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Self-Synchronous Propulsion System for Rapid Transit Railcars - Advanced Subsystem Development Program. Volume I: Program Synopsis

General Motors Corp., Goleta, CA. Delco Electronics Div.

Prepared for

Urban Mass Transportation Administration, Washington, DC

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ADVANCED SUBSYSTEM DEVELOPMENT PROGRAM

SELF-SYNCHRONOUS PROPULSION SYSTEM FOR RAPID TRANSIT RAILCARS

FINAL PROJECT REPORT

Volume I - Program Synopsis

Prepared for
The BOEING VERTOL COMPANY
Philadelphia, PA 19142
Under P.O. No. CS 200955

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16. Abstract

Development of the Self-Synchronous Propulsion System was conducted under the Advanced Subsystem Development Program (ASDP), which is a part of the Urban Rapid Rail Vehicle and Systems (URRV&S) Program sponsored by the Urban Mass Transportation Administration. The Self-Synchronous Propulsion System was one of the advanced subsystems that had been identified during the Advanced Concept Train (ACT) proposal evaluation as showing outstanding merit, and was planned to be developed for evaluation by the Transit Authorities. The objective of the overall ASDP was to develop advanced subsystems suitable for application in existing or future transit cars. This report, Volume I, summarizes the content of Volume II, and follows essentially the same outline. Volume II discusses the program technical effort, program scope, objectives, and background; summarizes the design and testing efforts and problem areas; contains conclusions and recommendations; discusses system functional characteristics, train performance characteristics, major component design, interfaces, and product assurance; covers developmental, major component and system level testing; contains a description of the changes made during system testing; discusses the status of the final configuration; and addresses unresolved problems. Volume III contains appendix material which was considered either too bulky or too detailed to incorporate into Volume II. Appendixes A through G are: Train Control Electronics (TCE) Flow Diagrams; Train Performance Analysis Computer Program; List of Drawings and Specifications; Diagostics Unit RAM Memory Code Identification; Diagnostics Unit Subroutine Flow Diagrams; Motor, Power Supply System, U.S. Patent No.3,866,094; and Mapham Inverter and Analytic Model Description, respectively.

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PREFACE

The final documentation submitted under the ASDP Self-Synchronous Propulsion System contract consists of the following:

- Final Project Report – R78-14
    - Volume I - Program Synopsis
    - Volume II - Detailed Technical Discussion
    - Volume III - Appendixes
- Traction Motor Final Report – R78-15
    - Volume I - Technical Discussion
    - Volume II - Appendixes
- Gear Drive and Axle Coupling Final Report – R78-16
    - Volume I - Technical Discussion
    - Volume II - Appendixes
- Reliability Analysis Report – R78-17
- Safety Analysis Report – R78-18
- Maintainability Report – R78-19
- Drawing Package
- Specifications
- Miscellaneous Backup Data

The major report emanating from this program is the Final Project Report, Delco Electronics No. R78-14, which was prepared in three volumes, as shown above.

The program technical effort is discussed in detail in Volume II of this report. Contained in Volume II are the following sections:

I Introduction
II Summary
III Conclusions
IV Recommendations
V System Design
VI Testing
VII Developmental System-Final Status

Section I discusses the program scope, objectives, and background. Section II summarizes the design and testing efforts as well as problem areas uncovered. Sections III and IV contain the conclusions and recommendations respectively. Section V is a detailed discussion and description of the design including system functional characteristics, train performance characteristics, major component design, interfaces, and product assurance. Section VI covers the testing in detail, including developmental, major component and system level testing. Section VII contains a description of the changes made during system testing, the status of the final configuration, and a discussion of unresolved problems.

Volume III contains appendix material which was considered either too bulky or too detailed to incorporate into Volume II. The appendixes included are as follows:

- Appendix A - Train Control Electronics (TCE) Flow Diagrams
- Appendix B - Train Performance Analysis Computer Program
- Appendix C - List of Drawings and Specifications
- Appendix D - Diagnostics Unit RAM Memory Code Identification
- Appendix E - Diagnostics Unit Subroutine Flow Diagrams.
- Appendix F - Motor Power Supply System, U.S. Patent No. 3,866,094
- Appendix G - Mapham Inverter and Analytic Model Description

This present report, Volume I of R78-14, summarizes the contents of Volume II and follows essentially the same outline.

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SECTION I

INTRODUCTION

1.1 PROGRAM SCOPE AND OBJECTIVES

Development of the Self-Synchronous Propulsion System was conducted under the Advanced Subsystem Development Program (ASDP) which is a part of the Urban Rapid Rail Vehicle and Systems (URRV&S) Program sponsored by the Urban Mass Transportation Administration (UMTA) with the Boeing Vertol Company as Systems Manager. The Self-Synchronous Propulsion System was one of the advanced subsystems that had been identified during the Advanced Concept Train (ACT) proposal evaluation as showing outstanding merit, and was planned to be developed for evaluation by the Transit Authorities. The objective of the overall ASDP was to develop advanced subsystems suitable for application in existing or future transit cars.

The ASDP propulsion system was planned to be incorporated into the two-car State-of-the-Art Car (SOAC) train for testing and evaluation at the Transportation Test Center (TTC) at Pueblo Colorado. Other advanced subsystems to be evaluated concurrently with the propulsion system were an Improved Ride Quality Monomotor Truck and a Synchronous Brake System.

1.2 PROGRAM BACKGROUND

Direct current motors, primarily the series-wound type, have provided (and continue to provide) relatively good service in electric traction applications for rail transit cars. Their inherent torque-speed characteristics, excellent overload capabilities and relative insensitivity to fluctuations in line voltage make them well suited to these applications.

However, due to their disadvantages there has long been a desire by many users to replace them with commutatorless ac motors. These disadvantages include:

- Requirement for frequent inspection of commutator and brushes
- Brush replacement and commutator maintenance
- Large size and weight (low power density)
- Difficult to seal from the environment.

Until recently, only the dc motor was considered practical for traction applications because of the low starting torque and limited speed range of ac motors — unless controlled from a variable frequency, variable voltage source. The use of ac motor drives only became practical with the advent of high power capacity thyristors which have made possible the development of compact, reliable, and efficient static power converters.

Laboratory development conducted by Delco Electronics - Santa Barbara Operations (DE-SBO) beginning in 1972 under an in-house funded effort had indicated that an ac propulsion system based on a self-controlled synchronous motor would be well suited to transit car drive application. The lower weight and reduced size of the traction motor would permit easy integration with a monomotor truck, improving ride dynamics and eliminating spin-slide within a truck. The inherently good electrical braking capability of the synchronous machine would permit greater energy recuperation in the regenerative mode and reduce wear of the friction brakes. It was also expected that the brushless motor design and solid state controls, combined with liquid cooling, would result in higher reliability and reduced maintenance. (The features of the system which made it an attractive candidate for transit application are summarized in Table 1-I.)

In 1972 DE-SBO participated in the Phase I effort of the ACT-1 program with the LTV Corporation. As the culmination of this effort, a proposal was submitted to LTV for the ACT-1 program in late 1972. Garrett was awarded the contract for ACT-1 in January 1974. Subsequently Boeing Vertol and UMTA continued to evaluate advanced subsystems from the "losing" proposals for the ASDP program. In April 1974, Boeing Vertol issued a sole source RFP to DE-SBO for the ASDP propulsion system; a proposal was submitted in May 1974. Due to funding limitations, contract award to DE-SBO was delayed to October 1975.

Contract-funded development effort on the propulsion system started in October 1975. The basic design and engineering effort was conducted essentially in accordance with the original schedule and within planned expenditures. PDR and CDR were successfully completed in February and June 1976, respectively. Fabrication of the Test Article to be used for system level qualification testing was started in July 1976 and completed in December 1976. During the checkout of the Test Article propulsion system, technical problems were uncovered requiring redesign and modifications, delaying the system level testing effort and resulting in significant cost overruns. By October 1977, most of the key technical problems

- Utilizes ac Synchronous Machine
  - Inherent dc traction motor performance characteristics
  - Brushless operation
  - Low weight and compact size (1260 lb)
- Utilizes Solid State Power Control Electronics
  - Stepless control
  - High efficiency (79% to 86% system efficiency)
  - High reliability and reduced maintenance (100,000 Mile MD BF)
- Controlled Environment through Liquid Cooling
  - Liquid cooling provides clean stable environment for motor and electric controller
- Provides Regenerative and/or Dynamic Braking
- Redundant Propulsion Systems Minimize "Dead Car" in Service

Table 1-I. Salient Features of the Self-Synchronous Propulsion System

were identified and laboratory test results indicated that the propulsion system concept could be successfully developed. However, it was identified that substantial additional funds would be required to complete full-scale engineering development. In addition, it appeared doubtful that the potential market was substantial enough to justify the additional required investment.

In November 1977 UMTA and Boeing Vertol decided to discontinue the development of the Self-Synchronous Propulsion System. It was decided to complete the development, fabrication, and delivery of all truck mounted equipment (traction motor, gear drive, and axle coupling, etc.), but to stop the system laboratory testing of the propulsion electronics equipment after completion of some additional tests. The Test Article and residual material for the four planned prototype systems (partially completed) were to be delivered for final disposition by Boeing and UMTA. A comprehensive set of reports and general documentation comprise the balance of deliverables under this contract.

SECTION II

CONCLUSIONS

Based on the experiences and results of the ASDP propulsion system program, several conclusions can be drawn. These can be grouped into two categories: program related conclusions and technical conclusions.

Program Related Conclusions

- In retrospect, it is obvious that the program was planned on an overly optimistic, success-oriented basis.

  The schedule from the start of design to delivery of qualified hardware was unrealistic for a new advanced system of this degree of sophistication.

- Too much reliance had been placed on the results achieved during extensive IR&D effort carried out prior to the ASDP program.

  It had been assumed that a prototype system (called a Test Article in this report) based on the IR&D designs could be fabricated, checked out, and debugged expeditiously in a straightforward routine manner.

  However, the IR&D effort had been carried out using breadboard electronics and modified commercial motors, which fact, combined with some laboratory equipment limitations, had not permitted complete verification of all key operating concepts over the complete motoring and braking torque-speed profiles. In retrospect, it appears obvious that the IR&D effort was not as extensive as originally assumed.

- The program experienced several unforeseen problems during Test Article system integration, checkout, and testing resulting in schedule delays and cost overruns. Technical problems arose with the Test Article which were difficult to troubleshoot and diagnose and which, in some cases, required extensive circuit rework to correct. In retrospect, it is obvious that insufficient contingency time and funding had been allocated for the solution of possible problems that might arise.

- Deliverable hardware was prematurely committed to manufacturing.

This was deemed necessary to meet schedules established for integration of equipment into the SOAC vehicles. As a result, there is a considerable amount of residual material and partially complete hardware that would require rework.

- The propulsion system design turned out to be more complex that originally envisioned, expecially in the areas of low level motor and train control electronics.

  To establish whether this was due to over-sophistication in the design approach, to overstated requirements, to the incorporation of too many "nice-to-have" features, or whether this is basic to the concept, would require extensive analysis and evaluation.

Technical Conclusions

Conclusions relative to the technical capabilities of the ASDP propulsion system can be discussed in relation to the expected advantages and benefits shown previously in Table 1-I.

- AC Synchronous Machine

  The traction motor development effort resulted in a successful self-synchronous machine design. Although some problems were encountered during testing, these have been resolved. The development cycle of this motor, however, cannot be considered complete until consistent high speed - high torque performance has been demonstrated and actual "in-service" experience has been accumulated.

  It has been demonstrated by testing and analyses that all major performance requirements (torque/speed, efficiency, electrical characteristics, etc.) are met or exceeded.

  - The inherent dc traction motor performance characteristics provided by field excitation proportional to armature current were demonstrated. The high torque required at low speeds for acceleration was achieved and maximum power operation over a 3.4:1 speed range was demonstrated.
  - Brushless operation was obtained by the successful development of a rotary transformer and rotating rectifier for field excitation. A problem relative to the transient protection of the rotating rectifier diodes was resolved by incorporating a crowbar circuit and fast recovery diodes.

- Low weight and compact size of the motor have resulted partly from high speed operation and partly by the use of liquid cooling. Although the original weight goal was not met, the ASDP traction motor still shows a 2 to 1 weight advantage over most transit dc motor designs such as the SOAC motors.
- High reliability and reduced maintenance cannot be demonstrated without actual operation in a transit car environment. The elimination of brushes and commutators, and the provision of a completely sealed design due to liquid cooling, however, promises significant improvements.

- Solid State Power Control Electronics

Extensive system level dynamometer testing indicates that the overall design approach is sound. Test results obtained in the motoring mode demonstrated that the power/torque/speed characteristics can be met throughout the full torque-speed regime. Furthermore, measured system efficiency exceeds the predicted values. All performance verifications tests were accomplished in an "open loop" mode of operation. No conclusions can be made, therefore, relative to "closed loop" system operation using the microprocessor based train control electronics.

- Smooth stepless control of the solid state power controller was verified by testing. Control is accomplished by simply varying the inverter frequency.
- System efficiency (from dc power input to motor shaft output) at full power level was measured at 79.3% to 87.2% over a wide speed range. This compares favorably with the predicted values of 79% to 86% for the same speed range.
- Reliability and maintenance advantages cannot be demonstrated without operation in the transit environment. The use of solid state components with liquid cooling and the elimination of most mechanical contactors used in other propulsion systems, however, promises potential for improvements in these areas.

- Liquid Cooling

  A unique feature of the Delco propulsion system is the liquid cooling of the motor and the power electronics using a fire resistant coolant (silicone). The effectiveness of the liquid cooling concept was verified during the extensive system level testing. Temperatures monitored inside the traction motor were below predicted levels and no high power solid state device failures could be attributed to inadequate cooling during testing. The only temperature related failure identified (a field supply transformer) is easily corrected by modifications to the transformer and cooling loop designs.

- Electrical Braking

  The test data obtained during systems testing in the dynamic braking mode of operation indicated that the full braking torque specified for the system can be realized throughout the speed range. Test data obtained demonstrated the maximum required capability below 2000 rpm. At higher speeds, full torque test data could not be obtained due to dynamometer and SCR voltage limitations. Analytical predictions correlated with test data indicate, however, that full dynamic braking capability can be provided essentially over the full torque/speed range.

  Regenerative braking capability was not verified prior to the termination of the program.

- Propulsion System Redundancy

  Provision was made in the design for redundant propulsion systems. Each truck is provided with an independent propulsion system to allow continued transit car operation (at reduced capability) after a failure in one of the drive systems.

Summary

Although development is incomplete (see paragraphs 5.3.3 and 6.2) the self-synchronous propulsion system concept is considered a good potential for transit car application.

The status of the Test Article hardware and documentation is considered to be such that continuing development can be undertaken, if so desired.

SECTION III
RECOMMENDATIONS

It is felt that the self-synchronous propulsion system represents a major advance in the state of the art. The extent of further development must carefully consider two key economic factors:

(1) Life-cycle costs
(2) The potential market.

A preliminary market analysis and life cycle cost assesment should be conducted prior to any further work. After that careful reassessment of these factors based on current information, a refinement of the life cycle costs would require further system and equipment development before final estimates could be made with a reasonable degree of confidence. This can be done only with respect to a specific, well-defined design. To this end a two-phase program would be recommended.

Phase I

- Continue dynamometer evaluation of the Test Article system by completing the "open loop" testing. One of the remaining major areas of investigation is the regenerative braking system performance.
- Update the Test Article design by incorporating the changes recommended in Section VII of Volume II of this report, as well as any additional modifications found necessary as a result of further system testing.
- Include the Train Control Electronics in the system test setup and conduct "closed loop" testing in motoring and braking. It is anticipated that a system simulation effort will be required to support the "closed loop" testing.
- Validate the propulsion system design by a comprehensive dynamometer test program that fully qualifies the system with respect to specification requirements and also verifies the operating advantages of self-synchronous ac drives.
- Conduct a comprehensive analysis to establish system life-cycle costs and the operating advantages of self-synchronous ac drives. Also conduct a survey of the transit industry to establish the potential marked for ac drives of this type.

Phase II

- Complete fabrication of the prototype equipment for one or two transit cars incorporating the changes recommended earlier.
- Install propulsion system equipment on one or two SOAC cars along with new trucks and brakes.
- Conduct engineering testing at Pueblo with the SOAC car(s) to evaluate performance of the propulsion system, monomotor trucks, and brakes under simulated transit car operating conditions.
- Conduct a 10-car demonstration program in revenue service after successful engineering evaluation at Pueblo.

Phase II should not be initiated until all Phase I efforts are completed. This includes demonstration of compliance with all technical objectives under laboratory conditions and the establishment of favorable life-cycle costs and operating advantages.

SECTION IV
DESIGN

4.1 GENERAL

The self-synchronous propulsion system design is a departure from convention in both the motor and the controller. The motor is a wound rotor synchronous machine made brushless by means of a rotary transformer and rotor mounted rectifier, and made self-controlled by the addition of a rotor position sensor. The field is excited with a current transformer to obtain a dc field current proportional to armature current (as in a series dc motor). The power control equipment was newly developed to match the special characteristics of the synchronous motor.

The propulsion system described here is considered well suited to transit car drive applications. The lightweight, compact traction motor is easily integrated with a monomoter truck to eliminate slip-slide within a truck and provide improved ride dynamics. The inherently good electrical braking capability of the synchronous machine provides high energy recuperation in the regenerative mode and less wear of friction brakes. The resultant low maintenance and reduced energy consumption lead directly to lower life cycle costs. Such features as redundancy, brushless motor design, contamination-free liquid cooling, and solid-state power circuitry assure high reliability and availability.

4.2 PERFORMANCE REQUIREMENTS

The major performance requirements affecting propulsion system design characteristics were based on an AW1 car weight of 95,200 lb and operation of a single car at a nominal 600-volt 3rd rail voltage.

Two sets of requirements were postulated: one for operation over the ACT-1 Synthetic Transit Route of the HSGTC at Pueblo, Colorado; the other was a set of discrete requirements. These can be summarized as follows:

Synthetic Transit Route

- For the conditions of new wheel diameter (30 in.) and no wind, propulsion system energy consumption over a round-trip shall not exceed 10.2 kW-hr/

car mile when regenerative braking is not used. With regenerative braking and a fully receptive line, consumption shall not exceed 6.4 kW-hr/car mile.

- With no time allowance between clockwise and counterclockwise runs, total round trip time for the 18.5 mile distance shall not exceed 39 minutes.

Discrete Requirements

- Under the conditions of no wind and level tangent track, the railcar shall be capable of maintaining a speed of 80 mph continuously with either new (30 in.) or worn (28 in.) wheels.
- Under the conditions of level tangent track and a 15 mph headwind, and with either new or worn wheels, the railcar shall be capable of intermittent 80 mph operation.
- With no wind, and with either new or worn wheels, the railcar shall be capable of maintaining a speed of 70 mph on a positive 3% grade for a distance of 6,000 ft.
- Under the conditions of level tangent track and no wind, and with new wheels, the railcar shall be capable of meeting the following acceleration requirements:
    - 3.0 ± 0.2 mphps to 25 mph
    - From stop, travel 700 ft in 20 sec (from input signal to the controller)
    - From stop, reach a speed of 60 mph in less than 38 sec.
- Under the conditions of level tangent track, no wind and new wheels, dynamic braking alone shall provide a deceleration level of -3.0 ± 0.2 mphps from 80 mph to 10 mph.
- For the case of new wheels, regenerative braking shall be available from 80 mph to 25 mph.
- Jerk rate shall not exceed 2 mphpsps.

