000.00	1590.97	3	32	96
7	33	600	6086.76	7.51	$569,291.24	249.80	1000.00	1590.97	3	32	96
7	34	600	6089.09	7.51	$569,334.06	259.44	1000.00	1590.97	3	32	96
7	35	600	6091.49	7.51	$569,378.07	269.21	1000.00	1590.97	3	32	96
7	36	600	6093.96	7.52	$569,423.28	279.11	1000.00	1590.97	3	32	96
7	37	600	6096.49	7.52	$569,469.69	289.15	1000.00	1590.97	3	32	96
7	38	600	6099.09	7.52	$569,517.29	299.31	1000.00	1590.97	3	32	96
7	39	600	6101.75	7.52	$569,566.09	309.61	1000.00	1590.97	3	32	96
7	40	600	6104.48	7.52	$569,616.08	320.03	1000.00	1590.97	3	32	96
7	41	600	6107.27	7.52	$569,667.27	330.59	1000.00	1590.97	3	32	96
7	42	600	6110.13	7.53	$569,719.66	341.28	1000.00	1590.97	3	32	96
7	43	600	6113.05	7.53	$569,773.24	352.10	1000.00	1590.97	3	32	96
7	44	600	6116.04	7.53	$569,828.02	363.06	1000.00	1590.97	3	32	96
7	45	600	6119.09	7.53	$569,883.99	374.14	1000.00	1590.97	3	32	96
7	46	600	6122.21	7.53	$569,941.16	385.36	1000.00	1590.97	3	32	96
7	47	600	8122.81	10.02	$758,819.02	362.23	1000.00	1590.97	4	32	128
7	48	600	8125.28	10.02	$758,864.38	372.15	1000.00	1590.97	4	32	128
7	49	600	8127.80	10.02	$758,910.63	382.17	1000.00	1590.97	4	32	128
7	50	600	8130.38	10.02	$758,957.79	392.28	1000.00	1590.97	4	32	128

Figure H-12.6 Three phase BJT input converter switch quantity characterization - Sheet 2 for 600 Hz switching frequency and variable power.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	di/dt SNUBBER INDUCTOR (uH)
2.5	0.1

ANTI-PARALLEL DIODE PARAMETERS			
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)	DIODES PER MODULE
0.998	0.000265	100	2

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	25	600	3.06	1629.24	1.29	0.85	2.14	0.63	0.06	0.09	0.15
7	26	600	3.23	1694.41	1.37	0.88	2.26	0.66	0.06	0.10	0.16
7	27	600	3.39	1759.58	1.46	0.92	2.38	0.69	0.06	0.10	0.17
7	28	600	3.56	1824.75	1.55	0.95	2.50	0.72	0.06	0.11	0.17
7	29	600	3.72	1889.92	1.64	0.99	2.62	0.75	0.06	0.12	0.18
7	30	600	3.90	1955.09	1.73	1.02	2.75	0.78	0.06	0.13	0.19
7	31	600	2.41	1346.84	0.95	0.70	1.66	0.50	0.06	0.06	0.13
7	32	600	2.50	1390.28	1.00	0.73	1.73	0.52	0.06	0.07	0.13
7	33	600	2.60	1433.73	1.05	0.75	1.80	0.54	0.06	0.07	0.14
7	34	600	2.70	1477.18	1.10	0.77	1.87	0.56	0.06	0.07	0.14
7	35	600	2.80	1520.62	1.15	0.79	1.95	0.58	0.06	0.08	0.14
7	36	600	2.91	1564.07	1.21	0.82	2.02	0.60	0.06	0.08	0.15
7	37	600	3.01	1607.52	1.26	0.84	2.10	0.62	0.06	0.09	0.15
7	38	600	3.12	1650.96	1.31	0.86	2.18	0.64	0.06	0.09	0.16
7	39	600	3.23	1694.41	1.37	0.88	2.26	0.66	0.06	0.10	0.16
7	40	600	3.33	1737.86	1.43	0.91	2.34	0.68	0.06	0.10	0.16
7	41	600	3.44	1781.30	1.49	0.93	2.42	0.70	0.06	0.11	0.17
7	42	600	3.56	1824.75	1.55	0.95	2.50	0.72	0.06	0.11	0.17
7	43	600	3.67	1868.19	1.61	0.98	2.58	0.74	0.06	0.12	0.18
7	44	600	3.78	1911.64	1.67	1.00	2.67	0.76	0.06	0.12	0.18
7	45	600	3.90	1955.09	1.73	1.02	2.75	0.78	0.06	0.13	0.19
7	46	600	4.01	1998.53	1.79	1.04	2.84	0.80	0.06	0.13	0.19
7	47	600	2.83	1531.48	1.17	0.80	1.97	0.58	0.06	0.08	0.15
7	48	600	2.91	1564.07	1.21	0.82	2.02	0.60	0.06	0.08	0.15
7	49	600	2.99	1596.65	1.25	0.83	2.08	0.61	0.06	0.09	0.15
7	50	600	3.06	1629.24	1.29	0.85	2.14	0.63	0.06	0.09	0.15

Figure H-12.7 Three phase BJT input converter switch loss estimation - Sheet 3 for 600 Hz switching frequency and variable power.