In addition to the above, thermal design criteria for the propulsion system equipment were specified as follows:

- The continuous thermal rating and design shall be based on operation over the Synthetic Transit Route.

- The maximum capability thermal design shall be based on a duty cycle consisting of full power acceleration to 80 mph followed immediately (no steady-state) by full dynamic braking (supplemented at low speed with friction braking) from 80 mph to zero, rest for 20 sec., and then repeat over a 30 min. period. (This assumes that operation is within the acceleration, deceleration, and jerk constraints previously stated.)

4.3 OVERALL SYSTEM FUNCTIONAL DESCRIPTION

4.3.1 GENERAL

The ASDP propulsion system consists of the following major elements: train control electronics (TCE), motor control electronics (MCE), power control electronics, traction motor, gearboxes, cooling unit, and dynamic brake resistor. Duplicate independent propulsion systems (except for the line filter inductor) are provided for each truck of the transit car. A simplified block diagram of the dual propulsion systems is shown in Figure 4-1.

The TCE is implemented with a digital computer utilizing a microprocessor and conventional input/output interface devices. The MCE is a hard wired assembly of combinatorial and sequential logic elements, operational amplifiers, comparators, and passive components. The power control electronics portion of the propulsion system contains a line filter inductor, a power control switchgear assembly, a resonating inductor module, and a power converter assembly. The latter contains five liquid cooled modules; inverter, cycloconverter, capacitor, field supply, and brake control.

The TCE receives and interprets the P-signal, a tractive effort command generated by the motorman. Using the P-signal, a desired torque is computed. Based on motor operating parameters an actual torque is also computed. The torque command signal from the TCE to the MCE is then corrected to eliminate the error.

The MCE controls the power control electronics in response to the torque command signals and thereby provides closed loop torque control. In the motoring mode, this is accomplished by a voltage controlled oscillator (VCO) which changes the frequency of the inverter. In the braking mode, torque is controlled by some combination of motor field excitation control and brake module SCR phase delay gating control. The MCE also implements motor commutation and power factor advance control.

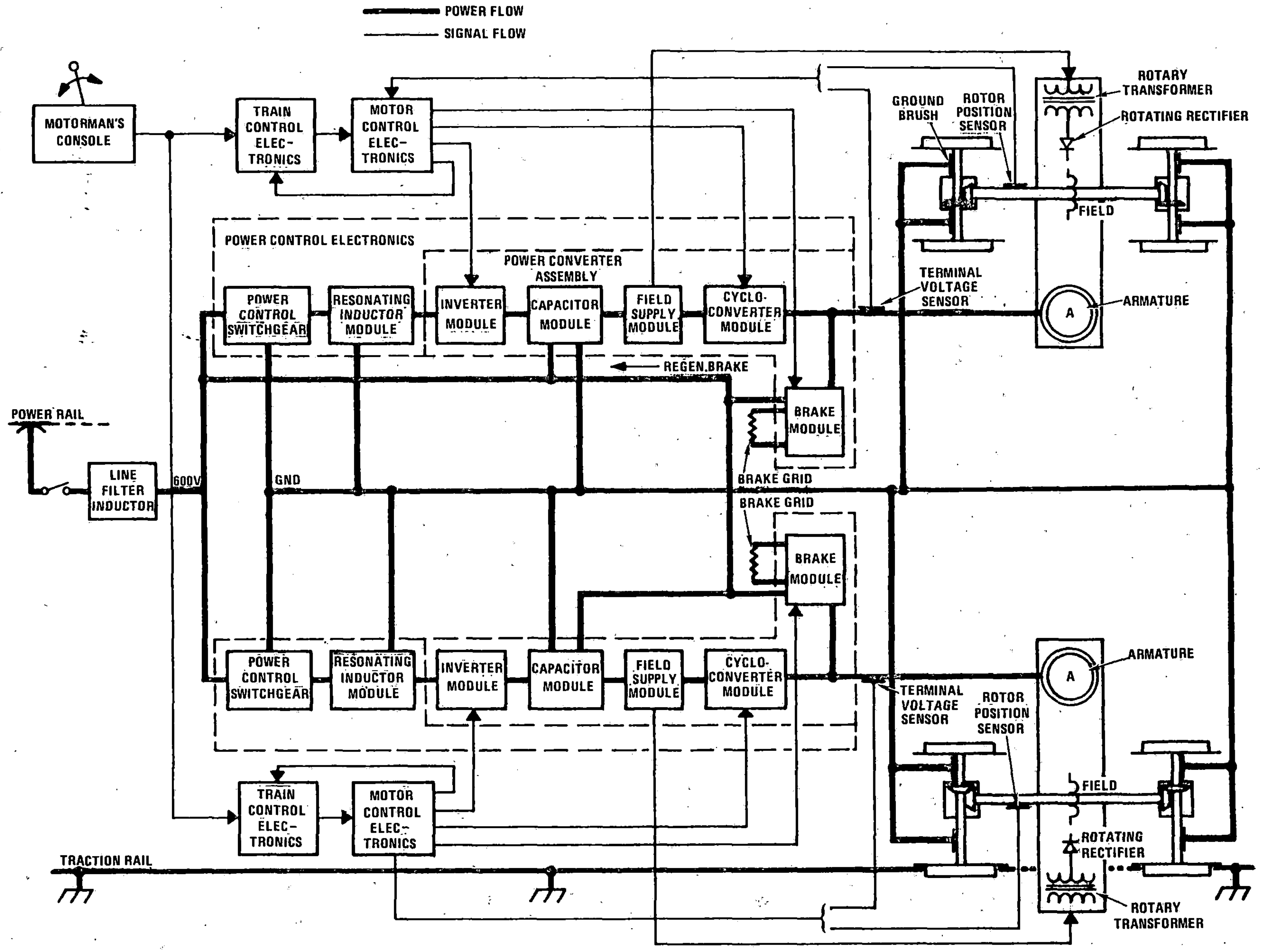


Figure 4-1. Propulsion System Block Diagram

A line filter inductor serves as an input line filter element for both propulsion systems. The high projected reliability of the single inductor permitted its use with the otherwise redundant propulsion systems with a negligible effect on overall reliability.

The power control switchgear unit contains the main contactor and blocking diode, electrolytic capacitor bank, and overcurrent relay.

The traction motor (one per truck) is a brushless four-pole synchronous machine with forced convection liquid cooling. In motoring it has an output capability of 1560 lb-ft of torque from 0 to 1646 r/min and 489 hp from 1646 to 5642 r/min (80 mph). In dynamic braking it has an output capability of 1405 lb-ft from maximum speed to about 600 r/min. It can regenerate from maximum speed down to about 25 mph. The machine is fitted with a rotary transformer-rotating rectifier in lieu of the usual exciter-rotating rectifier found in constant speed synchronous alternators. A rotor position sensor is installed in one end of the motor. The double ended motor drives two hypoid gear sets (5.875 to 1 reduction), having output shafts coupled to the axles by a rubber bushed flexible linkage.

Each of two independent cooling units consists of a double-ended ac motor driving separate pumps for cooling of the power electronics and traction motor with a fire resistant silicone fluid. Heat is extracted from the coolant by a single two-section liquid-to-air heat exchanger. Air flow is provided by an ac motor and propellor fan.

Power supply current is collected from a nominal 600 Vdc third rail by means of a pickup shoe and returned to earth through the contact between the wheels and the traction rails. Ground brush assemblies on each axle complete the rotating connection between the vehicle power ground and the wheels.

4.3.2 TRAIN CONTROL FUNCTIONAL CHARACTERISTICS

The ASDP Train Control Electronics (TCE) provides the interface control for the major subsystems of the SOAC car. It gathers information from the Train Lines (T/L), Synchronous Brake System (SBS), Motor Control Electronics (MCE), the motor, and the Master Controller. In turn, it produces the required control responses. The nerve center of the TCE is an 8-bit microprocessor system. The CPU is an Intel 8080A which operates with a 1 MHz crystal oscillator. The program memory provides room for 8,000 instruction bytes and scratchpad memory provides 2,000 locations for data and intermediate solutions.

The Propulsion-signal (P-signal) current sensor is part of the TCE. This signal is a zero to 1.0 ampere current where 0.55A to 1.0A represents zero to maximum motoring effort and 0.45A to 0.0A represents zero to maximum braking effort. The TCE interprets the P-signal, develops the appropriate system mode commands, and computes a desired torque based on the P-signal tractive effort command. The computation compensates for items such as speed, car weight, coolant temperature and pressure, and wheel diameter. The TCE also monitors motor current, voltage, speed, etc., and based on these inputs computes the actual torque being developed by the motor. Based on a comparison of the actual and desired torque levels, the TCE then modifies the motoring or braking mode torque command signals sent to the MCE.

If operation is in the braking mode the braking rate command signal and the actual electrical braking effort being developed are also sent to the SBS. If the electrical braking effort is less than that commanded, the SBS provides supplemental friction braking.

The TCE determines whether a motor should provide dynamic or regenerative braking by testing the receptivity of the line. Depending on how receptive the line is determined to be, one or both motors of a car are allowed to attempt regenerative braking. If regeneration is not allowed, dynamic braking is selected. One motor may regenerate while the other is in dynamic braking.

The TCE always maintains spin control authority. Slide control authority is divided between the SBS and the TCE. Below a predetermined speed, slide authority is transferred to the SBS and all electric brake effort is removed. When the TCE has slide authority and a slide is sensed the SBS is notified and electrical tractive effort is reduced.

The TCE opens and closes the main contactor and monitors its proper operation. Both line voltage and car battery voltage are monitored by the TCE. Improper operation of either of these voltages results in some positive action on the part of the TCE. Propulsion trip and reset capability is channeled through the TCE. If motor speed exceeds 6,000 r/min the TCE signals a system shutdown. The TCE prevents rollback and provides logical safety decisions which are required during rail gap transitioning.

The microprocessor train controller performs its functions in a cyclical fashion. At turn on, before motion is commanded, it determines if all the conditions for propulsion and safety are satisfactory. This test must be complete and total compliance confirmed before motion is achievable. Once the preliminary checks are satisfied the operational instructions are executed serially. This total loop time for the motoring mode is approximately 25 milliseconds. Data memory is updated each loop. Any of the safety and alarm signals that require immediate servicing are handled through the priority interrupt system in a matter of a few microseconds.

4.3.3 MOTOR CONTROL FUNCTIONAL CHARACTERISTICS

4.3.3.1 Motoring Mode Operation

In the motoring mode, (Figure 4-2), filtered dc power is converted to variable frequency ac power by the three-phase inverter. The inverter frequency is varied over a range of 350 to 1200 Hz by the tractive effort signal to control the reactance of, and hence the current through, the coupling capacitors. This current is converted to a lower frequency motor stator current by the action of the cycloconverter. The reactance of the coupling capacitors also gives the cycloconverter a current source output characteristic.

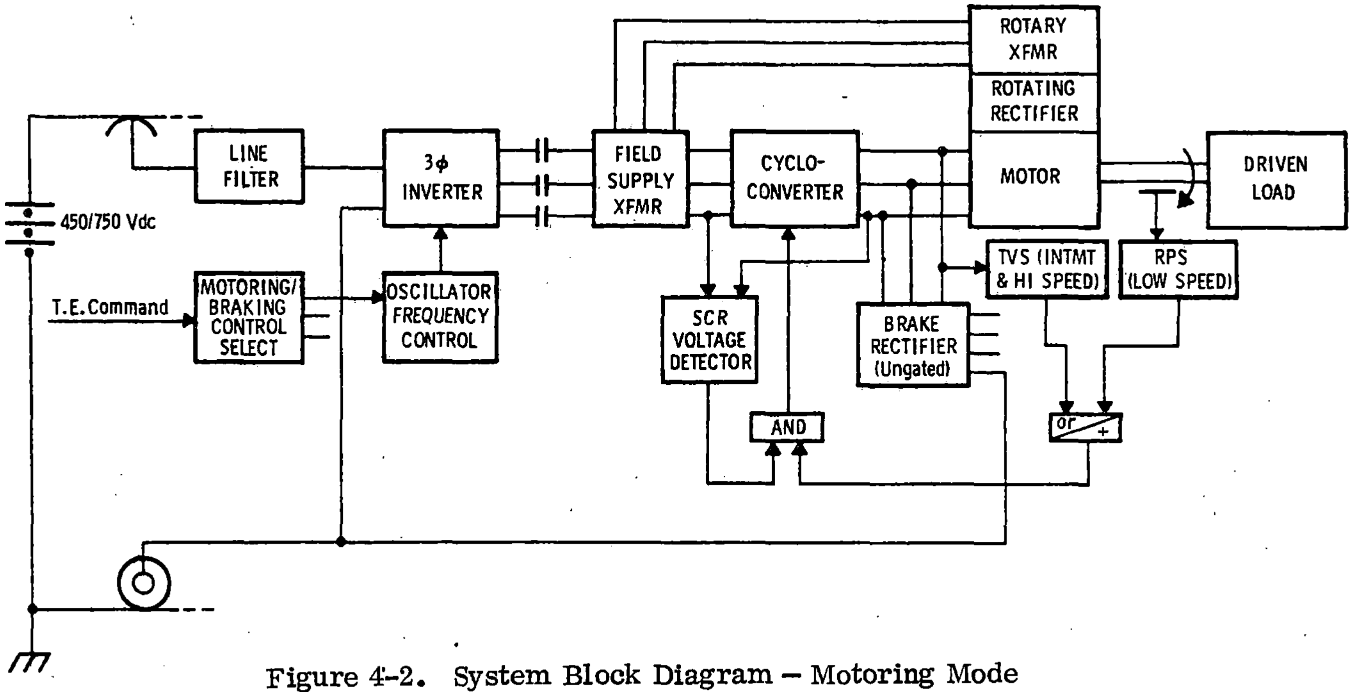


Figure 4-2. System Block Diagram – Motoring Mode

Inverter Stage

Figure 4-3 shows the simplified circuit of the three-phase inverter. This unit consists of three single-phase series inverters gated to produce three-phase output voltage and current. The inductors and capacitors are key elements of the inverter since they largely determine its efficiency. The use of these low-loss inductors and capacitors yield an inverter efficiency of approximately 95% over a relatively wide frequency range.

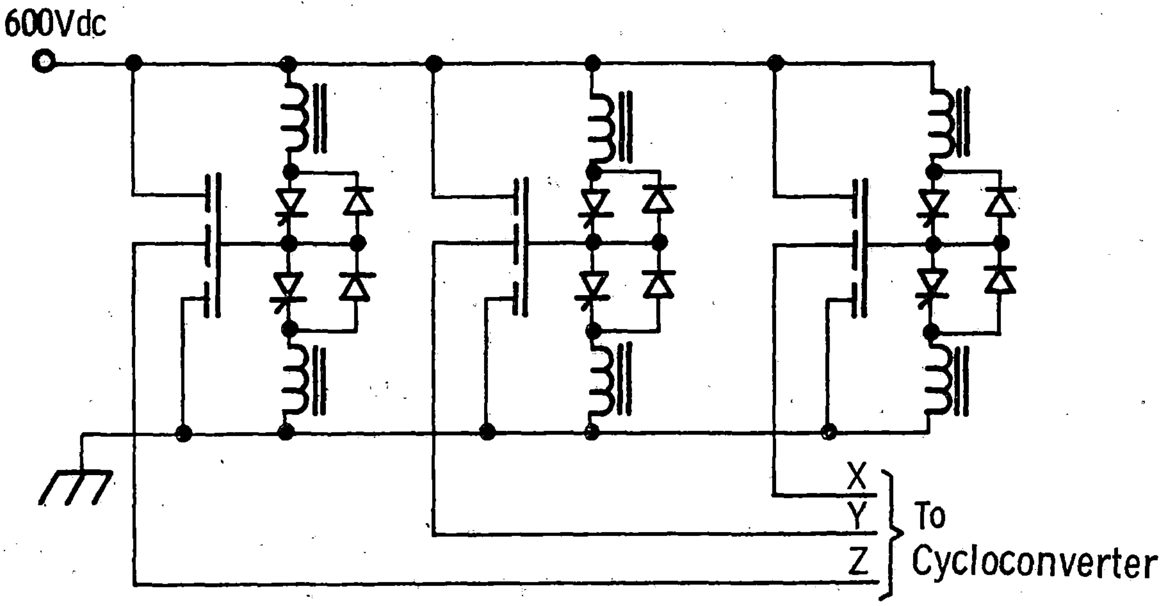


Figure 4-3. Input Inverter Stage

The inverter SCRs are 150μs turn-off time devices with 2000 V blocking capability. The diodes anti-parallel to the SCRs are a fast recovery type. dV/dt suppression circuits (not shown) connected across each SCR/diode pair prevent spurious SCR turn-on with a minimum of dV/dt circuit power loss.

Cycloconverter Stage

The cycloconverter is an arrangement of six groups of three SCRs as shown in Figure 4-4. At any instant of time two SCR groups, one for positive and one for negative current, are gated to form the equivalent of a full wave rectifier supplying current into one motor phase and out of another. Again, at any instant of time (except for periods of commutation overlap), the voltage and current conditions in the external circuit cause conduction in two of the six gated SCRs.

Cycloconverter gate pulse timing is derived from three control signals. Two of the signals accomplish motor self control; at low speeds by the rotor position sensor (RPS), and at intermediate and higher speeds by the motor CEMF sensor (TVS). Use of CEMF at intermediate and high speeds permits the desired power factor control. The composite RPS - TVS signal is ANDed with a signal which indicates the voltage across the cycloconverter SCRs to produce an SCR gate pulse which is applied when individual SCR anode voltages become positive. (See Figure 4-2.)

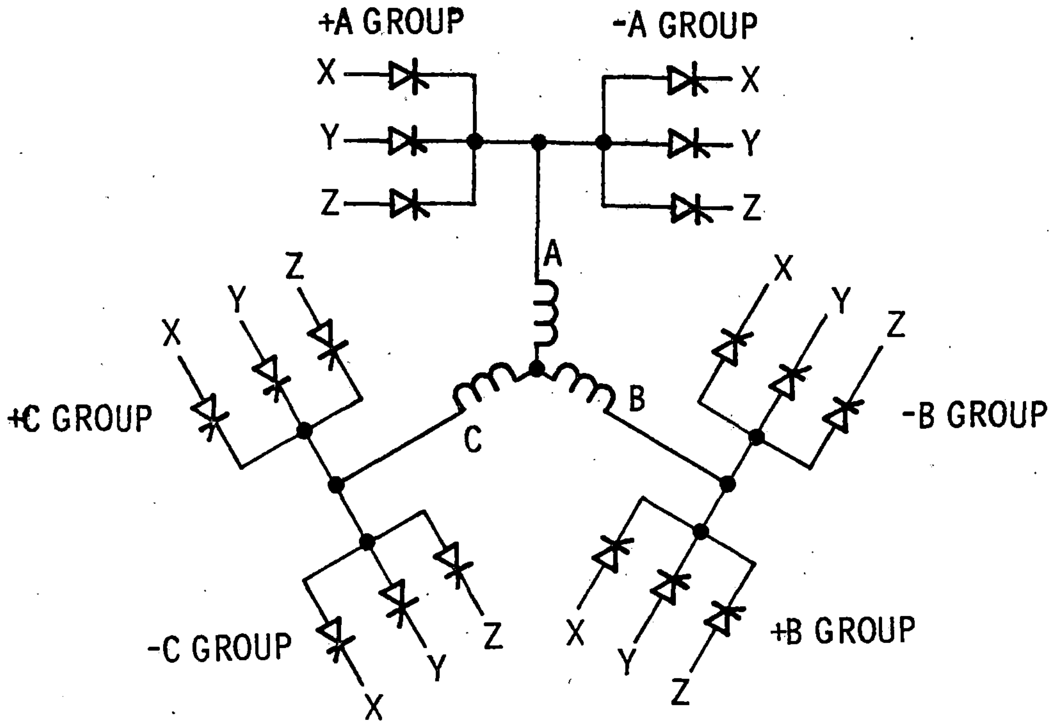


Figure 4-4. Cycloconverter Circuit

Motor Field Excitation

The synchronous traction motor makes use of a rotary transformer and a rotating rectifier for brushless field excitation. The primary of the rotary transformer is powered from a current transformer having primary windings in series with the cycloconverter input current. Two advantages result from this form of field power supply over the alternative use of a separate field supply inverter. First, the transformer supply is smaller and much less complex than an inverter. Second, the current transformer provides (except at low frequencies where rotary transformer magnetizing current is significant) motor field current proportional to armature current. This gives the traction motor a desirable motor speed-torque characteristic similar to a dc series motor and also maintains the motor torque angle approximately constant for stable operation and reliable commutation.

Motor Current Commutation

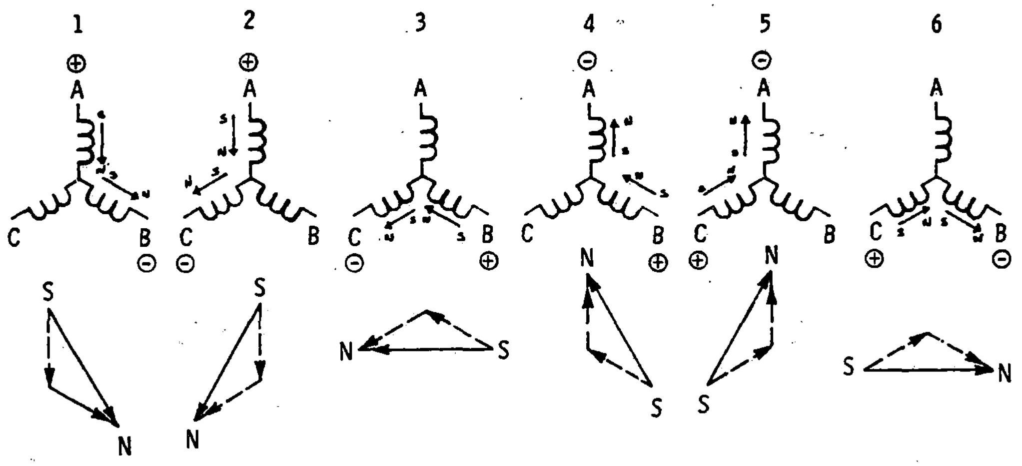
The commutation, or transfer, of current from one motor phase to another occurs in three modes: input line commutation, motor output line commutation, and mixed input/output line commutation. The commutation is initiated by the simultaneous removal of SCR gate pulses from the three SCRs in the phase to be turned off and the application of gate pulses to the three SCRs in the phase to be turned on. The one SCR of the three in the off-going group that was conducting is turned off by the application of reverse voltage from the external circuit.

At low motor speeds, where motor CEMF is much less than the inverter voltage, the SCR reverse voltage following gate current removal is derived from reversals of the cycloconverter input line voltage. At high motor speeds and accompanying high CEMF, the cycloconverter is timed to operate at a leading power factor. This produces a negative voltage on the off-going SCR when the on-coming SCR group is gated into conduction. At medium motor speeds, both input and output voltage provide commutation.

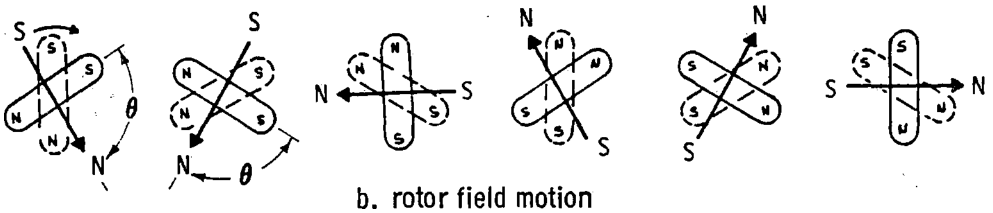
Motor Torque Production

The creation of rotor torque from stator current and field flux can be visualized with the aid of Figure 4-5. The field is depicted as a rotating magnet producing a flux Φ having north and south poles while the stationary armature (stator) is shown as three wye-connected coils. With the rotor in position No. 1, the RPS signals, augmented by the CEMF sensor signals, direct the cycloconverter to inject current into phase A and remove it from phase B. The resulting A-B armature MMF vector lies at an angle θ with respect to the field magnet vector. Torque is produced according to the proportionality $T \alpha I \Phi \sin\theta$.

Because of the high frequency of the cycloconverter rectification process and the armature inductance, current is relatively constant. Torque thus varies with $\sin\theta$. As the rotor turns against the load torque, the transition from position No. 1 to position No. 2 is made where the composite RPS/CEMF signal directs the cycloconverter to transfer (commutate) current from phase B to phase C. At the transfer point, the armature MMF steps ahead 60°. Once again, torque varies as $\sin\theta$, where θ is referenced 60° in advance of the original reference in position No. 1. The self-controlled torque production process described above continues indefinitely as long as motor torque is able to overcome the load torque.



a. armature MMF switching



b. rotor field motion

Figure 4-5. Generation of Self-Synchronous Rotating Stator Field

4.3.3.2 Braking Mode Operation

In braking, the traction motor is operated as a separately excited generator connected to phase delay controlled dynamic and regenerative brake rectifiers (see Figure 4-6).

Field Excitation

Field excitation is provided by the same high frequency transformer used in motoring. The transformer is modified by de-energizing the low impedance primary winding by removing the cycloconverter SCR gate signals and by connecting high impedance windings through a relay to the inverter. Generator field current is then controlled by varying the inverter frequency over a range from 350 Hz to 1100 Hz. Inverter input power varies from approximately 1.0 to 30.0 kW over this frequency range. Braking effort in dynamic and regenerative braking is controlled by a combination of field current control and rectifier phase control.

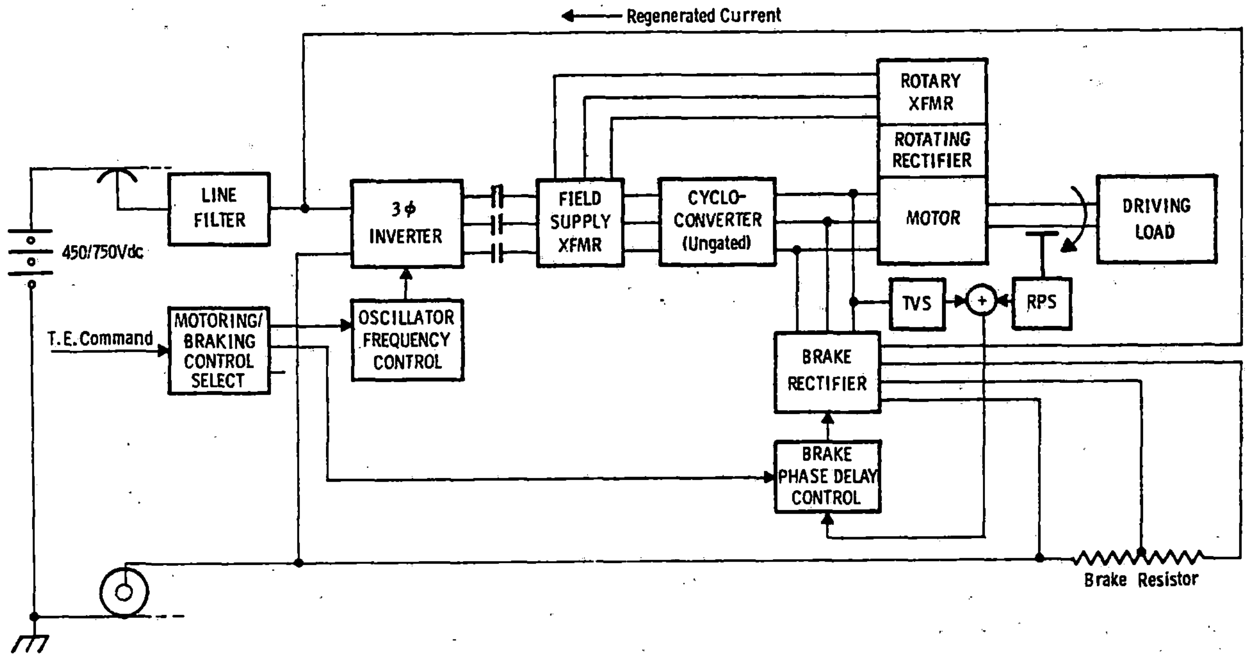


Figure 4-6. System Block Diagram – Braking Mode

Braking Effort Control

The braking control modes available are:

1. Both trucks in dynamic braking
2. Both trucks in regenerative braking
3. One truck in dynamic and one truck in regenerative braking.
4. Each truck in simultaneous dynamic and regenerative braking.

In mode 1, tractive effort can be controlled by field current. This is desirable to minimize motor heating and torque pulsations. In modes 2, 3 and 4, a combination of field and phase delay control is used. Phase control is also used for those control functions which require rapid modulation of tractive effort such as slide control, jerk control during mode transitioning, motor overvoltage control, and dc line overvoltage limit control during regenerative braking.

Dynamic braking is accomplished with only one brake resistance change to maintain full braking effort while slowing from 80 mph to approximately 7 mph. This single resistance change contrasts with the typically six resistance changes required for a dc motor propelled transit car.

Brake Rectifier

The brake rectifier unit consists of nine SCRs in a dual semi-converter circuit with a tenth SCR used for brake resistor shunting. These are ungated in the motoring mode.

4.4 EQUIPMENT DESCRIPTION

Overall Design

The propulsion system provides one motor for each truck of a transit car, a separate gear drive and coupling assembly for each axle, separate power controls and cooling units, and miscellaneous equipment to interface with the car. This configuration provides redundant propulsion units whereby the car may continue to operate at a reduced performance level should one drive system become disabled (see Figure 4-7).

In service, the system obt ains nominal 600 Vdc power from third rail shoes; this is routed through the line filter to individual power control switchgear assemblies containing power contactors and overcurrent protection equipment. The filtered dc power provided to each drive system is then convertered to 3-phase ac power suitable for the traction motors.

As shown in Figure 4-7, the traction motors are also connected to the brake modules of the power converter assemblies. During electrical braking, when the motor is functioning as a generator, power is directed back through the line filter for regenerative braking, or to the resistor grid for dynamic braking. A separate cooling assembly for each drive system routes a liquid coolant through each traction motor and power converter. An electronic control unit containing the low level circuitry for both train control and propulsion control is mounted in the operator's cab and powered from the car battery. Diagnostic equipment is also provided for system checkout, monitoring, and fault isolation.

The overall arrangement of the propulsion system components on the SOAC car is illustrated in Figure 4-8.

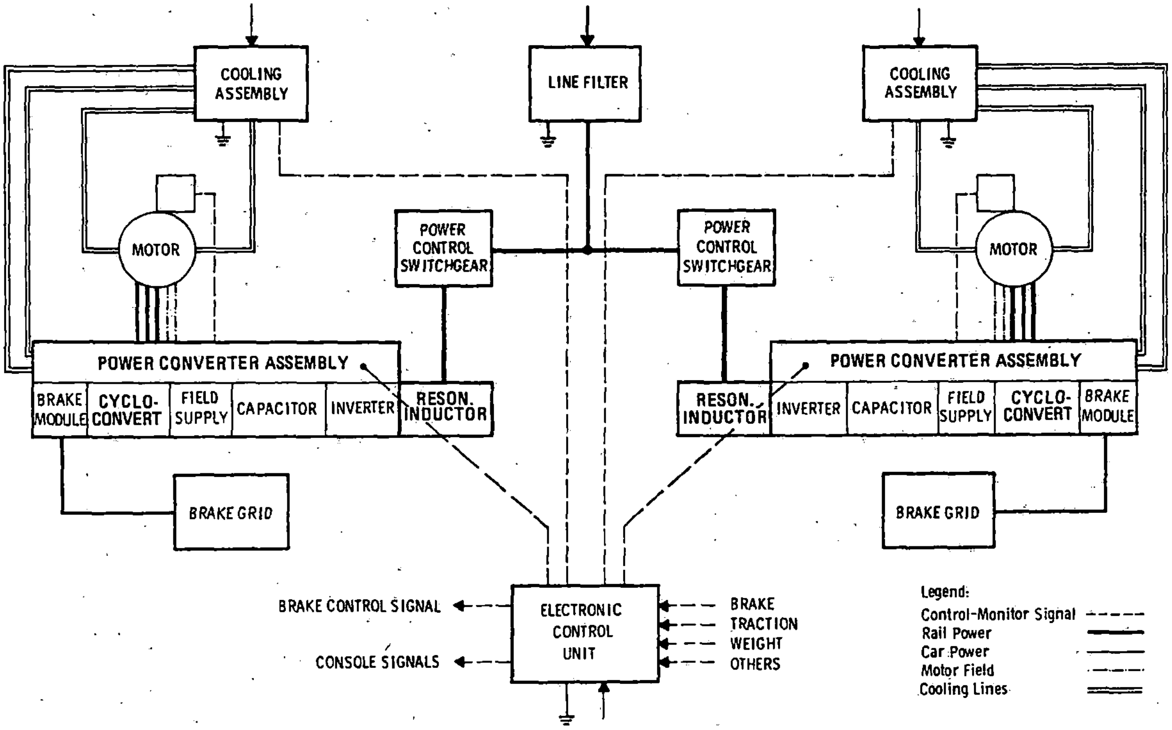


Figure 4-7. Propulsion System Block Diagram

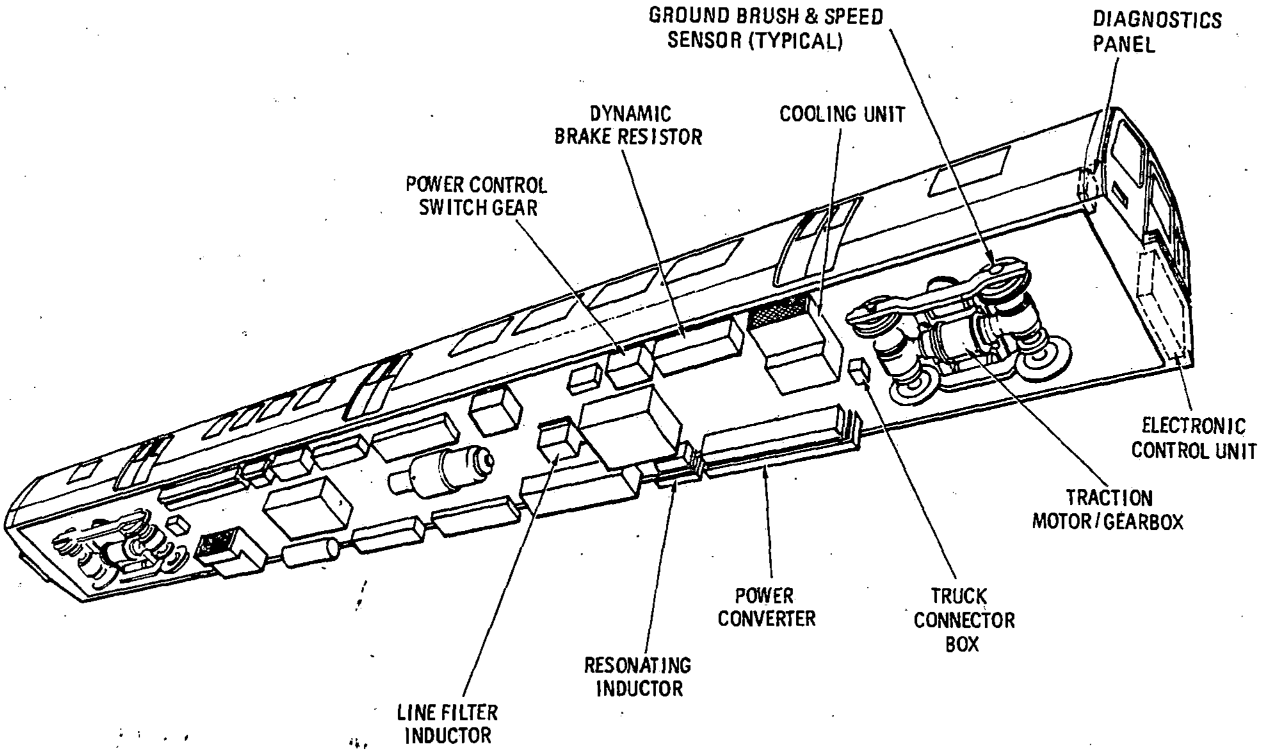


Figure 4-8. Propulsion Equipment Location

The sizes and weights of the ASDP propulsion system components are shown in Table 4-I. Also shown are the quantity per car of each component and the Delco Electronics envelope drawing number applicable to each item. The equipment is grouped according to its mounting location on the railcar: truck, under-carbody, or cab.

Monomotor Truck Drive

In this drive concept a single ac synchronous motor is used to drive both axles of one truck. With an output shaft at each end, the motor is centered longitudinally on the truck and drives each axle through a single-reduction hypoid bevel gear set designed for bi-directional service. Torque is transmitted from the gear drive output to the truck axle through a flexible coupling, which allows radial axle movement for the primary suspension motions.

As illustrated in Figure 4-9, the motor and gear drives together form a rigid assembly which, when mounted on the truck frame, significantly reduces the unsprung mass and truck mass moment of inertia. This reduces the shock loads and stresses on the motor, gears, and bearings while improving the ride characteristics. The elimination of slip-slide between the two axles of each truck provides improved traction. Use of a single drive for both axles reduces the overall complexity, maintenance, and cost of the propulsion system.

Traction Motor

The ac traction motor is a four-pole, salient-pole, self-synchronous machine designed to produce 490 hp (365 kW) from 1646 to 5642 r/min. The motor assembly, illustrated in Figure 4-10, consists of:

- A salient pole synchronous machine with a three-phase stationary armature and rotating field
- A three-phase rotating transformer and rectifier to provide dc field excitation
- A rotor position sensor to provide signals to control the switching of the commutating thyristors.