BASIS TRANSFORMER PARAMETERS					
MVA RATING '50% DUTY CYCL	MASS (kg)	VOLUME (m^3)	FREQUENCY (Hz)	FULL LOAD POWER LOSS (kW	ESTIMATED COST
6	6984	9.748	60	30.00	$75,394.00

RECTIFICATION POWER FACTOR (PF)
0.8

INPUT PARAMETERS			CACULATED RESULTS				
OUTPUT VOLTAG (kVDC)	OUTPUT POWER (MW)	LINE FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST COST	TOTAL EST LOSS (kW)	TRANSFORMER MVA RATING
7	26	60	24923.63	34.79	$269,056.71	107.06	32.72
7	26	60	25677.91	35.84	$277,199.41	110.30	34.05
7	27	60	26425.71	36.88	$285,272.09	113.61	35.38
7	28	60	27167.34	37.92	$293,278.17	116.70	36.71
7	29	60	27903.10	38.95	$301,220.83	119.86	38.04
7	30	60	28633.25	39.97	$309,102.99	123.00	39.37
7	31	60	29237.25	40.81	$315,623.27	125.59	40.48
7	32	60	29949.55	41.80	$323,312.75	128.65	41.80
7	33	60	30656.77	42.79	$330,947.42	131.69	43.12
7	34	60	31359.12	43.77	$338,529.45	134.70	44.45
7	35	60	32056.78	44.74	$346,060.88	137.70	45.77
7	36	60	32749.93	45.71	$353,543.61	140.68	47.09
7	37	60	33438.74	46.67	$360,979.42	143.64	48.42
7	38	60	34123.36	47.63	$368,370.00	146.58	49.74
7	39	60	34803.92	48.58	$375,716.92	149.50	51.07
7	40	60	35480.59	49.52	$383,021.65	152.41	52.40
7	41	60	36153.47	50.46	$390,285.61	155.30	53.73
7	42	60	36822.70	51.40	$397,510.12	158.17	55.06
7	43	60	37488.39	52.32	$404,696.42	161.03	56.39
7	44	60	38150.65	53.25	$411,845.71	163.88	57.72
7	45	60	38809.59	54.17	$418,959.12	166.71	59.06
7	46	60	39465.31	55.08	$426,037.70	169.52	60.39
7	47	60	39991.80	55.82	$431,721.31	171.79	61.47
7	48	60	40636.33	56.72	$438,679.20	174.55	62.79
7	49	60	41277.83	57.61	$445,604.35	177.31	64.12
7	50	60	41916.38	58.51	$452,497.64	180.05	65.44

Figure H-12.8 Three phase BJT input transformer sizing - Sheet 4 for 600 Hz switching frequency and variable power.

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES	
CONTROLLER FIXED COST	BUS & FRAME % INC IN COST
$1,500.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	BRAKING POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	8.5	100	1130.63	11.24	$284,495.40	41.49	33.06	99.51%	99.13%	0.98	12.20
7	8.5	150	1211.73	11.42	$290,597.71	50.79	40.46	99.41%	98.94%	0.97	11.44
7	8.5	200	1292.87	11.60	$296,704.84	60.08	47.87	99.30%	98.75%	0.96	10.73
7	8.5	250	1374.06	11.77	$302,816.87	69.39	55.29	99.19%	98.55%	0.96	10.06
7	8.5	300	1455.30	11.95	$308,933.94	78.71	62.71	99.08%	98.36%	0.95	9.43
7	8.5	350	1536.58	12.13	$315,056.17	88.04	70.14	98.97%	98.17%	0.94	8.83
7	8.5	400	1617.91	12.31	$321,183.67	97.38	77.58	98.87%	97.98%	0.93	8.27
7	8.5	450	2311.88	13.59	$432,887.79	142.36	113.42	98.35%	97.08%	0.92	11.61
7	8.5	500	2431.65	13.85	$441,834.83	155.90	124.20	98.20%	96.81%	0.91	10.87
7	8.5	550	2551.45	14.11	$450,786.85	169.45	135.00	98.05%	96.54%	0.90	10.17
7	8.5	600	2671.30	14.37	$459,743.97	183.01	145.80	97.89%	96.28%	0.89	9.51
7	8.5	650	2791.19	14.63	$468,706.31	196.58	156.61	97.74%	96.01%	0.88	8.89
7	8.5	700	2911.13	14.89	$477,674.01	210.16	167.43	97.59%	95.75%	0.88	8.31
7	8.5	750	3878.18	16.77	$609,720.68	285.85	227.74	96.75%	94.30%	0.87	10.35
7	8.5	800	4036.76	17.11	$621,523.81	303.66	241.93	96.55%	93.97%	0.86	9.67
7	8.5	850	4195.39	17.45	$633,332.30	321.48	256.12	96.36%	93.64%	0.85	9.03
7	8.5	900	4354.06	17.80	$645,146.30	339.30	270.32	96.16%	93.31%	0.84	8.43
7	8.5	950	4512.78	18.14	$656,965.93	357.14	284.54	95.97%	92.98%	0.83	7.86
7	8.5	1000	5713.72	20.52	$806,289.00	458.73	365.47	94.88%	91.16%	0.82	9.16
7	8.5	1050	5911.18	20.94	$820,951.44	480.81	383.06	94.65%	90.77%	0.81	8.54
7	8.5	1100	6108.68	21.37	$835,619.70	502.90	400.66	94.41%	90.39%	0.81	7.95
7	8.5	1150	7465.73	24.08	$996,451.18	621.70	495.31	93.18%	88.39%	0.80	8.88
7	8.5	1200	7702.03	24.58	$1,013,966.50	648.04	516.29	92.92%	87.95%	0.79	8.26
7	8.5	1250	7938.37	25.09	$1,031,487.91	674.38	537.28	92.65%	87.52%	0.78	7.67
7	8.5	1300	9451.27	28.13	$1,203,781.10	810.30	645.57	91.30%	85.38%	0.77	8.31
7	8.5	1350	9726.44	28.72	$1,224,152.43	840.90	669.94	91.00%	84.91%	0.76	7.71

Figure H-13.1 GTO braking chopper summary - Sheet 1 for 8.5 MW braking power and variable switching frequency.

GTO PARAMETERS							
VOLTAGE RATING (kV)	POWER DISS PER GTO (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS PER AMP (J/A)	FIXED SW LOSS (J)	MINIMUM OFF TIME (s)	MAXIMUM Itgq (A)
6	2900	1.77	0.00118	0.003167	1.05	1.77E-04	3000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
21.15	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$9,304.40	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	BRAKING POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX CURRENT/ PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	8.5	100	482.16	0.53	$64,600.07	41.49	894.74	886.79	2	3	6
7	8.5	150	532.92	0.56	$65,530.74	50.79	851.02	839.65	2	3	6
7	8.5	200	583.71	0.60	$66,461.86	60.08	809.17	794.71	2	3	6
7	8.5	250	634.52	0.63	$67,393.45	69.39	769.14	751.93	2	3	6
7	8.5	300	685.36	0.66	$68,325.51	78.71	730.90	711.23	2	3	6
7	8.5	350	736.23	0.69	$69,258.06	88.04	694.39	672.54	2	3	6
7	8.5	400	787.12	0.73	$70,191.11	97.38	659.58	635.80	2	3	6
7	8.5	450	1245.90	1.13	$105,932.34	142.36	626.38	600.92	3	3	9
7	8.5	500	1320.99	1.18	$107,308.99	155.90	594.76	567.83	3	3	9
7	8.5	550	1396.10	1.23	$108,686.06	169.45	564.64	536.45	3	3	9
7	8.5	600	1471.24	1.28	$110,063.58	183.01	535.95	506.69	3	3	9
7	8.5	650	1546.40	1.33	$111,441.54	196.58	508.64	478.48	3	3	9
7	8.5	700	1621.59	1.37	$112,819.96	210.16	482.63	451.74	3	3	9
7	8.5	750	2251.70	1.89	$151,702.19	285.85	457.86	426.39	4	3	12
7	8.5	800	2351.21	1.95	$153,526.66	303.66	434.28	402.36	4	3	12
7	8.5	850	2450.75	2.02	$155,351.57	321.48	411.81	379.57	4	3	12
7	8.5	900	2550.32	2.08	$157,176.92	339.30	390.41	357.96	4	3	12
7	8.5	950	2649.91	2.14	$159,002.74	357.14	370.00	337.46	4	3	12
7	8.5	1000	3427.06	2.75	$200,580.74	458.73	350.55	318.02	5	3	15
7	8.5	1050	3551.04	2.83	$202,853.69	480.81	331.99	299.56	5	3	15
7	8.5	1100	3675.04	2.91	$205,127.08	502.90	314.28	282.03	5	3	15
7	8.5	1150	4550.37	3.58	$248,505.12	621.70	297.37	265.39	6	3	18
7	8.5	1200	4698.80	3.68	$251,226.26	648.04	281.22	249.57	6	3	18
7	8.5	1250	4847.25	3.77	$253,947.85	674.38	265.78	234.54	6	3	18
7	8.5	1300	5820.65	4.51	$299,123.79	810.30	251.02	220.25	7	3	21
7	8.5	1350	5993.54	4.62	$302,293.51	840.90	236.89	206.66	7	3	21

Figure H-13.2 GTO braking chopper switch quantity characterization - Sheet 2 for 8.5 MW braking power and variable switching frequency.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
6	2.4

ANTI-PARALLEL DIODE PARAMETERS		
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)
1.1	0.001583	380