ITEM	DESCRIPTION	QTY/ CAR	ENVELOPE DRAWING NO.	APPROXIMATE SIZE (L × W × H) (inches)	WT (WET) - lb	
					UNIT WT	TOTAL WT/CAR
1	Traction Motor	2	7558253	48 × 22 × 21.2	1905	3810
2	Gear Drive and Axle Couplings	4	7557706	37 × 27.2 × 24	1093	4372
3	Motor/Gearbox Coupling	4	7557740	7.75 dia × 10.2	32	128
4	Ground Brush and Speed Sensor Assembly	8	7557738	6.3 dia × 5.1	10	80
	Sub Total Truck Mounted					8390
5	Truck Connector Box	2	7559843	17.6 × 11.2 × 5.3	50	100
6	Power Converter Assy	2	7559837	78 × 24.3 × 21.3	910	1820
7	Resonating Inductor Module	2	7559835	30.1 × 22.6 × 19.6	675	1350
8	Cooling Assembly	2	7557707	45.7 × 41.0 × 26.5	645	1290
9	Power Control Switchgear	2	7559867	41.1 × 24 × 18.1	230	460
10	Line Filter Inductor	1	7559836	19.6 × 25.9 × 14.6	775	775
11	Dynamic Brake Resistor	2	7557708	49 × 20 × 10	265	530
	Sub Total Car Mounted					6325
12	Electronic Control Unit	1	7557736	46 × 13.5 × 29.8	85	85
13	Diagnostic Panel Assy	1	N/A	15 × 4.5 × 23.5	15	15
	Sub Total Cab Mounted					100
	Total Propulsion System					14,815

Table 4-I. Propulsion System Weight and Size Summary

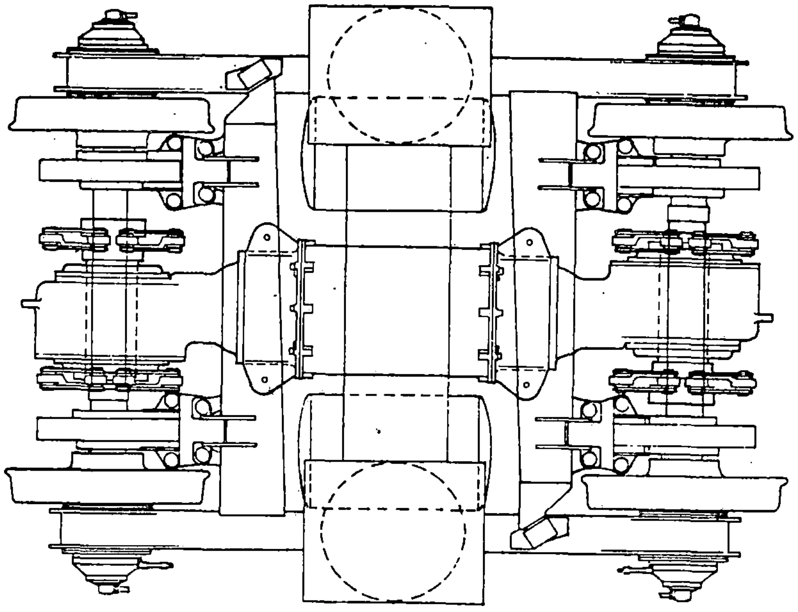


Figure 4-9. Monomotor Truck Drive

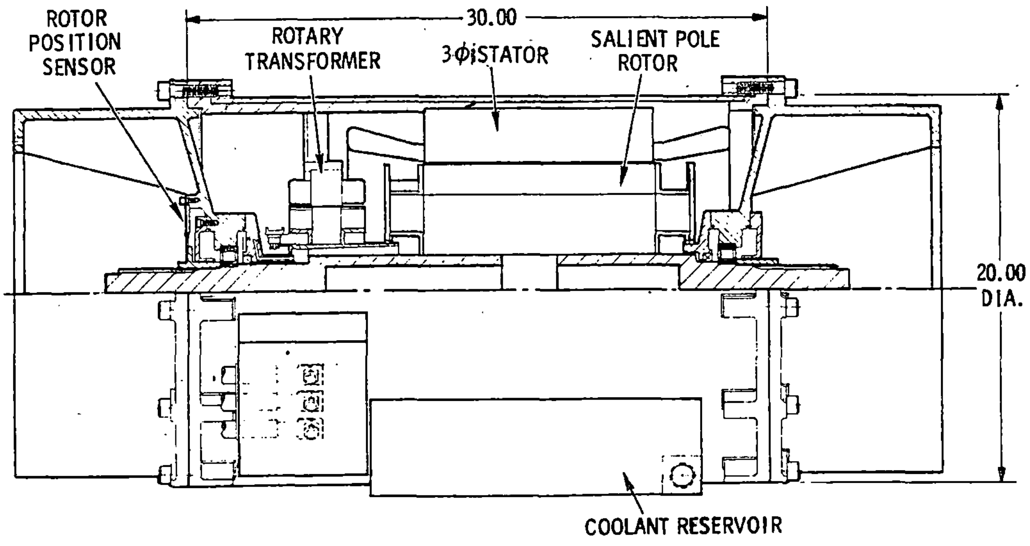


Figure 4-10. AC Traction Motor

The stator laminations are conventional with semi-closed slots and the windings are multiple strands of round wire with Class "H" insulation. The rotor is a one-piece forging with four poles, with laminated pole head assemblies bolted to each pole to secure the prewound coils. Damper bars are incorporated in the pole head.

The rotary transformer uses conventional three-phase laminations and a four-pole winding. The transformer primary is supplied from a high frequency current source to obtain a nearly constant output from zero to maximum speed. A rotating rectifier, consisting of six diodes in a full wave three-phase bridge, is located between the rotary transformer secondary and the main rotor windings.

A rotor position sensor is used to indicate rotor angular position relative to the stator windings. This consists of a laminated magnetic assembly having nine coils on the stator and two lobes on the rotor. The null points are detected to provide signals to the thyristor triggering circuits.

To cool the motor a fire resistant silicone fluid is sprayed on the stator conductors, the end turns of the rotor windings, and the rotating transformer/rectifier. The coolant is collected in a sump at the bottom of the motor frame and is recycled back to the cooling assembly.

The motor shaft, shrunk into the rotor forging, has a splined extension on either end. The roller bearings are grease-lubricated and have face seals to prevent entry of cooling fluid into the bearing housing. The motor has built-in temperature sensors to provide diagnostic monitoring signals.

Gear Drive and Coupling

This monomotor truck drive concept depends on the use of a gear drive and coupling combination which allows radial play of the axle with respect to the truck mounted motor/gearbox subassembly. The gear drive and coupling, shown in Figure 4-11, consists of a hollow shaft hypoid bevel gear axle drive and a flexible rubber joint cardan coupling developed by Brown-Boveri for high speed locomotives and transit cars.

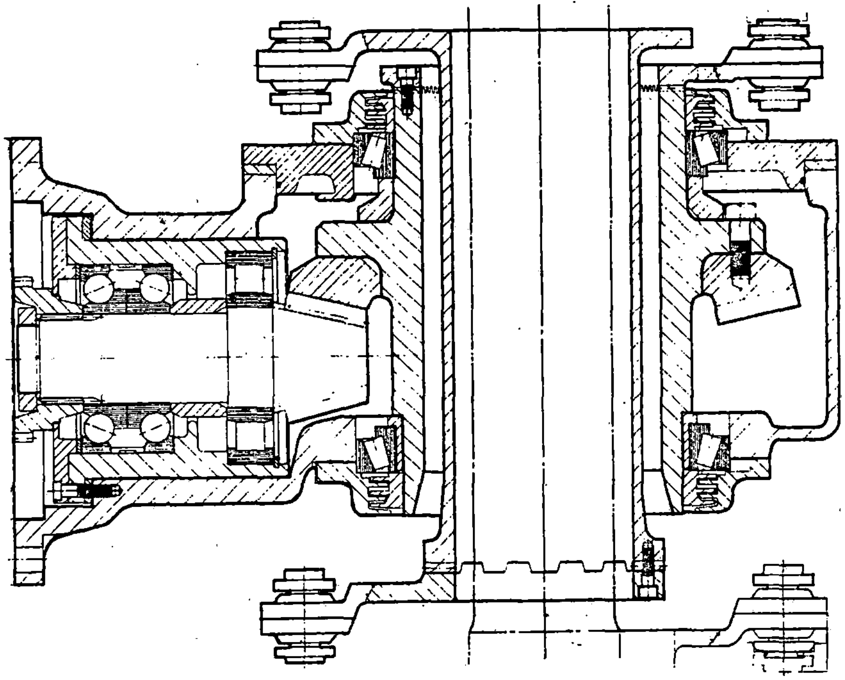


Figure 4-11. Gear Drive and Axle Coupling

The gear drive unit is bolted directly to the traction motor flange, and motor torque is transmitted to the pinion shaft through a toothed coupling capable of accommodating small misalignments. A single-stage hypoid gear set provides a 5.875 to 1 reduction between the motor and axle. A ring gear mounted on a hollow shaft transmits torque to the axle through a rubber joint cardan drive. There is a small offset (0.8 in.) provided to minimize gear sliding losses at high speed. The gear teeth are case hardened and lapped for minimum wear. The roller bearings are cylindrical for the pinion shaft and tapered for the output shaft to obtain maximum rigidity and service life.

The gears and bearings are oil splash lubricated. Labyrinth seals are provided to hold the oil in the gearbox. Breathers, magnetic plugs, sight gages, and inspection openings are provided for maintenance and servicing.

The rubber-joint cardan coupling is designed for high speed operation and permits combined axle motions of ±0.75 in. radial, ± 0.50 in. lateral and ±1.3 degrees angular. In the tangential direction (torque transmission) the coupling is made rigid to preclude angular vibrations between the coupled axles of the monomotor drive.

The cardan drive consists of two rubber-joint link-type couplings connected with a quill shaft through the hollow shaft of the gearbox. The approximate symmetry of the overall drive assembly allows a disc brake to be located on each side.

Power Converter

The power converter assembly shown in Figure 4-12 contains the electrical power circuits and components required to control one traction motor. The assembly – consisting of a lightweight frame, five modules (inverter, capacitor, field supply, cycloconverter and brake control), interconnecting cabling and coolant lines, and a hinged protective cover – is shock mounted to the car's underframe. The electrical components are packaged in replaceable subassemblies (modules) in accordance with the function they perform. The modular design employs slide-out modules and quick disconnect electrical and cooling fluid connections for ease of maintenance and replacement at the subassembly level.

The individual modules are sealed enclosures with liquid cooling provided for each module. As can be seen in a typical module shown in Figure 4-13, the module components are attached to a mounting plate and immersed in a container filled with an insulating, cooling fluid. Up to four thyristors, separated by specially developed heat sinks, are combined to make a stack which is then attached to the mounting plate with a spring loaded clamp. Coolant is passed first through the heat sinks and then into the container for additional heat transfer from the exterior of the heat sink. This arrangement provides a thermal resistance of 0.06^{o}C/watt between the thyristor case and inlet coolant.

All electrical cabling and coolant connections are routed through the mounting plate used to bolt the module to the structural frame assembly. An O-ring seal is provided between the mounting plate and the flanged container.

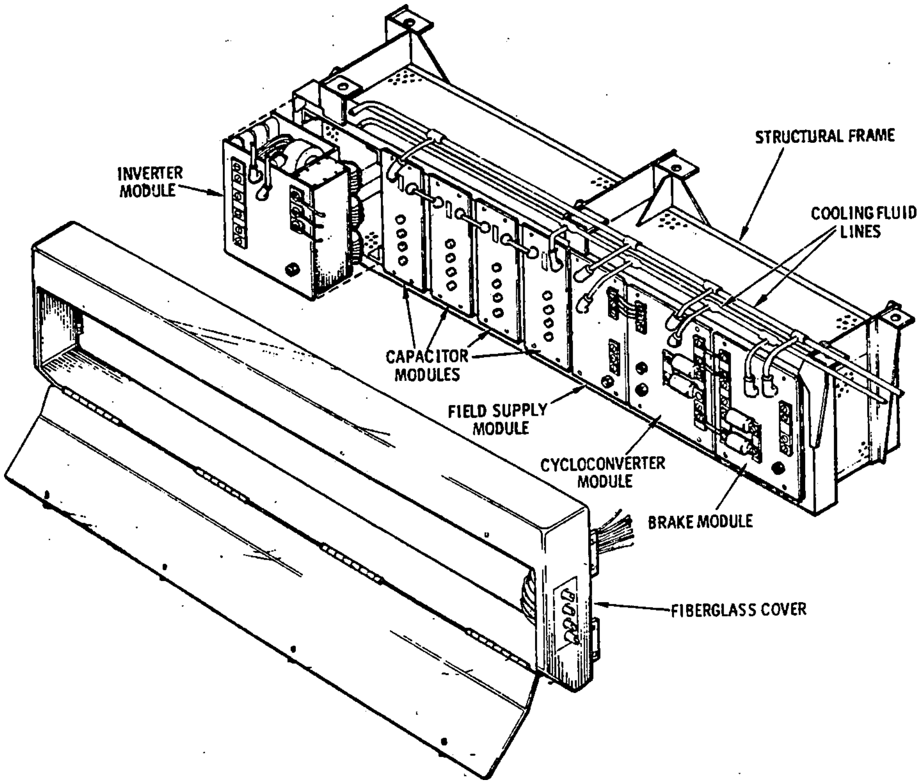


Figure 4-12. Power Converter Assembly

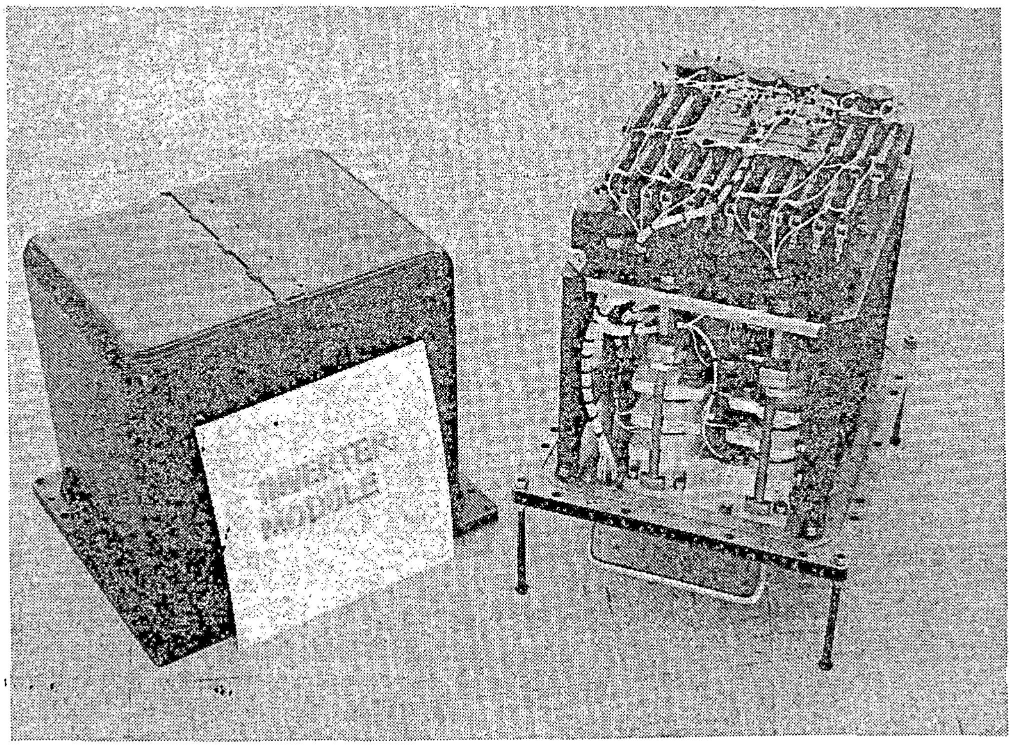


Figure 4-13. Inverter Module

Resonating Inductor Module

The resonating inductor module contains linear and saturating inductors and current limiting fuses. The inductor elements of the module are sized to carry the current demands of the power converter.

Each of the six shell-type inductors is wound with insulated magnet wire on a laminated core. The core is formed from epoxy impregnated grain-oriented silicon steel laminations. Tests of the inductors in free space gave Q = 180 at 1000 Hz, indicating close to otpimum inductor design.

Each of six saturable inductors is connected in series with one of the linear inductors. The saturable reactor snubs the reverse recovery current of the associated inverter power diode to reduce the power loss in the inverter dV/dt suppression circuits.

The housing is a welded, structurally ribbed, aluminum enclosure which, together with the front panel, provides a seal against dirt and moisture contamination and coolant leakage. A chassis assembly, which is interior to the enclosure, supports the stacked inductor assemblies. At one end the inductor assembly end cap also acts as the coolant manifold directing liquid through the coils and out the opposite end into the enclosure.

A photograph of the resonating inductor is shown in Figure 4-14.

Cooling System

Liquid cooling of each motor and power converter enables a reduction in motor size and weight and permits system operation in a totally closed, clean, thermally-controlled environment. The thermal mass of the coolant also serves to constrain any transient fluctuations in component temperatures during the typical intermittent-power operation of a transit car. The DC 200-50CS silicone fluid used as a coolant was selected in a trade study which considered fire resistance, dielectric strength, thermal properties, viscosity, toxicity, and compatibility with materials.

The cooling assembly shown in Figure 4-15 contains two independent cooling loops: one for the traction motor and one for the power converter. Heat is transferred to the ambient air via fluid-to-air heat exchangers which use forced convection provided by a fan. The major

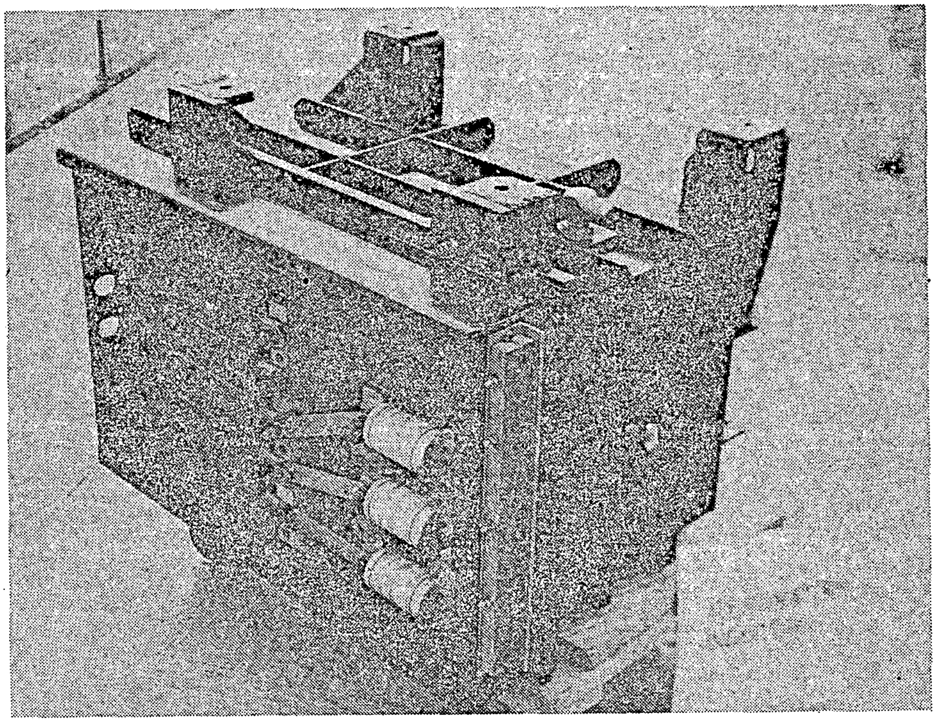


Figure 4-14. Resonating Inductor Module

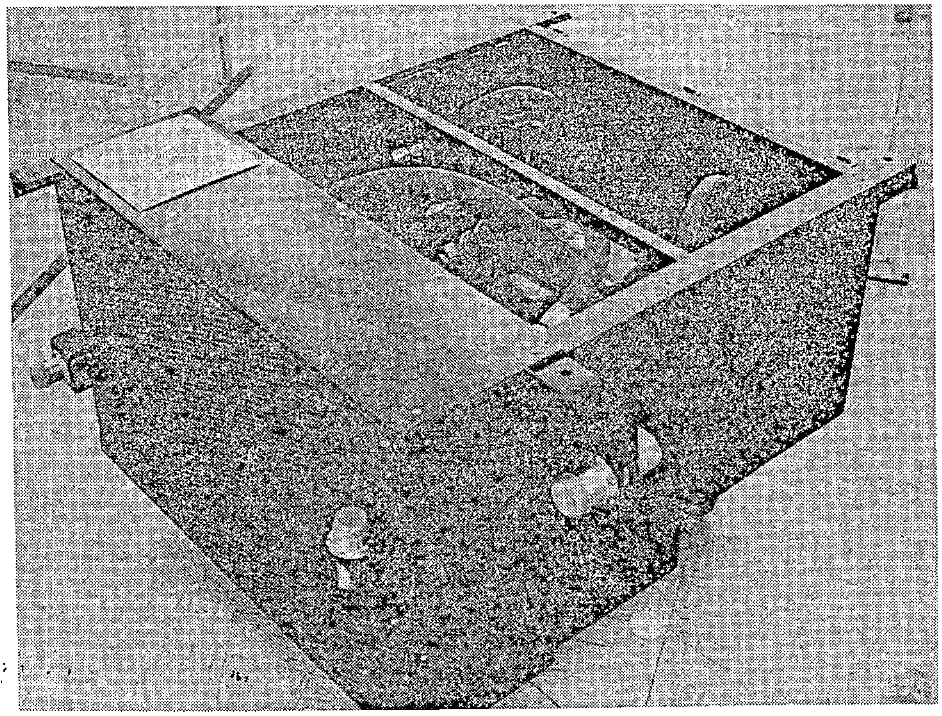


Figure 4-15. Cooling Assembly

components are: a two-section radiator cooled by a propeller-type fan, two positive displacement pumps driven by a single motor, oil filters with replaceable filter elements, and transducers for pressure and temperature monitoring.