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	BRAKING POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	8.5	100	6.92	612.59	1.50	0.30	1.80	1.25	2.70	0.12	1.05
7	8.5	150	8.46	615.37	1.50	0.45	1.95	1.24	4.05	0.18	1.05
7	8.5	200	10.01	618.18	1.49	0.60	2.09	1.24	5.40	0.24	1.04
7	8.5	250	11.57	621.04	1.49	0.75	2.24	1.24	6.75	0.30	1.04
7	8.5	300	13.12	623.93	1.48	0.91	2.39	1.23	8.10	0.36	1.03
7	8.5	350	14.67	626.87	1.48	1.06	2.54	1.23	9.45	0.43	1.03
7	8.5	400	16.23	629.85	1.47	1.22	2.69	1.23	10.80	0.49	1.02
7	8.5	450	15.82	421.91	0.88	1.07	1.95	0.69	12.15	0.35	0.68
7	8.5	500	17.32	423.96	0.88	1.20	2.07	0.68	13.50	0.39	0.68
7	8.5	550	18.83	426.03	0.87	1.32	2.19	0.68	14.85	0.43	0.67
7	8.5	600	20.33	428.13	0.87	1.44	2.31	0.68	16.20	0.47	0.67
7	8.5	650	21.84	430.27	0.87	1.57	2.44	0.68	17.55	0.51	0.67
7	8.5	700	23.35	432.44	0.86	1.69	2.56	0.68	18.90	0.55	0.66
7	8.5	750	23.82	325.98	0.61	1.56	2.17	0.46	20.25	0.45	0.49
7	8.5	800	25.30	327.65	0.61	1.67	2.28	0.46	21.60	0.48	0.49
7	8.5	850	26.79	329.36	0.60	1.78	2.38	0.45	22.95	0.51	0.49
7	8.5	900	28.28	331.09	0.60	1.89	2.49	0.45	24.30	0.55	0.49
7	8.5	950	29.76	332.84	0.60	2.00	2.60	0.45	25.65	0.58	0.48
7	8.5	1000	30.58	267.70	0.46	1.90	2.36	0.34	27.00	0.50	0.39
7	8.5	1050	32.05	269.15	0.46	2.00	2.45	0.33	28.35	0.53	0.38
7	8.5	1100	33.53	270.63	0.46	2.10	2.55	0.33	29.70	0.56	0.38
7	8.5	1150	34.54	226.77	0.37	2.03	2.40	0.26	31.05	0.51	0.32
7	8.5	1200	36.00	228.04	0.37	2.13	2.49	0.26	32.40	0.53	0.31
7	8.5	1250	37.47	229.34	0.36	2.22	2.58	0.26	33.75	0.56	0.31
7	8.5	1300	38.59	197.70	0.30	2.18	2.48	0.22	35.10	0.52	0.27
7	8.5	1350	40.04	198.85	0.30	2.27	2.57	0.21	36.45	0.54	0.26

Figure H-13.3 GTO braking chopper switch loss estimation - Sheet 3 for 8.5 MW braking power and variable switching frequency.

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$39,440.00	164.5	0.7967	400	1	9.77	0.0131

CONTROLLER	
MASS (kg)	VOLUME (m^3)
5	0.01

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES	
CONTROLLER FIXED COST	BUS & FRAME % INC IN COST
$1,500.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	BRAKING POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
7	0.5	600	1144.99	11.20	$216,996.60	52.35	41.71	90.52%	84.17%	0.89	3.17
7	1	600	1148.01	11.22	$217,694.00	54.00	43.02	94.88%	91.16%	0.89	3.17
7	1.5	600	1151.35	11.24	$218,441.52	55.77	44.43	96.42%	93.74%	0.89	3.17
7	2	600	1155.01	11.27	$219,239.13	57.64	45.92	97.20%	95.08%	0.89	3.17
7	2.5	600	1158.99	11.30	$220,086.86	59.62	47.50	97.67%	95.89%	0.89	3.17
7	3	600	1163.28	11.33	$220,984.68	61.71	49.17	97.98%	96.44%	0.89	3.17
7	3.5	600	1899.21	12.72	$336,520.35	113.38	90.33	96.86%	94.50%	0.89	6.34
7	4	600	1902.95	12.75	$337,330.49	115.28	91.84	97.20%	95.08%	0.89	6.34
7	4.5	600	1906.65	12.78	$338,165.69	117.23	93.40	97.46%	95.53%	0.89	6.34
7	5	600	1910.90	12.81	$339,025.93	119.24	95.00	97.67%	95.89%	0.89	6.34
7	5.5	600	1915.12	12.83	$339,911.24	121.31	96.64	97.84%	96.19%	0.89	6.34
7	6	600	1919.49	12.86	$340,821.59	123.42	98.33	97.98%	96.44%	0.89	6.34
7	6.5	600	1924.03	12.89	$341,757.00	125.60	100.06	98.10%	96.64%	0.89	6.34
7	7	600	2658.73	14.29	$457,100.59	176.84	140.89	97.54%	95.66%	0.89	9.51
7	7.5	600	2662.82	14.32	$457,965.01	178.86	142.50	97.67%	95.89%	0.89	9.51
7	8	600	2667.01	14.34	$458,846.14	180.92	144.14	97.79%	96.10%	0.89	9.51
7	8.5	600	2671.30	14.37	$459,743.97	183.01	145.80	97.89%	96.28%	0.89	9.51
7	9	600	2675.70	14.40	$460,658.50	185.14	147.50	97.98%	96.44%	0.89	9.51
7	9.5	600	2680.21	14.43	$461,589.73	187.30	149.22	98.07%	96.58%	0.89	9.51
7	10	600	2684.82	14.46	$462,537.66	189.50	150.98	98.14%	96.71%	0.89	9.51
7	10.5	600	3418.91	15.85	$577,783.13	240.53	191.63	97.76%	96.05%	0.89	12.68
7	11	600	3423.16	15.88	$578,674.70	242.61	193.29	97.84%	96.19%	0.89	12.68
7	11.5	600	3427.50	15.91	$579,578.79	244.72	194.97	97.92%	96.32%	0.89	12.68
7	12	600	3431.91	15.94	$580,495.40	246.85	196.66	97.98%	96.44%	0.89	12.68
7	12.5	600	3436.41	15.97	$581,424.55	249.01	198.39	98.05%	96.54%	0.89	12.68
7	13	600	3440.98	16.00	$582,366.22	251.20	200.13	98.10%	96.64%	0.89	12.68

Figure H-13.4 GTO braking chopper summary - Sheet 1 for 600 Hz switching frequency and variable braking power.

GTO PARAMETERS							
VOLTAGE RATING (kV)	POWER DISS PER GTO (W)	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS PER AMP (J/A)	FIXED SW LOSS (J)	MINIMUM OFF TIME (s)	MAXIMUM Itgq (A)
6	2900	1.77	0.00118	0.003167	1.05	1.77E-04	3000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
21.15	2	0.04535	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
200.00%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$9,304.40	$100.00	$1,000.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	BRAKING POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX CURRENT/ PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
7	0.5	600	484.64	0.42	$37,315.33	52.35	535.95	506.69	1	3	3
7	1	600	485.61	0.42	$37,333.04	54.00	535.95	506.69	1	3	3
7	1.5	600	486.72	0.42	$37,353.47	55.77	535.95	506.69	1	3	3
7	2	600	487.98	0.42	$37,376.60	57.64	535.95	506.69	1	3	3
7	2.5	600	489.39	0.42	$37,402.45	59.62	535.95	506.69	1	3	3
7	3	600	490.95	0.43	$37,431.01	61.71	535.95	506.69	1	3	3
7	3.5	600	974.66	0.85	$73,629.39	113.38	535.95	506.69	2	3	6
7	4	600	975.96	0.85	$73,653.20	115.28	535.95	506.69	2	3	6
7	4.5	600	977.34	0.85	$73,678.38	117.23	535.95	506.69	2	3	6
7	5	600	978.78	0.85	$73,704.90	119.24	535.95	506.69	2	3	6
7	5.5	600	980.30	0.85	$73,732.79	121.31	535.95	506.69	2	3	6
7	6	600	981.90	0.85	$73,762.03	123.42	535.95	506.69	2	3	6
7	6.5	600	983.57	0.85	$73,792.62	125.60	535.95	506.69	2	3	6
7	7	600	1466.72	1.27	$109,980.60	176.84	535.95	506.69	3	3	9
7	7.5	600	1468.18	1.27	$110,007.36	178.86	535.95	506.69	3	3	9
7	8	600	1469.68	1.28	$110,035.01	180.92	535.95	506.69	3	3	9
7	8.5	600	1471.24	1.28	$110,063.58	183.01	535.95	506.69	3	3	9
7	9	600	1472.85	1.28	$110,093.04	185.14	535.95	506.69	3	3	9
7	9.5	600	1474.51	1.28	$110,123.41	187.30	535.95	506.69	3	3	9
7	10	600	1476.21	1.28	$110,154.69	189.50	535.95	506.69	3	3	9
7	10.5	600	1959.07	1.70	$146,337.35	240.53	535.95	506.69	4	3	12
7	11	600	1960.61	1.70	$146,365.58	242.61	535.95	506.69	4	3	12
7	11.5	600	1962.19	1.70	$146,394.48	244.72	535.95	506.69	4	3	12
7	12	600	1963.80	1.70	$146,424.06	246.85	535.95	506.69	4	3	12
7	12.5	600	1965.45	1.70	$146,454.31	249.01	535.95	506.69	4	3	12
7	13	600	1967.14	1.71	$146,485.25	251.20	535.95	506.69	4	3	12

Figure H-13.5 GTO braking chopper switch quantity characterization - Sheet 2 for 600 Hz switching frequency and variable braking power.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
6	2.4

ANTI-PARALLEL DIODE PARAMETERS		
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)
1.1	0.001583	380