All components are mounted in a single unitized frame and shock-mounted to the car body. The radiators are of the conventional plate/fin type with brazed aluminum alloy core. Two positive-displacement rotary pumps each deliver 20 gpm coolant at a nominal 50 psi pressure. The coolant flow is routed through a replaceable 40-micron filter, with replaceable coarse air filter panels provided at the intake side. Self-sealing, wrenching-type disconnects and rubber hoses are used to connect the cooling unit to the motor and power converter.

Line Filter Inductor

The line filter inductor assembly is a single unit containing two filter inductors, one for each of two propulsion systems per car. It consists of two parallel windings on two separate laminated silicon steel E-cores which shsre a common I section. The windings are sheet copper with Nomex paper insulation. The inductor assembly is vacuum dipped and baked with solvent-less epoxy varnish. The nominal inductance is about 2.5 mH with a saturation current of 800A. The saturated inductance is approximately 340 mH.

The inductor chassis and the laminations are welded together to form a unitized construction. Steel plates located across the faces of the inductor windings provide protection against airborne rocks and other debris.

A photograph of the line filter inductor is presented in Figure 4-16.

Power Control Switchgear

This assembly contains a line contactor and some auxiliary contactors, current and voltage sensors, and a capacitor bank which in conjunction with the line filter inductor provides filtering of the 3rd rail power, diodes, and fuses.

The single-pole, normally open contactor provides the means to electrically disconnect the system from the line when necessary. It has overcurrent hold-in characteristics that magnetically prevent the armature from releasing if the fault current exceeds 2,000 amps.

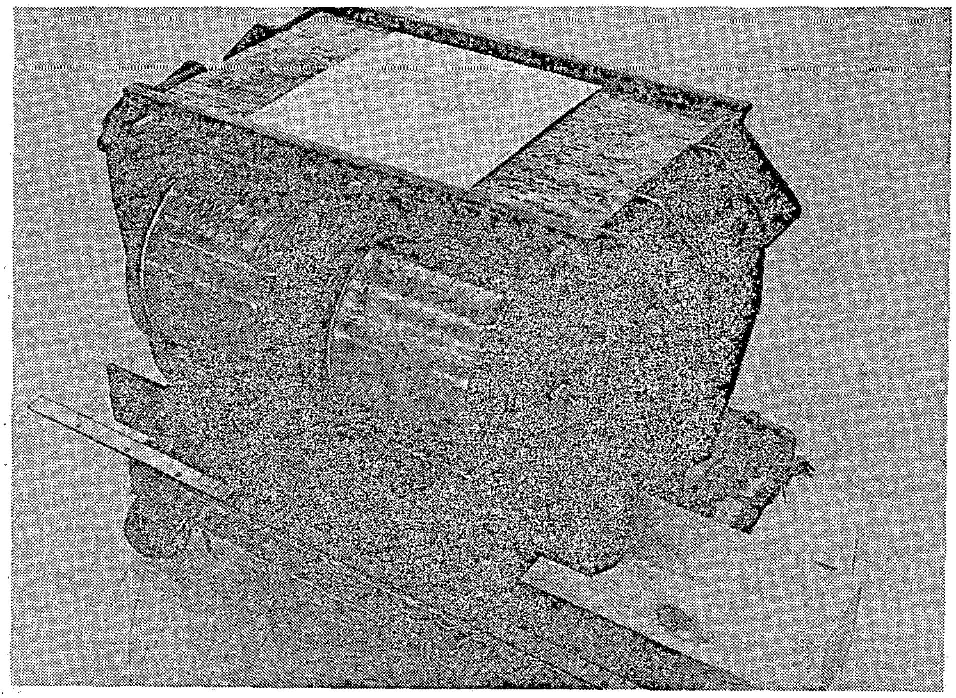


Figure 4-16. Line Filter Inductor

A blocking diode is provided to prevent the capacitor bank from discharging back into the source in the event the source voltage is low, shorted, or grounded. The filter capacitor bank has a nominal capacitance of 8800 microfarads. A bleeder resistor is provided across the assembly in order to discharge the capacitor bank to 50 volts or less within 30 seconds.

The chassis is a welded aluminum structure which provides a high strength lightweight housing. Front and rear panels and cable stuffing tubes seal the enclosure against dirt, dust, and moisture. A cover switch is actuated when thecover is closed, indicating to the train control that the cover has been replaced.

Figure 4-17 is a photograph of the PCS unit.

Dynamic Brake Resistor

The brake resistor is required to dissipate railcar kinetic energy during the dynamic braking mode of operation.

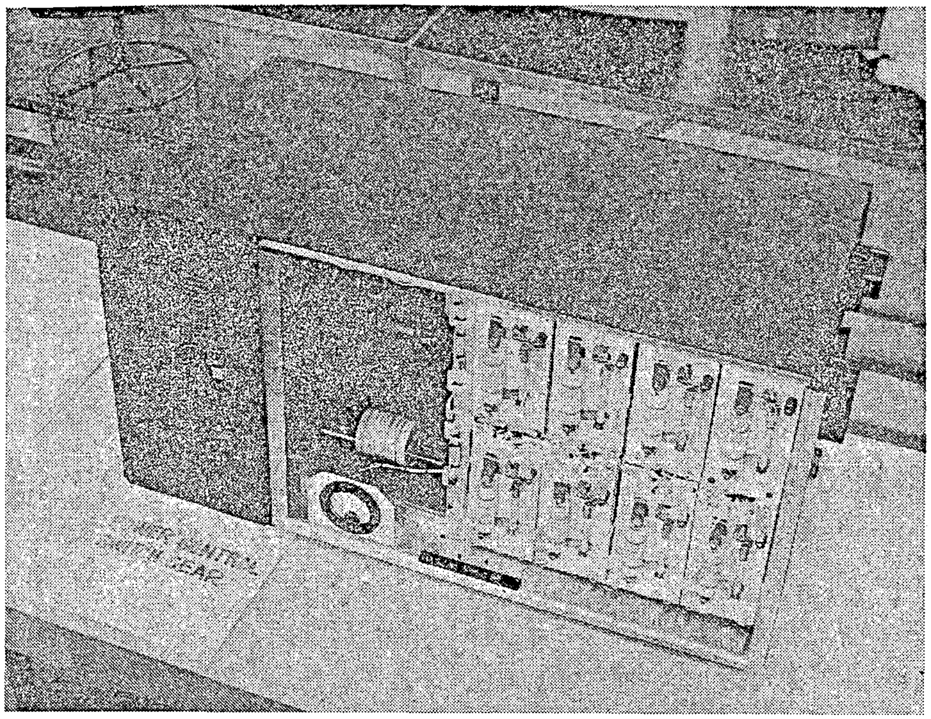


Figure 4-17. Power Control Switchgear Assembly

Two resistors are used per railcar, one for each of the two propulsion systems. Analysis showed that the motor braking torque of 1405 lb-ft could be maintained from maximum speed (80 mph) to approximately base speed (23 mph) with a resistor value of 0.78 ohms. This torque level is maintained down to about 10 mph by tapping the resistor at 0.26 ohms.

The dynamic brake resistor consists of several controlled impedance coils which are bussed to provide the two desired resistance values. The coils are captivated at regular intervals in high temperature ceramic feedthrough tubes which are in turn supported by insulator blocks. The terminations are connected in a bussing arrangement with taps at the appropriate impedances.

The structure consists of steel extrusions designed to provide structural integrity at elevated resistor temperatures. The coils are enclosed in protective perforated diamond pattern sheet metal panels to permit the passage of air in and around the coil assembly.

The brake resistor assembly is shown in the photograph of Figure 4-18.

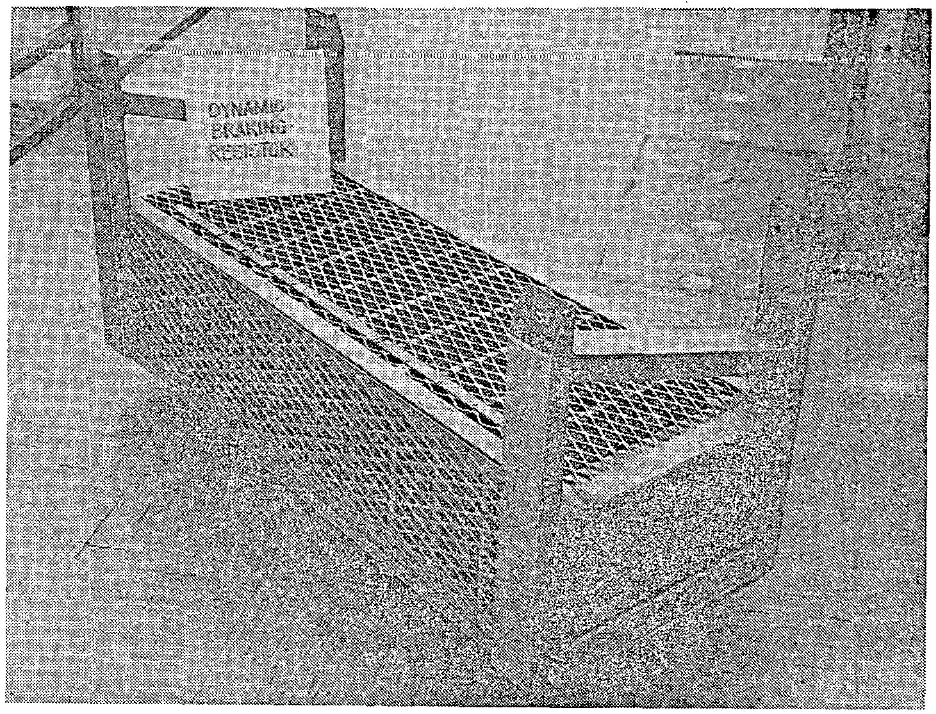


Figure 4-18. Dynamic Braking Resistor

Ground Brush

The ground brush provides a low resistance return path to the truck axle, and thence to ground, for the line current, bypassing the axle bearings.

There are eight ground brushes per car, one at each end of all four axles. The current capability was established such that any four brushes on a car can safely handle the total line current. Each brush is rated for 250A dc continuously and 400A dc for 5 minutes.

The ground brush assembly consists of a copper/graphite brush, a spring-loaded brush-holder, and a housing. The assembly is mounted on the axle bearing cover and the brush is held securely by means of spring loading against a brass disc mounted on the end of the axle. The brush shunt is connected to the truck frame.

A speed sensor consisting of a commercially available magnetic transducer activated by a toothed wheel is incorporated in one of the ground brush assemblies on each axle of the car. The ground brush assembly containing the speed sensor is shown in Figure 4-19.

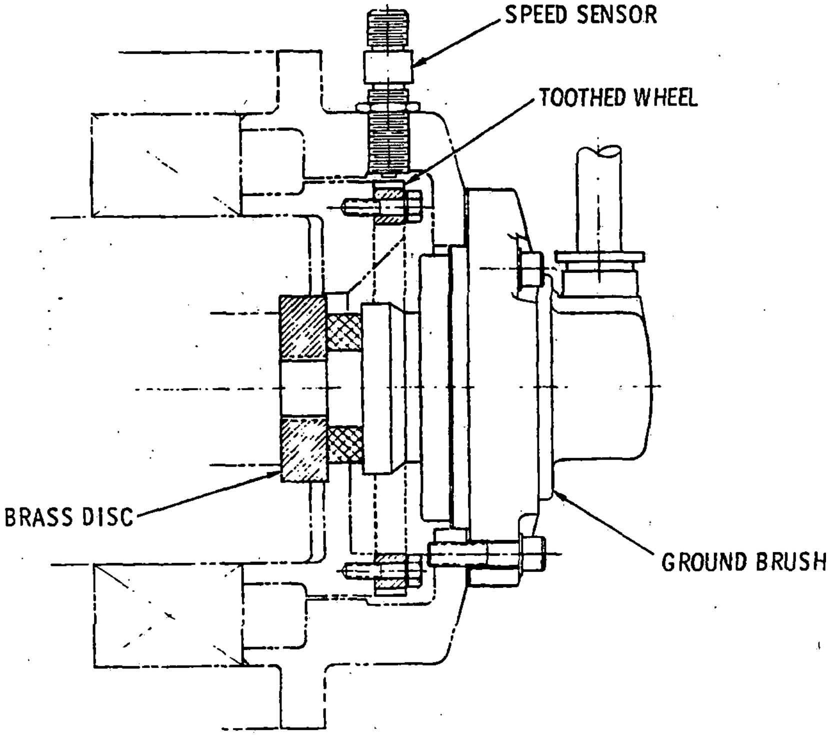


Figure 4-19. Ground Brush and Speed Sensor Installation

Truck Connector Box

The truck connector box serves as a junction point for cables between carbody mounted equipment and the power source, and between truck-mounted equipment and its associated carbody equipment. There are two connector boxes per car, one for each propulsion system.

The housing is a split aluminum weldment. When the cover and cable interconnect hardware are removed, one-half of the housing may be separated with the truck. Flat gaskets, as well as the sealing tubes, are used at the various interfaces to seal against dirt and moisture contamination.

Electronic Control Unit

The Electronic Control Unit (ECU) contains the train control and motor control electronics, related power supplies, and vital relays required for control of the two propulsion systems of a car. For ease of maintenance the major subassemblies are packaged in slide-mounted horizontal pullout drawers with tilt-up and tilt-down capability. Figure 4-20 shows the overall assembly.

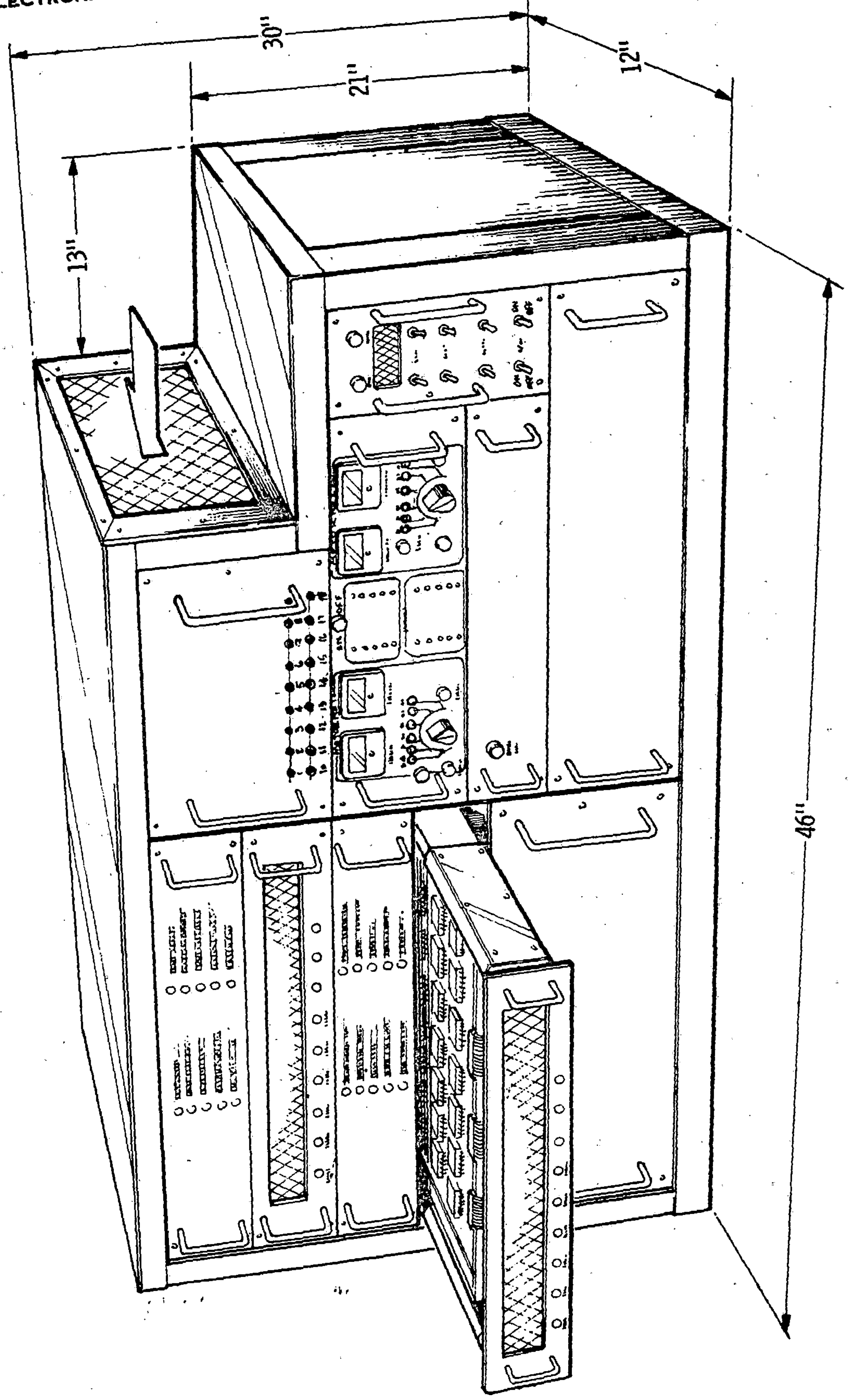


Figure 4-20. Electronic Control Unit

The unit enclosure is a modularized cabinet made from commercially available aluminum end caps and extrusions. The side and rear panels are also aluminum and are welded to the extrusions to provide a solid unitized structure. The unit is customized to fit in the motorman's cab area under the fron window.

The unit is cooled by a forced air system. Conditioned air enters the unit through filtered inlets on the front panels and in the stepped area. It is then drawn directly across the components and through protective grilles by the backwall-mounted exhaust fans.

A backwall harness assembly interconnects the individual drawers with one another and with the interconnect panel.

Train Control Electronics (TCE). The complexity of the TCE electronics dictates the use of a computer-type packaging approach. As a result, the TCE for each propulsion system is partitioned into an input/output (I/O) drawer and a central processor (CPU) drawer. Both drawers each contain two augat wirewrap assemblies that may be pivoted upward (for the top assembly) or downward (for the lower assembly). Harness interconnections are made along the rear of the augat board to minimize the service loop.

Since the majority of the system interface enters the TCE on the I/O boards, all indicators and test points are displayed on the I/O assembly front panel.

Motor Control Electronics (MCE). The MCE as packaged in the ECU services two propulsion systems (one for each truck). Quick shutdown capability to prevent the possibility of further system damage is provided. The MCE is packaged into the major subassemblies located in the right ECU bay. There are the MCE logic assembly, the MCE power supply, and the mode select panel. The MCE logic assembly has three frame-mounted wirewrap-type augat boards capable of hinging up or down.

Diagnostic Unit

The ASDP Diagnostic Unit provides access to control signals and operational status through analog and digital displays. Its internal memory provides the capability of recording a time history of train operation for permanent record or troubleshooting. Signals available for storage or display include train lines, motor controls, synchronous brake system, and all train control inputs, outputs, and intermediate solutions.

A QSD or manual command will stop the flow of data into diagnostics memory. Sixteen seconds of high frequency data and thirty minutes of slowly varying data become preserved in memory for later analysis.

The diagnostic panel is shown in Figure 4-21. OPERATION STATUS LED's produce an instantaneous discrete reading of important conditions existing in both trucks. The two panel meters can display from a selection of up to 256 signals. LOCATION CODE below the meters indicates the parameter presently being displayed and the respective scale factor is found on the CODE CALLUP PLACARD. Test jacks on the lower right panel provide parallel connections across the meters for external instrumentation hookup.

Signals may also be displayed on the digital DATA DISPLAY that includes the location code in the readout. A thermal printer is built into the diagnostic unit for high speed hard copy printouts.

The memory, displays, and printer are microprocessor controlled. Instructions to modify memory storage, print, or change displays are entered through the hex keyboard. OPERATION STATUS is always in real time, but the other displays and printer can readout real time data or read from memory. A playback capability will allow an oscilloscope to be attached to the test jacks and signals can be repetitively produced on a CRT.

4.5 PERFORMANCE CHARACTERISTICS

Two types of computer runs were made to evaluate train and propulsion system performance characteristics:

(1) Round-trip runs over the ACT-1 Synthetic Transit Route consisting of 28 segments

(2) Runs over single segments to verify "discrete" performance requirements.

In the motoring mode, motor torque-speed characteristics as verified by laboratory testing were used. In the braking mode, similar test results were not available for the full torque-speed range; therefore, braking capabilities as calculated by the motor designers were used.

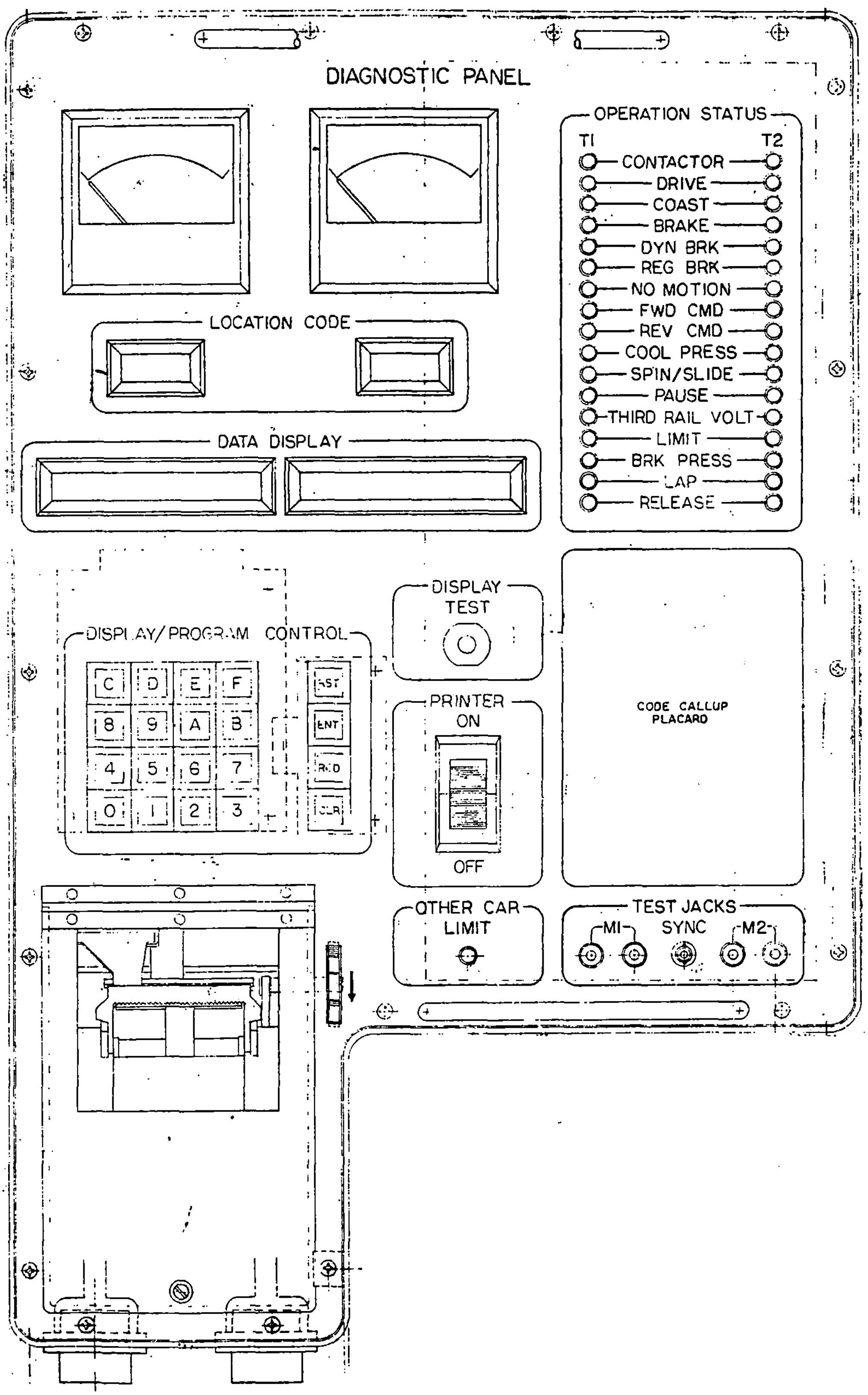


Figure 4-21. Diagnostics – Front View

SYNTHETIC TRANSIT ROUTE

One car at AW1 weight (95,200 lb) was operated over the ACT-1 Synthetic Transit Route while using dynamic braking supplemented with friction braking at low speed. The results indicated a round-trip time of 38.3 min. for the 18.5 mile run and an energy consumption rate of 9.80 kW-hr/car mile. Both these values meet specified requirements.

Other results of interest for single car operation, particularly for system thermal design, were as follows:

- Average motor power output (each) – 280 hp
- Average power dissipation (each)
  - Gearbox – 10.4 kW
  - Power Control Electronics – 11.6 kW
  - Motor – 16.1 kW

In the case of a 2-car AW1 weight train, energy consumption is reduced to 9.20 kW-hr/car mile while round trip time remains essentially the same.

In the case of regenerative braking and a fully receptive line, energy consumption is 6.07 kW-hr/car mile for single car AW1 operation and 5.41 kW-hr/car mile for a 2-car train – again within specficiation.

Thus it appears that all Transit Route related performance requirements would be met by the system design. (See Subsection 4.2.)

SINGLE-SEGMENT RUNS

Results from these runs can be summarized as follows:

- Under conditions of level tangent track, 28-inch wheels and no wind, a motor output (each) of 254 hp is required in order for a single AW1 car to maintain 80 mph.
- Under conditions of level tangent track, 28-inch wheels and a 15 mph headwind, a motor output (each) of 334 hp is required in order for a single AW1 car to maintain 80 mph.

- Under conditions of tangent track, 28-inch wheels and a +3% grade, a motor output (each) of 455 hp is required in order for a single AW1 car to maintain 70 mph.

Since power outputs exceeding the above values have been demonstrated in the laboratory, speed capability requirements are considered to have been met.

Acceleration capabilities were analyzed for a single AW1 car for the conditions of level tangent track, 30-inch wheels, and no wind.

Speed and distance as functions of time were computed. The results indicate that a speed of 60 mph is attained in 32.4 sec, and that a distance of 705 ft is covered in 0 to 20 sec. Both values exceed specified requirements. (See Subsection 4.2.)

SECTION V
TESTING

This section summarizes the testing that was performed relative to the ASDP self-synchronous propulsion system. Discussed are the following types of tests:

Developmental Tests - These encompass tests performed both prior to and following ASDP contract award in support of self-synchronous propulsion system design and development.

Major Component Tests - These were conducted on the first item of each major component manufactured in order to establish its suitability for incorporation into the overall propulsion system for system level testing.

System Level Tests - These were tests conducted in a dynamometer laboratory with a complete Test Article propulsion system (less Gear Drive and Axle Coupling Assembly).

5.1 DEVELOPMENTAL TESTING

Developmental tests were conducted in the early stages of the program using breadboard test hardware from a pre-contract IR&D effort. The major development tests conducted were as follows:

- Cycloconverter gate drive development
- Brake control circuit development
- High frequency motor tests
- Cycloconverter output current capability tests
- Motor shock torque tests
- Coolant fluid testing
- Heat sink development.

Based on the results of these early breadboard tests, the propulsion system design was finalized and the Test Article hardware was built.

5.2 MAJOR COMPONENT TESTS

These tests generally consisted of visual inspections, continuity checks, resistance, dielectric and inductance measurements, and simple functional tests. Exceptions were the Gear Drive and Axle Coupling Assembly, which was fully qualified as a separate entity apart from the rest of the propulsion system, and the Traction Motor, whose performance could only be partially verified prior to system level testing. A brief summary of the testing conducted follows.

Resonating Inductor

The Test Article resonating inductor tests included measurements of inductance, Q factor, dielectric strength and insulation resistance.

Thyristor Modules (Inverter, Cycloconverter, and Brake Control)

The gate driver circuits were checked for gate current rise time, peak current and pulse width. The SCRs and diodes were measured for leakage current and voltage breakdown. The dV/dt suppression circuits were tested to establish volt-ampere characteristics.

Field Supply Module

The field supply transformer turns ratio was verified. The coupling capacitors leakage current and capacitance were measured. The power control and signal relays were checked for pull-in and drop-out voltages.

Power Control Switchgear

In addition to routine visual and continuity checks, the current relays were calibrated and the line filter capacitor discharge time through the shunting resistor was measured.

Line Filter Inductor

Inductance and resistance values were measured.

Dynamic Brake Resistor

Resistance values and dielectric strength were checked.

Cooling Assembly Acoustic Noise

Acoustic noise tests conducted on the cooling assembly as originally designed indicated that the specified maximum noise level of 65 dBA was being exceeded by as much as 22 dBA. After sound dampening acoustic foam was added on the interior faces of various panels and around the pump assemblies, readings were reduced to 75.4 and 69.4 dBA for high-speed and low-speed fan operation, respectively.

Coolant Flow

Flow tests were conducted on the liquid cooled modules of the power control modules to determine pressure drop as a function of flow rate. It was determined that actual flow rates through the modules compared favorably with the established design goals.

Train Control Electronics

All circuit boards were checked out and the software was tested by verifying all subroutine operations through the use of a teletype. The test console built to simulate train signal interfaces was also checked out.

Traction Motor

Most of the traction motor testing was conducted by the supplier, Delco Products, Dayton, Ohio. The evaluation of motor performance in conjunction with the ASDP drive electronics, however, was performed at Delco Electronics during system level testing.

Tests conducted at Delco Products included all routine insulation resistance, dielectric strength, resistance, no load saturation, inductance, etc., type tests. In addition, the moment of inertia was established, the overspeed capability verified, and the motor weighed. The major motor performance tests included a motoring test at 1800 rpm (60 Hz) at full power (489 hp), a test as an alternator at speeds up to 3,000 rpm at full torque capability (1405 lb-ft), and thermal capability for the specified duty cycle.

Tests conducted with the motor at Delco Electronics as part of the system level testing covered motoring throughout the complete specified torque/speed range. Full dynamic braking torque capability was demonstrated at speeds up to 2000 r/min. Dynamometer limitations did not allow braking tests to the full torque level at high speed. Analytical predictions made, however, projected full required braking capability in this untested area.

Some problems were encountered during the system level testing such as magnetic seal, bearing, and rotating rectifier Zener diode failures, but all have been resolved. These are discussed in paragraph 5.3.3.

Based on the results obtained from these extensive motor evaluation tests, it was concluded that the traction motor met or exceeded all performance requirements specified.

Gear Drive and Axle Coupling

All performance testing on the gear drive and axle coupling was conducted by the subcontractor Thyssen-Henschel of West Germany.

Some initial engineering tests resulted in evidence of gear scoring. As a result, the hypoid gear set was redesigned.

The qualification tests were conducted in two parts. The first series of tests included 27 hours of normal load tests in accordance with a simulated transit car operating profile, 100 hours of endurance testing at constant speed and torque conditions, and shock torque tests at gradually increasing torque values. At the maximum specified shock torque (24,000 lb-ft), the axle coupling failed. A decision was made to redesign the failed component and requalify the complete gear drive and coupling assembly.

The second series of qualification tests consisted of approximately 30 hours of endurance tests in accordance with a simulated operating profile, high speed tests up to the maximum overspeed requirements, and shock torque tests up to the maximum axle shock torque specified.

On the basis of these tests, it was concluded that the Gear Drive and Axle Coupling satisfies the requirements of the specification and that it is suitable for incorporation into the ASDP cars.

5.3 SYSTEM LEVEL TESTING

This subsection contains a description of the laboratory facilities and equipment used and discussions of the motoring and braking tests conducted – including the results obtained and problem areas encountered and their resolution.

5.3.1 LABORATORY FACILITIES

Test Equipment

The ASDP motor drive test facility consists of two dynamometer rooms isolated from a control room by reinforced concrete walls and shatter-proof windows. Figure 5-1 shows the facility layout.

Due to their specific capabilities and limitations, the A lab dynamometer was used for low torque operation over the entire speed range; the B lab dynamometer was used for high torque tests at speeds up to about 2000 rpm. The ASDP propulsion system control and power electronics were common to the two labs; however, separate ASDP traction motors were used in the two test setups to expedite testing.

The A lab contains a cycloconverter-controlled ac synchronous dynamometer machine, connected through an in-line torque transducer and speed increasing (3.2 to 1 ratio) gearbox to the motor under test, the dynamometer ac/ac power converter, and a 350 kVA multi-tap isolation transformer and rectifier to simulate a transit property dc supply. The dynamometer machine is rated at 500 kW and has a nominal maximum speed of 1800 r/min, although it has some overload and overspeed capability. With the 3.2 to 1 gearbox used to permit testing of the ASDP motor over its full speed range, torque capability was limited to on the order of 1000 ft-lb. Additional A lab equipment includes ASDP propulsion system and dynamometer disconnect switches, a dynamometer field supply transformer and rectifier, and a 400 Hz m/g set control cabinet. The 500 kVA distribution transformer and the ASDP cooling assembly and brake grid, as well as the oil cooler for the dynamometer cycloconverter are installed in an open area next to the south wall. ASDP static equipment under test in the A lab consists of the line filter inductor, power control switchgear (PCS), resonating inductor, and the power converter assembly (PCA). A photograph of the A lab dynamometer machine, speed increaser, and ASDP motor under test are shown in Figure 5-2.

The B lab contains a dc machine dynamometer (Electro-Motive Division D-79 modified locomotive traction motor) connected through an in-line torque transducer to the motor under test, a 150 kVA isolation transformer, and dynamometer field and armature rectifiers. The torque capability of the EMD machine is 5000 ft-lb from zero to 1000 r/min decreasing to 1500 ft-lb at 1600 r/min and to 700 ft-lb at its maximum operating speed of