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	BRAKING POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
7	0.5	600	17.45	75.55	0.13	0.77	0.90	0.08	16.20	0.15	0.12
7	1	600	18.00	151.11	0.26	0.92	1.18	0.18	16.20	0.20	0.24
7	1.5	600	18.59	226.66	0.41	1.06	1.47	0.30	16.20	0.26	0.35
7	2	600	19.21	302.21	0.57	1.20	1.78	0.43	16.20	0.34	0.47
7	2.5	600	19.87	377.77	0.75	1.35	2.10	0.57	16.20	0.41	0.59
7	3	600	20.57	453.32	0.93	1.49	2.43	0.74	16.20	0.50	0.71
7	3.5	600	18.90	264.44	0.49	1.13	1.62	0.36	16.20	0.30	0.41
7	4	600	19.21	302.21	0.57	1.20	1.78	0.43	16.20	0.34	0.47
7	4.5	600	19.54	339.99	0.66	1.28	1.94	0.50	16.20	0.37	0.53
7	5	600	19.87	377.77	0.75	1.35	2.10	0.57	16.20	0.41	0.59
7	5.5	600	20.22	415.54	0.84	1.42	2.26	0.65	16.20	0.46	0.65
7	6	600	20.57	453.32	0.93	1.49	2.43	0.74	16.20	0.50	0.71
7	6.5	600	20.93	491.09	1.03	1.56	2.59	0.82	16.20	0.55	0.77
7	7	600	19.65	352.58	0.69	1.30	1.99	0.52	16.20	0.39	0.55
7	7.5	600	19.87	377.77	0.75	1.35	2.10	0.57	16.20	0.41	0.59
7	8	600	20.10	402.95	0.81	1.40	2.20	0.63	16.20	0.44	0.63
7	8.5	600	20.33	428.13	0.87	1.44	2.31	0.68	16.20	0.47	0.67
7	9	600	20.57	453.32	0.93	1.49	2.43	0.74	16.20	0.50	0.71
7	9.5	600	20.81	478.50	1.00	1.54	2.54	0.79	16.20	0.53	0.75
7	10	600	21.06	503.69	1.06	1.59	2.65	0.85	16.20	0.56	0.79
7	10.5	600	20.04	396.65	0.79	1.38	2.18	0.61	16.20	0.43	0.62
7	11	600	20.22	415.54	0.84	1.42	2.26	0.65	16.20	0.46	0.65
7	11.5	600	20.39	434.43	0.89	1.46	2.34	0.69	16.20	0.48	0.68
7	12	600	20.57	453.32	0.93	1.49	2.43	0.74	16.20	0.50	0.71
7	12.5	600	20.75	472.21	0.98	1.53	2.51	0.78	16.20	0.52	0.74
7	13	600	20.93	491.09	1.03	1.56	2.59	0.82	16.20	0.55	0.77

Figure H-13.6 GTO braking chopper switch loss estimation - Sheet 3 for 600 Hz switching frequency and variable braking power.

HEAT EXCHANGER ESTIMATES						
FIXED COST	COST PER kW LOSS ($/kW)	PRIME POWER (kVA/kW LOSS)	FIXED MASS (kg)	MASS PER kW LOSS (kg/kW)	FIXED VOLUME (m^3)	VOLUME/kW LOSS (m^3/kW)
$5,900.00	0	0.7967	200	0	0.6	0

CONTROLLER/RECTIFIER	
MASS (kg)	VOLUME (m^3)
10	0.02

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES	
CONTROL/RECT FIXED COST	BUS & FRAME % INC IN COST
$3,000.00	10.00%

LABOR AND SERVICES ESTIMATES (% OF TOTAL COST)			
MATERIAL	FAB LABOR	FAB SERVICES	TEST LABOR
41.82%	30.66%	13.49%	14.03%

INPUT PARAMETERS			CACULATED RESULTS								
INPUT VOLTAGE (kVDC)	CHARGING POWER (MW)	SWITCH FREQ (Hz)	MASS (kg)	VOLUME (m^3)	COST ($)	INVERTER LOSS (kW)	HEAT EX POWER (kVA)	INVERTER EFFICENCY	TOTAL EFFICENCY	MAXIMUM DUTY CYCLE	MAXIMUM MW
0.28	0.1	0	291.49	0.75	$57,805.93	2.20	1.76	97.84%	96.19%	1.00	0.27
0.28	0.1	1	291.49	0.75	$57,806.08	2.21	1.76	97.84%	96.18%	1.00	0.27
0.28	0.1	2	291.50	0.75	$57,806.22	2.21	1.76	97.84%	96.18%	1.00	0.27
0.28	0.1	3	291.50	0.75	$57,806.37	2.21	1.76	97.83%	96.18%	1.00	0.27
0.28	0.1	4	291.50	0.75	$57,806.52	2.22	1.77	97.83%	96.17%	1.00	0.27
0.28	0.1	5	291.51	0.75	$57,806.66	2.22	1.77	97.83%	96.17%	1.00	0.27
0.28	0.1	6	291.51	0.75	$57,806.81	2.22	1.77	97.83%	96.16%	1.00	0.27
0.28	0.1	7	291.51	0.75	$57,806.95	2.22	1.77	97.82%	96.16%	1.00	0.27
0.28	0.1	8	291.52	0.75	$57,807.10	2.23	1.77	97.82%	96.15%	1.00	0.27
0.28	0.1	9	291.52	0.75	$57,807.25	2.23	1.78	97.82%	96.15%	1.00	0.27
0.28	0.1	10	291.52	0.75	$57,807.39	2.23	1.78	97.82%	96.14%	1.00	0.27
0.28	0.1	11	291.53	0.75	$57,807.54	2.24	1.78	97.81%	96.14%	1.00	0.27
0.28	0.1	12	291.53	0.75	$57,807.69	2.24	1.78	97.81%	96.13%	1.00	0.27
0.28	0.1	13	291.53	0.75	$57,807.83	2.24	1.79	97.81%	96.13%	1.00	0.27
0.28	0.1	14	291.54	0.75	$57,807.98	2.24	1.79	97.80%	96.12%	1.00	0.27
0.28	0.1	15	291.54	0.75	$57,808.13	2.25	1.79	97.80%	96.12%	1.00	0.27
0.28	0.1	16	291.54	0.75	$57,808.27	2.25	1.79	97.80%	96.11%	1.00	0.27
0.28	0.1	17	291.55	0.75	$57,808.42	2.25	1.79	97.80%	96.11%	1.00	0.27
0.28	0.1	18	291.55	0.75	$57,808.57	2.26	1.80	97.79%	96.11%	1.00	0.27
0.28	0.1	19	291.55	0.75	$57,808.71	2.26	1.80	97.79%	96.10%	1.00	0.27
0.28	0.1	20	291.56	0.75	$57,808.86	2.26	1.80	97.79%	96.10%	1.00	0.27
0.28	0.1	21	291.56	0.75	$57,809.01	2.26	1.80	97.79%	96.09%	1.00	0.27
0.28	0.1	22	291.56	0.75	$57,809.15	2.27	1.81	97.78%	96.09%	1.00	0.27
0.28	0.1	23	291.57	0.75	$57,809.30	2.27	1.81	97.78%	96.08%	1.00	0.26
0.28	0.1	24	291.57	0.75	$57,809.44	2.27	1.81	97.78%	96.08%	1.00	0.26
0.28	0.1	25	291.57	0.75	$57,809.59	2.28	1.81	97.78%	96.07%	1.00	0.26