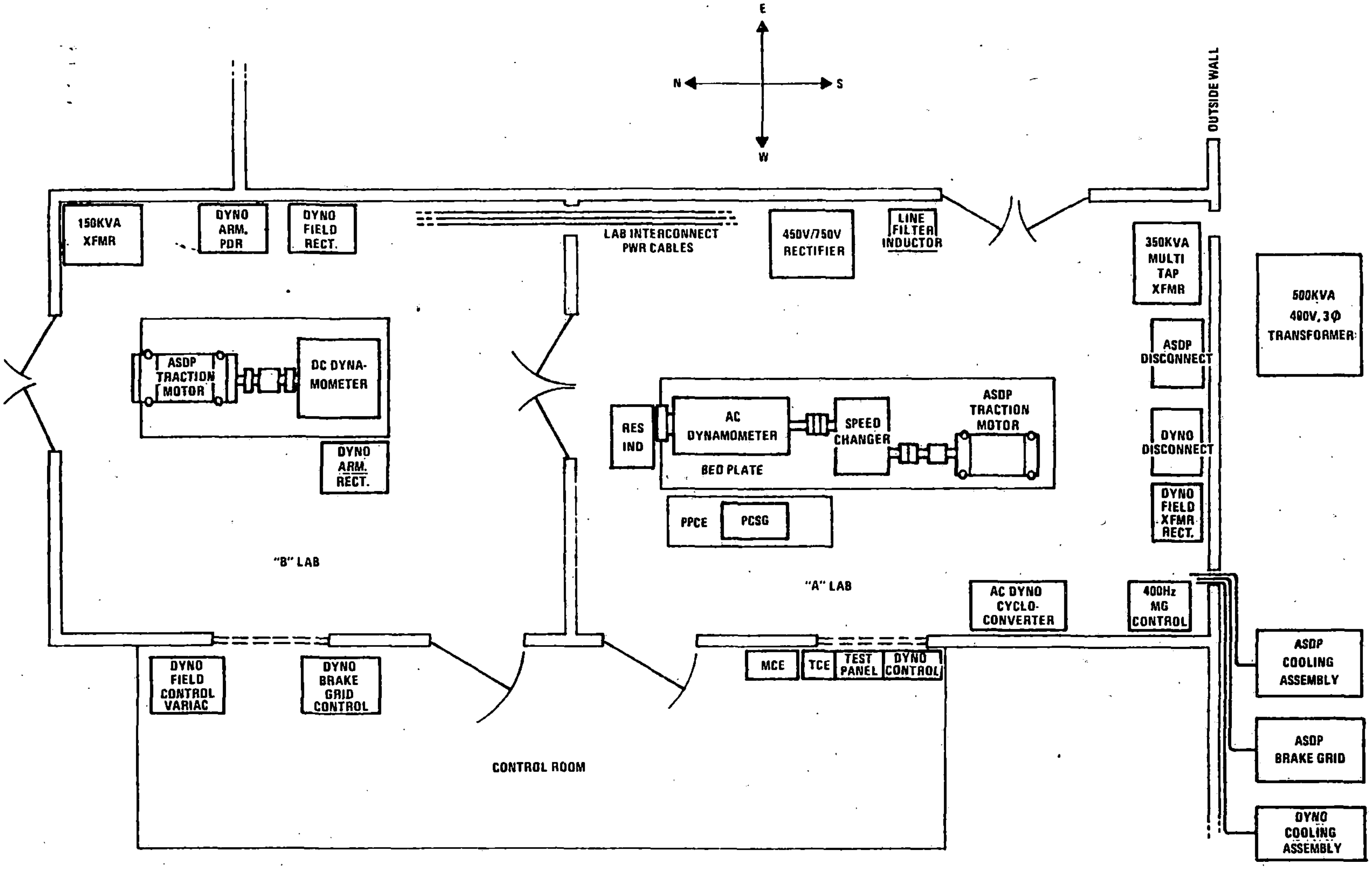


Figure 5-1. ASDP Laboratory Layout

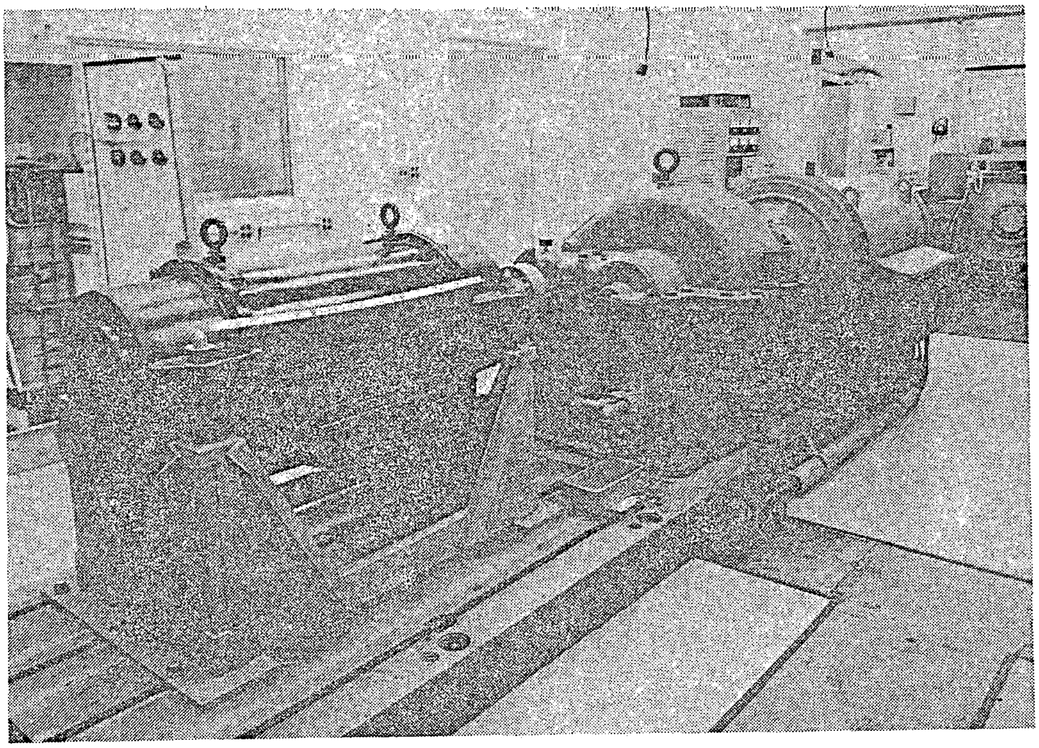


Figure 5-2. A Lab Rotating Equipment

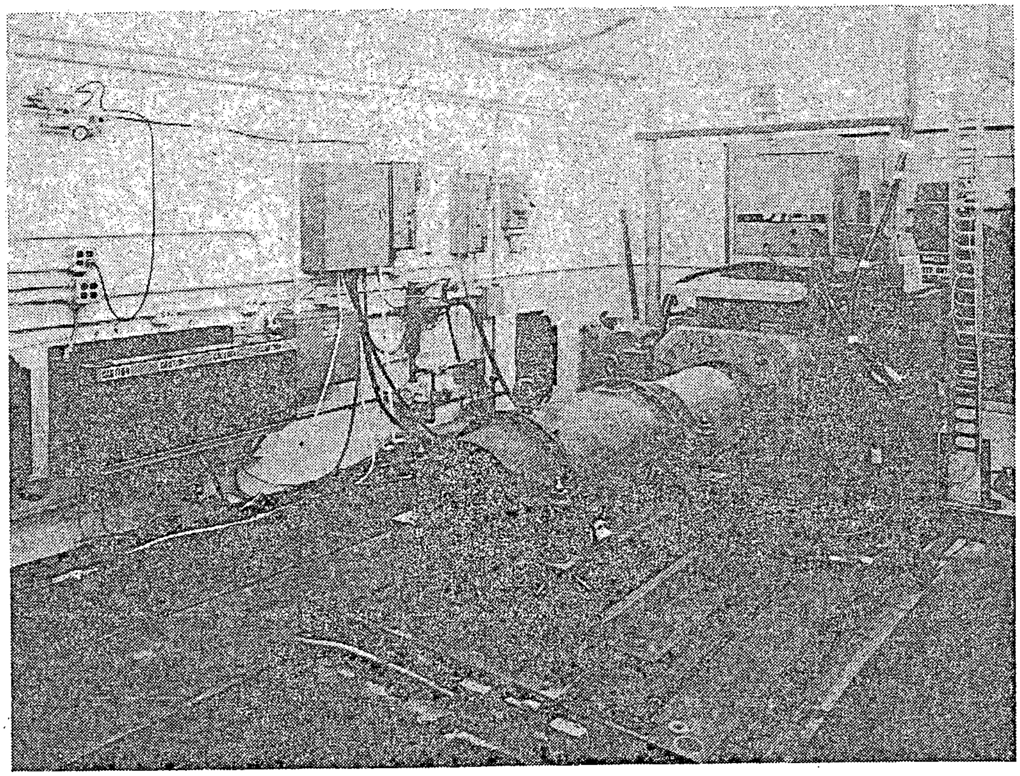


Figure 5-3. B Lab Rotating Equipment

2200 r/min. A photograph of the B lab dynamometer machine and an ASDP machine under test is shown in Figure 5-3.

The control room contains the motor control electronics (MCE) rack and a console incorporating the train control electronics (TCE) panel, the dynamometer remote control panel, and a test panel. The B lab dynamometer field supply Variac and a control panel for selecting the B lab dynamometer brake resistance are also installed in the control room. The dynamometer brake resistors with tap select relays are mounted in a weatherproof enclosure on the roof of the B lab.

Laboratory Instrumentation

Torque and speed in the A andB labs are measured with in-line strain gage torque transducers, each equipped with a 60-tooth gear and speed pickup. The torque transducer signal conditioners provide RF excitation to the strain gage bridges and synchronous detection of the bridge output signals. Speed in r/min is indicated by frequency counters operating on the speed pickup signals.

Direct current (dc) into the ASDP power control electronics and D-79 dynamometer is measured with a blade-type shunt and a digital voltmeter. Voltages are indicated with conventional panel meters. For more accurate measurements, where required, dc voltage is measured with a digital voltmeter.

Alternating-current (ac) motor phase currents are measured with commercial current transformers. The transformer secondary current is indicated by panel meters having iron-vane movements. These meters indicate true rms and have reasonably wide bandwidth. Motor phase current readings are not used for power determinations; hence high absolute accuracy is not a requirement.

Alternating current motor line voltages are monitored on panel meters having iron-vane movements. For accurate readings at frequencies other than 60 Hz, rectifier-d'Arsonval movement panel meters are utilized.

5.3.2 SYSTEM LEVEL TEST RESULTS

5.3.2.1 Overview

Checkout of the integrated ASDP propulsion system Test Article in preparation for motoring mode testing was initiated in early February 1977 and power was applied for the first time on February 24, 1977. Braking mode tests were considered lower in priority. As a result significant effort was not expended until approximately 6 months later. Table 5-I presents a chronological summary of significant events occurring during the testing. All system level laboratory testing was stopped on December 9, 1977 due to the planned program termination, although some additional tests were conducted in January 1978 for purposes of motor bearing evaluation.

During system level testing performance was demonstrated by obtaining a large number of data points at gradually increasing power levels for both the motoring and braking modes of operation. A summary of the torque-speed test results for the motoring and braking modes of operation is illustrated in Figure 5-4.

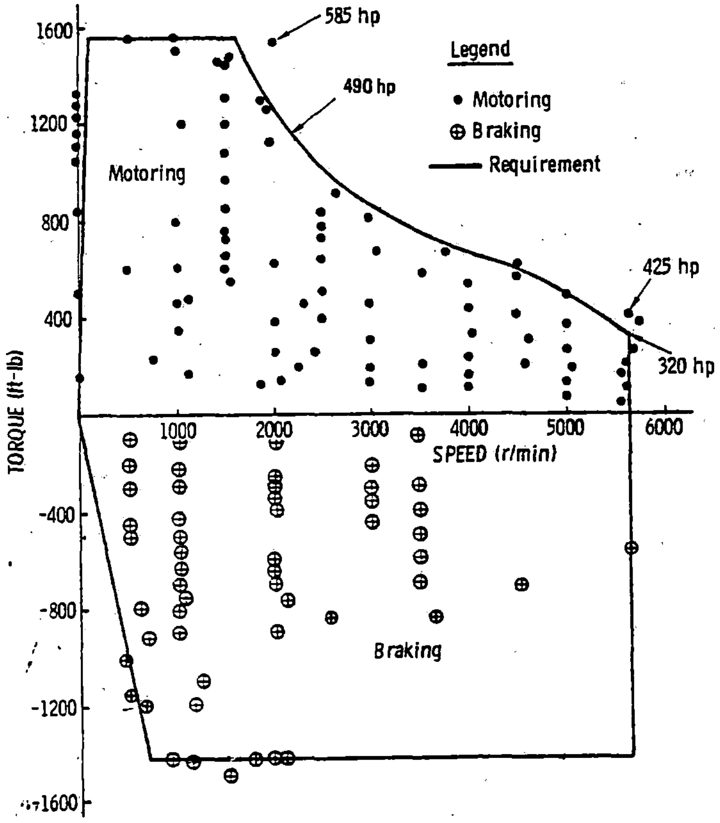


Figure 5-4. Demonstrated Motoring/Braking Test Results

DATE	EVENT
2/8/77	Moved control electronics into ASDP motor-dynamometer lab.
2/24/77	First power-up of system
3/11/77	First rotating rectifier Zener diode failure
3/15/77	Achieved 3000 rpm, 200 ft-lb.
3/15/77	First motor bearing failure
4/18/77	Achieved 900 rpm, 320 ft-lb.
4/21/77	Second Zener diode failure (See 3/11/77 Item)
5/2/77	Third Zener diode failure (See 3/11/77 Item)
5/9/77	Initiated replacement of ASDP motor with 225 hp Delco Products Motor.
6/4/77	Initiated conversion to synchronous gating.
6/12/77	Discovered cycloconverter gate drive was inadequate; initiated redesign.
7/16/77	Added linear and saturating reactors between inverter and cycloconverter.
8/1/77	First DSAS failure (SCR overvoltage protection device)
8/2/77	726 ft-lb, 1140 rpm 1140 ft-lb, 605 rpm Achieved
8/2/77	Initiated testing/verification of dynamic braking mode
8/5/77	Completed braking mode SCR gate drive and control circuit modifications (similar to motoring).
8/5/77	Achieved specified motoring torque-speed to 2000 rpm using workhorse motor.
8/6/77	Replaced workhorse motor with ASDP motor.
8/28/77	1) Achieved specified dynamic braking torque to 2000 rpm and partial torque (dynamometer limited) to 3500 rpm. 2) Identified need for increased voltage rating on braking mode SCR's.
8/31/77	Installed improved motor bearing seal.
9/20/77	Achieved specified motoring torque-speed over full profile.
10/20/77	Installed fast recovery diodes in rotating rectifier circuit (to prevent false triggering of crowbar.
10/20/77	Motor bearing and seal failure analysis completed—corrections recommended
10/22/77	General requirements for power factor advance profile defined.
11/15/77	Completed dynamic braking tests to full speed and maximum torque limit of dynamometer: a. Cycloconverter overvoltage problem found and circumvented b. SCR gate drive noise problem found and circumvented
11/15/77	Initiated installation of automatic power factor advance (PFA) control electronics.
12/8/77	Completed verification of automatic PFA.
12/9/77	Took final data set demonstrating: a. RPS <-> CEMF transitioning b. Automatic PFA control.
12/9/77	Terminated all system level laboratory development work.
1/78	Motor bearing evaluation tests concluded

Table 5-I. Chronological Summary of Events

The general procedure for the performance demonstration tests was to operate the ASDP system in an "open-loop" mode. This means that data was recorded at fixed operating points in terms of motor torque and speed. Torque controlling adjustments to establish the operating points were made manually to the ASDP propulsion system and to the dynamometer.

The discussion which follows presents additional test results and related interpretation.

5.3.2.2 Motoring Mode Test Results

The motoring mode capability of the system is best demonstrated by the final set of demonstration data taken on 12/9/78. This data was taken in the A lab over the full ASDP system speed range and over the torque range limited only by the A lab dynamometer capability. This data is supplemented by data taken in the B lab to demonstrate high torque capability.

Review of Final A Lab Performance Data

The Test Article drive system was operated in the motoring mode with the automatic power factor advance circuit operational. The motor speed was varied with the dynamometer load for each of several inverter frequencies. Quantities measured included the cycloconverter trigger angle, motor torque, and inverter SCR turn-off time. Motor output power at each inverter frequency level was computed from torque and speed.

Torque versus speed is plotted for various inverter frequencies in Figure 5-5. Because the dynamometer machine was loaded with a rectifier and resistor load, it was not possible to maintain load torque to very low speeds. At each inverter frequency, torque decreases approximately inversely with speed, with a torque discontinuity at the 2000 r/min RPS/CEMF switching point.

Overall system efficiency (shaft power out/dc power in) at inverter frequencies of 500, 900, and 1050 Hz is plotted in Figure 5-6. These frequencies represent low, medium, and high power settings. The data shows an efficiency of 80-81 percent at low power increasing to 84-85 percent at high power. Efficiency is reasonably independent of speed for speeds in excess of 2000 r/min.