Figure H-14.1 IGBT Superconducting coil converter summary - Sheet 1.

GTO PARAMETERS							
VOLTAGE RATING (kV)	POWER DISS PER IGBT MOD (W	V THRESHOLD (VOLTS)	DYNAMIC r (OHMS)	INC. SW LOSS PER AMP (J/A)	FIXED SW LOSS (J)	MINIMUM OFF TIME (s)	MAXIMUM Itgq (A)
1	1875	0.9	0.00106	0.00346	0	3.00E-06	3000

SWITCH MODULE PARAMETERS			
FIXED MASS (kg)	MASS PER SNUB LOSS (kg/kW)	FIXED VOL (m^3)	VOL PER SNUB LOSS (m^3/kW)
7.73	2	0.00819	0.002244

BUS WORK & FRAME ESTIMATES	
% INCREASE IN TOTAL MASS	% INCREASE IN TOTAL VOLUME
41.46%	71.43%

COST ESTIMATES				
FIXED COST PER MODULE	COST PER SNUB LOSS ($/kW)	DRIVER FIXED COST	DRIVER COST PER MODULE	BUS & FRAME % INC IN COST
$4,090.19	$100.00	$0.00	$35.00	10.00%

INPUT PARAMETERS			CACULATED RESULTS									
INPUT VOLTAGE (kVDC)	BRAKING POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MASS (kg)	TOTAL EST VOLUME (m^3)	TOTAL EST MAT'L COST	TOTAL EST SW LOSS (kW)	MAXIMUM PEAK CURRENT	MAX CURRENT/ PARALLEL (Arms)	PARALLEL MODULES REQ	SERIES MODULES REQ	TOTAL MODULES REQ
0.28	0.1	0	10.93	0.01	$4,537.71	1.10	971.57	971.57	1	1	1
0.28	0.1	1	10.94	0.01	$4,537.73	1.10	970.44	970.44	1	1	1
0.28	0.1	2	10.94	0.01	$4,537.75	1.11	969.30	969.30	1	1	1
0.28	0.1	3	10.94	0.01	$4,537.76	1.11	968.17	968.17	1	1	1
0.28	0.1	4	10.94	0.01	$4,537.78	1.11	967.05	967.04	1	1	1
0.28	0.1	5	10.94	0.01	$4,537.80	1.11	965.92	965.91	1	1	1
0.28	0.1	6	10.94	0.01	$4,537.82	1.11	964.79	964.78	1	1	1
0.28	0.1	7	10.94	0.01	$4,537.84	1.11	963.67	963.66	1	1	1
0.28	0.1	8	10.94	0.01	$4,537.86	1.11	962.55	962.54	1	1	1
0.28	0.1	9	10.94	0.01	$4,537.88	1.12	961.43	961.41	1	1	1
0.28	0.1	10	10.94	0.01	$4,537.89	1.12	960.31	960.29	1	1	1
0.28	0.1	11	10.94	0.01	$4,537.91	1.12	959.19	959.18	1	1	1
0.28	0.1	12	10.94	0.01	$4,537.93	1.12	958.08	958.06	1	1	1
0.28	0.1	13	10.94	0.01	$4,537.95	1.12	956.96	956.95	1	1	1
0.28	0.1	14	10.94	0.01	$4,537.97	1.12	955.85	955.83	1	1	1
0.28	0.1	15	10.94	0.01	$4,537.99	1.12	954.74	954.72	1	1	1
0.28	0.1	16	10.94	0.01	$4,538.01	1.12	953.63	953.61	1	1	1
0.28	0.1	17	10.94	0.01	$4,538.02	1.13	952.53	952.50	1	1	1
0.28	0.1	18	10.94	0.01	$4,538.04	1.13	951.42	951.40	1	1	1
0.28	0.1	19	10.94	0.01	$4,538.06	1.13	950.32	950.29	1	1	1
0.28	0.1	20	10.94	0.01	$4,538.08	1.13	949.22	949.19	1	1	1
0.28	0.1	21	10.94	0.01	$4,538.10	1.13	948.12	948.09	1	1	1
0.28	0.1	22	10.95	0.01	$4,538.12	1.13	947.02	946.99	1	1	1
0.28	0.1	23	10.95	0.01	$4,538.14	1.13	945.92	945.89	1	1	1
0.28	0.1	24	10.95	0.01	$4,538.15	1.14	944.83	944.79	1	1	1
0.28	0.1	25	10.95	0.01	$4,538.17	1.14	943.74	943.70	1	1	1

Figure H-14.2 IGBT Module switch quantity characterization - Sheet 2 for superocnducting coil.

SNUBBER PARAMETERS	
dv/dt SNUBBER CAPACITOR (uF)	dI/dt SNUBBER INDUCTOR (uH)
1	0.1

ANTI-PARALLEL DIODE PARAMETERS		
DIODE VT (V)	DIODE r (OHMS)	DIODE Irr (AMPS)
1.6	0.000163529412	578

INPUT PARAMETERS			CACULATED SWITCH MODULE CURRENTS AND LOSSES BASED ON DESIRED OUTPUT MVA								
INPUT VOLTAGE (kVDC)	CHARGING POWER (MW)	SWITCH FREQ (Hz)	TOTAL EST MOD LOSS (kW)	MODULE PEAK CURRENT (A)	MODULE COND LOSS (kW)	MODULE SWITCH LOSS (kW)	TOTAL MODULE LOSS (kW)	ANTI-PARALLEL LOSS (kW)	dv/dt SNUBBER LOSS (kW)	di/dt SNUBBER LOSS (kW)	CONDUCTOR LOSS (kW)
0.28	0.1	0	1.10	357.14	0.46	0.00	0.46	0.59	0.00	0.00	0.05
0.28	0.1	1	1.10	357.14	0.46	0.00	0.46	0.59	0.00	0.00	0.05
0.28	0.1	2	1.11	357.14	0.46	0.00	0.46	0.59	0.00	0.00	0.05
0.28	0.1	3	1.11	357.14	0.46	0.00	0.46	0.59	0.00	0.00	0.05
0.28	0.1	4	1.11	357.15	0.46	0.00	0.46	0.59	0.00	0.00	0.05
0.28	0.1	5	1.11	357.15	0.46	0.01	0.46	0.59	0.00	0.00	0.05
0.28	0.1	6	1.11	357.15	0.46	0.01	0.46	0.59	0.00	0.00	0.05
0.28	0.1	7	1.11	357.15	0.46	0.01	0.47	0.59	0.00	0.00	0.05
0.28	0.1	8	1.11	357.15	0.46	0.01	0.47	0.59	0.00	0.00	0.05
0.28	0.1	9	1.12	357.15	0.46	0.01	0.47	0.59	0.00	0.00	0.05
0.28	0.1	10	1.12	357.15	0.46	0.01	0.47	0.59	0.00	0.00	0.05
0.28	0.1	11	1.12	357.15	0.46	0.01	0.47	0.59	0.00	0.00	0.05
0.28	0.1	12	1.12	357.15	0.46	0.01	0.47	0.59	0.00	0.00	0.05
0.28	0.1	13	1.12	357.15	0.46	0.02	0.47	0.59	0.00	0.00	0.05
0.28	0.1	14	1.12	357.15	0.46	0.02	0.47	0.59	0.00	0.00	0.05
0.28	0.1	15	1.12	357.15	0.45	0.02	0.48	0.59	0.00	0.00	0.05
0.28	0.1	16	1.12	357.15	0.46	0.02	0.48	0.59	0.00	0.00	0.05
0.28	0.1	17	1.13	357.15	0.46	0.02	0.48	0.59	0.00	0.00	0.05
0.28	0.1	18	1.13	357.15	0.46	0.02	0.48	0.59	0.00	0.00	0.05
0.28	0.1	19	1.13	357.15	0.46	0.02	0.48	0.59	0.00	0.00	0.05
0.28	0.1	20	1.13	357.15	0.46	0.02	0.48	0.59	0.00	0.00	0.05
0.28	0.1	21	1.13	357.15	0.46	0.03	0.48	0.59	0.00	0.00	0.05
0.28	0.1	22	1.13	357.15	0.46	0.03	0.48	0.59	0.00	0.00	0.05
0.28	0.1	23	1.13	357.16	0.46	0.03	0.49	0.59	0.00	0.00	0.05
0.28	0.1	24	1.14	357.16	0.46	0.03	0.49	0.59	0.00	0.00	0.05
0.28	0.1	25	1.14	357.16	0.46	0.03	0.49	0.59	0.00	0.00	0.05

Figure H-14.3 IGBT Module switch loss estimation - Sheet 3 for superconducting coil.

Advanced Power Conditioning for Maglev Systems,
US DOT, NMI, A Nerem, EE Bowles, S Chapelle,
RJ Callanan, 1992 -11-Advanced Systems