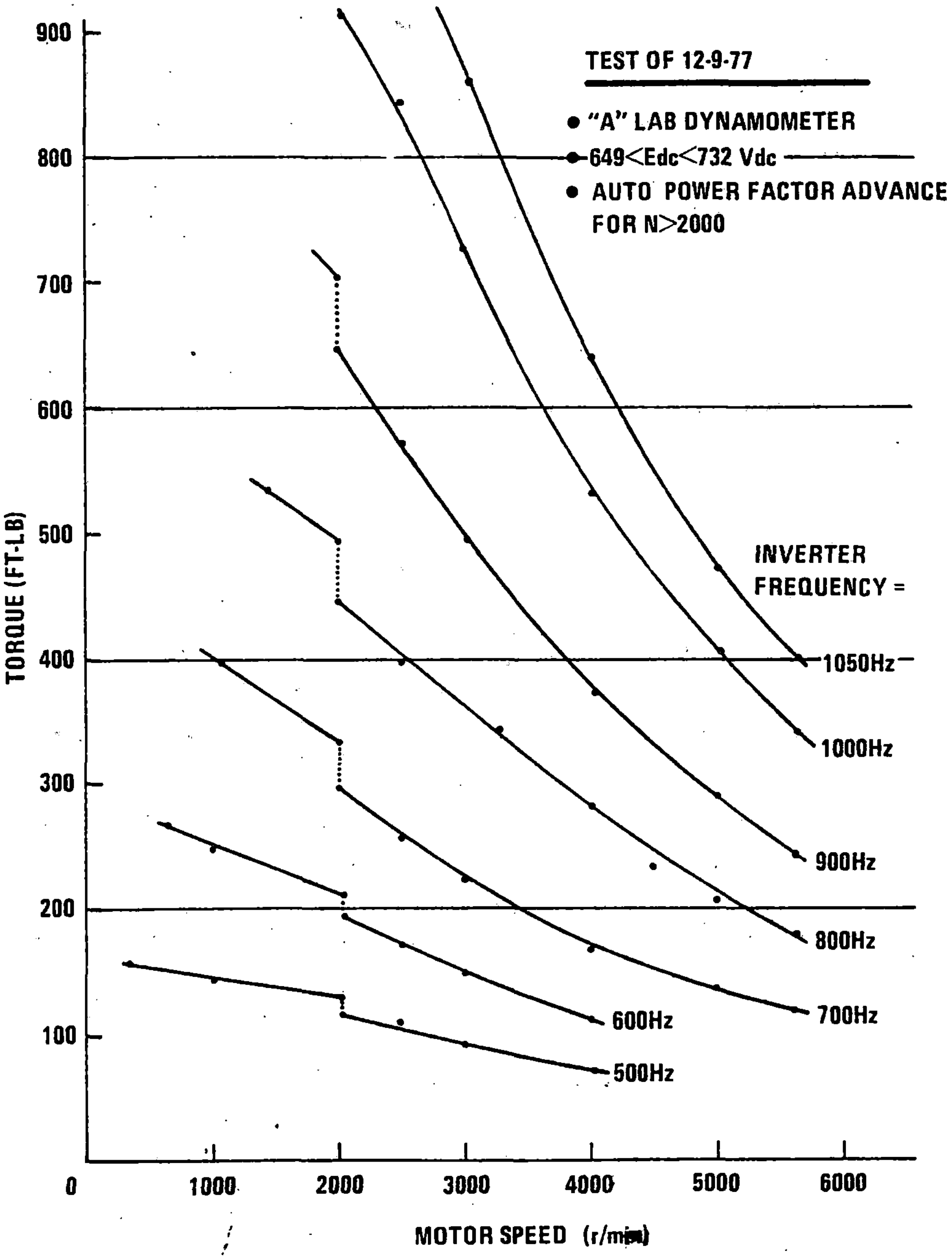


Figure 5-5. Torque-Speed Characteristics for Constant Inverter Frequencies

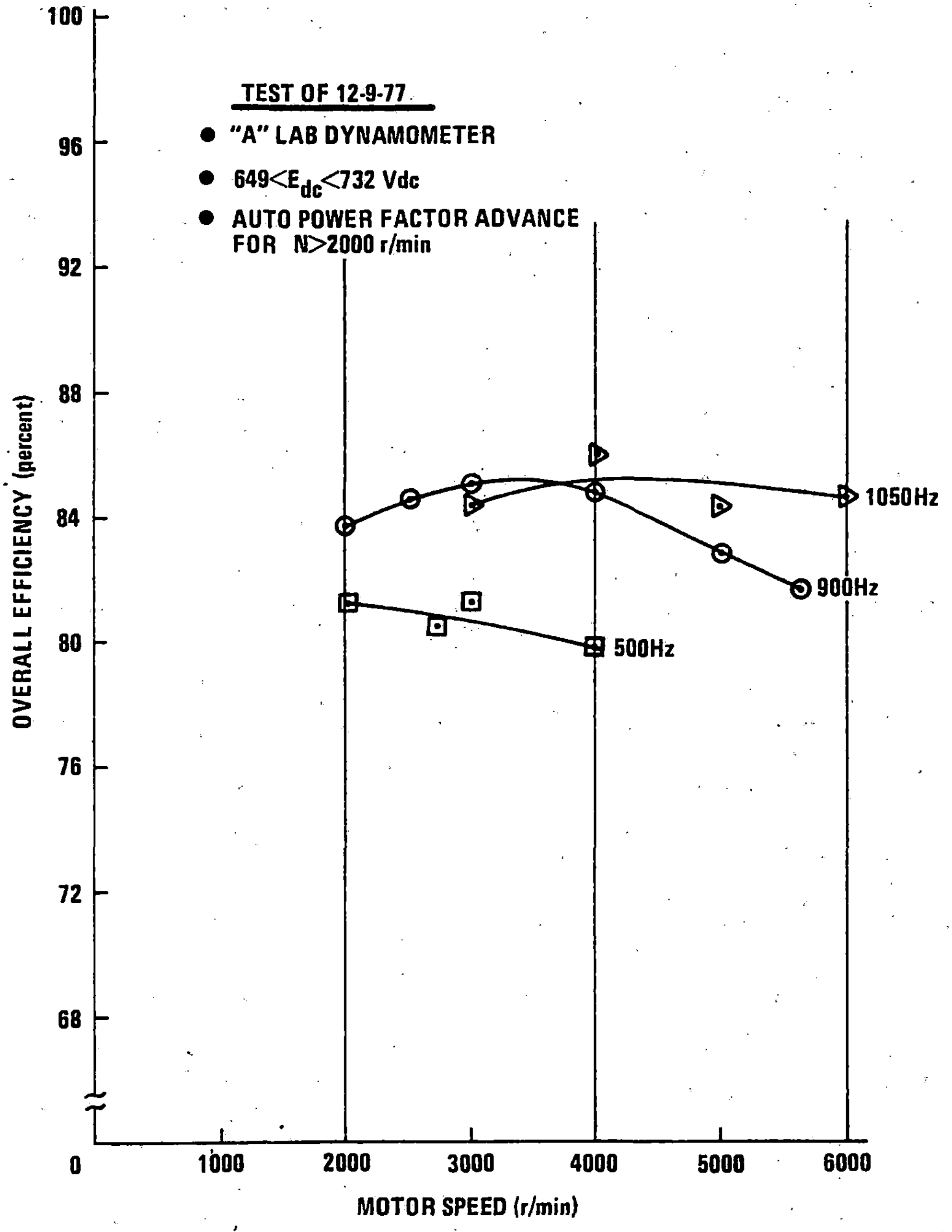
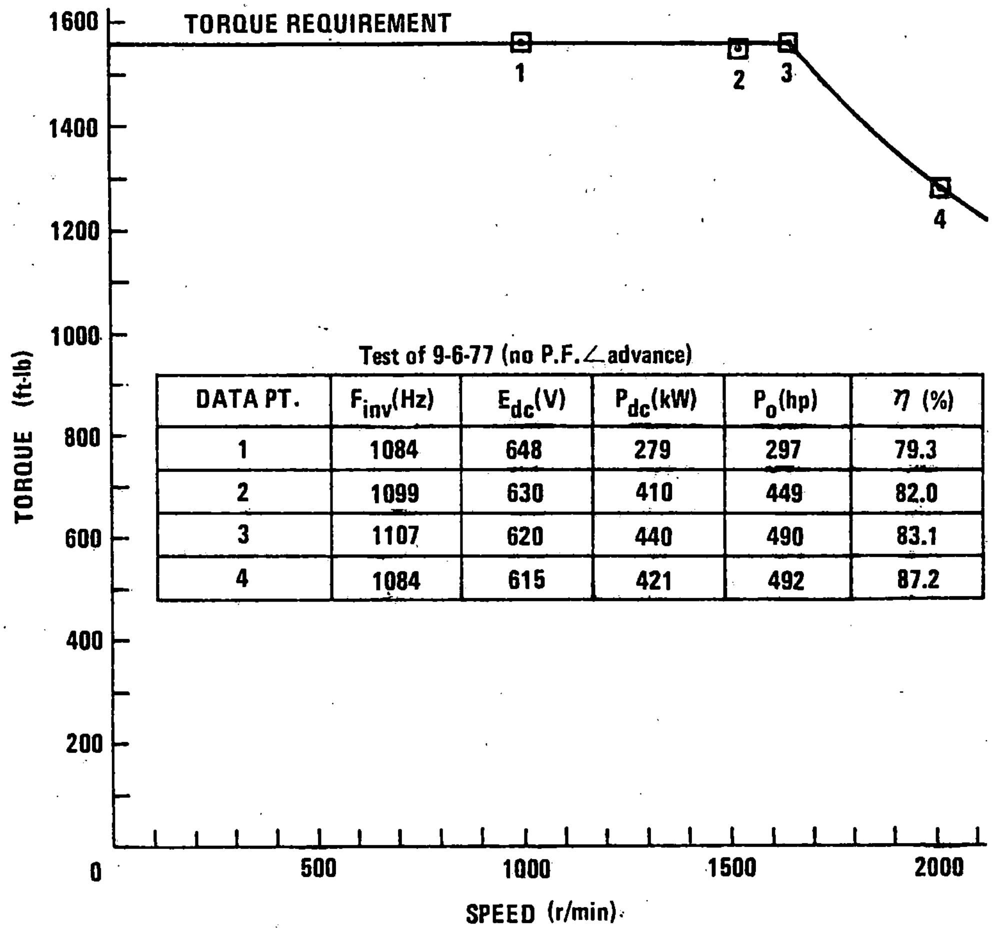


Figure 5-6. Overall System Efficiency vs Speed

Review of Final B Lab Performance Data

Since much B lab motoring testing was performed for the purpose of problem diagnosis, a consistent set of data with inverter frequency or other system parameters held constant is not available. Figure 5-7 shows four representative high power data points in the torque-speed plane as well as the ASDP torque versus speed requirement. The tabular data in Figure 5-7 also shows the inverter frequency, dc supply voltage and power, and overall efficiency for the four data points.



Test of 9-6-77 (no P.F. ∠ advance)

DATA PT.	F_{inv}(Hz)	E_{dc}(V)	P_{dc}(kW)	P_o(hp)	η (%)
1	1084	648	279	297	79.3
2	1099	630	410	449	82.0
3	1107	620	440	490	83.1
4	1084	615	421	492	87.2

Figure 5-7. Representative B Lab High Power Data Points

The 1646 r/min base speed torque and power requirements of 1560 ft/lb and 490 hp are met in data point No. 3. Maximum torque is achieved with a motor current of 557A rms. This is well within the maximum allowable current limitation of 600A rms given in the motor specification. Drive overall efficiency increases with speed from 79.3% at 1000 r/min to 87.2% at 2016 r/min.

5.3.2.3 Braking Mode Results

Braking mode development work and tests were considered lower in priority than motoring mode tests, based on an assumption that open loop operation in the braking mode was simpler and easier to accomplish than in motoring, an assumption which was proven correct. Thus, significant effort was not initiated until late in July 1977.

The testing was done in the dynamic braking mode by taking a matrix of data points within the specified torque-speed envelope. One limitation was that maximum torque capability, due to dynamometer limitations, could not be demonstrated at speeds above 2000 r/min. Two basic data sets were taken. In one set, torque at each speed was controlled by varying motor field excitation, i.e., by controlling VCO frequency. In the other, field excitation was maintained at a constant level and phase gating of the braking module SCRs was varied. No testing was accomplished in the regenerative braking mode.

Summary of Demonstrated Braking Performance Characteristics

Dynamic braking data included 491 separate data points. Recorded parameters at each point were: torque, r/min, brake grid voltage, brake grid resistance (full or one-third full value), phase delay rectifier gate control voltage, phase gate delay in electrical degrees, line-to-line voltage, phase current, SCR peak voltage, DSAS peak voltage, signals from the Hall current sensor and transformers used to sense current, motor field excitation (input ac amps to rotary transformer), and inverter frequency.

This data was then processed to correct the torque readings in accordance with a calibration curve, to predict brake grid current, to predict motor current, to calculate brake voltage/resistance and compare to predicted brake grid current, and to calculate dc field amps.

A composite plot of the maximum dynamic braking torque achieved in laboratory system testing is shown in Figure 5-8. The A lab data was obtained using Motor S/N 2B77 and the B lab data was obtained using Motor S/N 3.

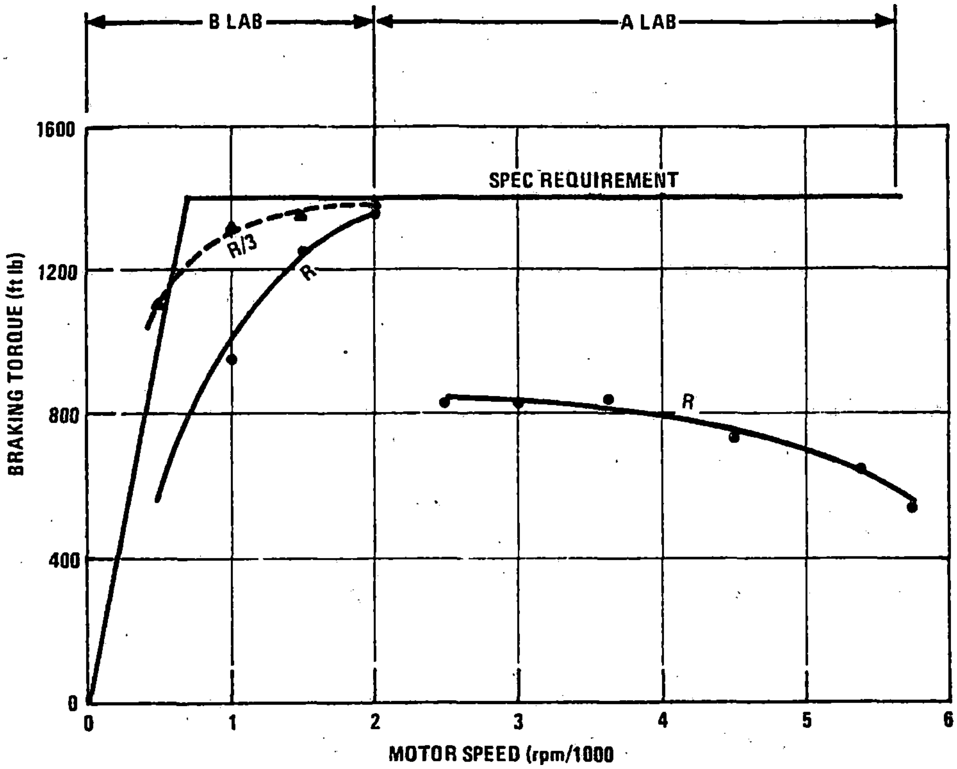


Figure 5-8. Dynamic Braking Performance

The points plotted are the highest torque points tested, but they do not represent the maximum capability of the system. The absence of data in the high torque, high speed corner of the plot was due to A lab dynamometer limitations. Analysis and extrapolation of the data indicates that the full braking torque specified for the system can be realized in the dynamic braking mode throughout the speed range with one possible minor exception. This is a small area in the low speed corner near the 700 r/min, 1405 ft-lb point. A higher field current is possible than was used in these tests and this might provide the specified torque. However, the increase might be marginal due to the field being highly saturated.

The maximum torque obtainable is independent of whether field control or phase gating is used since there is no gating delay when maximum torque is commanded.

Predicted versus Measured Torque Using Field Control

A three-way comparison of dc field excitation current versus dynamic braking torque was made. Compared were data obtained during motor component level tests by Delco Products, analytical predictions by Delco Electronics, and test data obtained during system level testing. The results are shown in Figure 5-9.

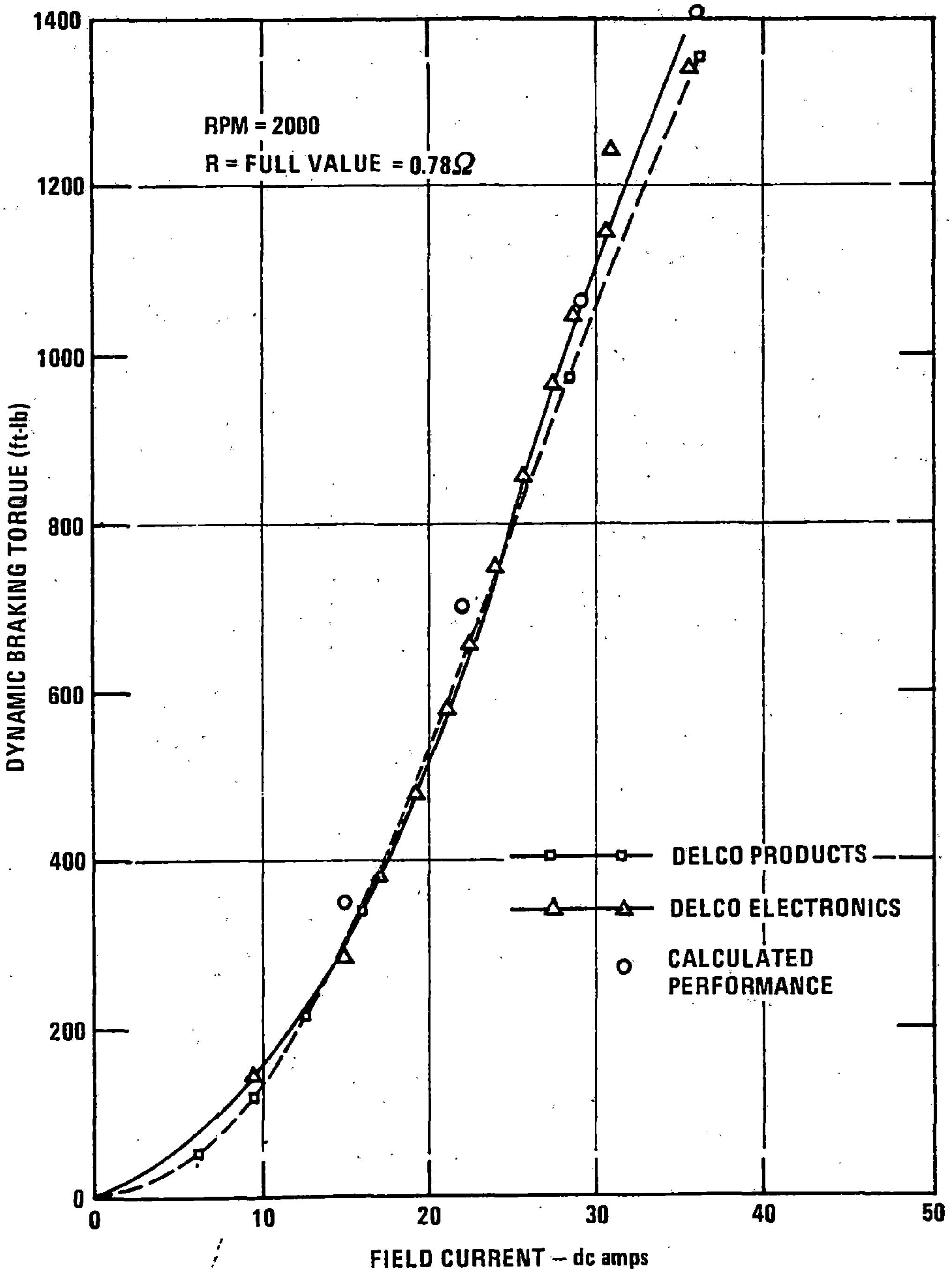


Figure 5-9. Field Current vs Braking Torque – Predicted vs Test Data

The comparisons were made at 2000 r/min since this was a speed at which motor component level test data was available. In general, there is very good correlation. This tends to confirm the validity of the analytical model of the motor for predicting braking performance at operating points where testing was not possible.

5.3.3 SYSTEM LEVEL TEST PROBLEMS

As can be seen from Table 5-I, the ASDP program experienced several problems during system integration and test, resulting in schedule delays and cost over-runs. In retrospect, it is obvious that there had been an insufficient allocation of contingency time for the solution of possible technical problems. It had been assumed that checkout and debugging of the prototype (Test Article) system would proceed smoothly as planned. This assumption was based on the extensive development effort carried out both prior to and during the early stages of the ASDP program (as discussed in subsection 6.1 of Volume II of this report. However, the development effort had been carried out using breadboard electronics and modified commercial motors, which fact, combined with some laboratory equipment limitations, had not permitted complete verification of all key operating concepts over the complete motoring and braking torque-speed profiles.

Unforeseen problems arose which were difficult to troubleshoot and diagnose and which, in some cases, required extensive rework to correct. These problems and the repair and replacement of failed components all proved to be extremely time consuming.

Some of these problems involved the motor and some involved the power conversion and control electronics. To define, understand, and resolve these problems, a series of developmental investigations was undertaken.

The problems involving the motor are briefly as follows:

1. There was inadequate energy dissipation capacity in a voltage surge protection circuit intended to protect the motor field winding. This resulted in Zener diode failures. The problem was solved by replacing the diode with a crowbar circuit. In addition, the bridge rectifier diodes were replaced with similar devices having fast recovery characteristics.

2. The bearing magnetic seals were defective resulting in contamination of the bearing lubricant by coolant fluid. This problem was solved by minor dimensional changes to the seal and seal mounting housing.
3. The axial load on the "fixed end" motor bearing exceeded the capacity of the roller bearing used in the original design. The solution was to replace the roller bearing with a ball bearing. A replacement bearing has been selected but could not be procured and tested prior to program termination.

Of the significant problems found in the power conversion and control electronics, some primarily affected motoring mode operation and some affected braking mode operation.

Motoring Mode Problems

Those problems primarily affecting motoring mode operation and the status of their solutions are summarized as follows:

1. The rise time and amplitude of the SCR gate drive for the cycloconverter, inverter and brake control modules were inadequate. This contributed to SCR failures. The problem was solved by redesign of the gate drive electronics.

2. The timing control of the SCR gate drive for the cycloconverter was inadequate. This resulted in a potential random "weak gate" condition which could result in SCR failures. The problem was solved by changing the gate timing control concept and modifying the timing control electronics accordingly.

3. There is an interaction between the inverter, cycloconverter, and motor, which results in loss of inverter SCR recovery time. Automatic system shutdowns (QSDs) then occur to prevent possible inverter faulting. This problem was alleviated by minor refinements in cyclconverter gate timing control and by other minor configuration refinements. The solutions effected were adequate to permit demonstration of full motoring capability throughout the complete torque-speed profile specified. This is still considered a latent problem, however, and additional investigation is needed to reduce the system fragility to undesired automatic shutdowns.

4. The suppression of di/dt in the cycloconverter was inadequate. This resulted in potential cycloconverter SCR degradation or failure. Linear and saturating inductors added between the inverter and cycloconverter to reduce di/dt solved this problem.

5. There was excessive noise in the motor self-control circuits; i.e., the RPS, CEMF and PFA control circuits. This resulted in commutation and power factor advance control problems. It may have also contributed to the previously mentioned interaction problem. The addition of filters and other detail control circuit changes reduced the noise greatly, such that in the final phase of laboratory testing, noise was not a significant problem. Repartitioning and other circuit changes will further reduce noise and are recommended.

6. Motor field excitation is not adequate when the system is operated at high speed and low torque. This results in cycloconverter faulting and automatic system shutdown (QSDs). A relatively simple modification was proposed in the field supply transformer circuit to increase the level of field excitation in the problem area. This was discussed in paragraph 7.2.3 of Volume II of this report. Lack of time prevented the installation and verification of this modification.

7. The energy dissipation capacity of the surge protection circuit for the cycloconverter SCRs was inadequate. This resulted in surge protection (DSAS device) failures at the instant of system shutdown. A solution, adequate for laboratory test purposes, was developed. It involved turning on braking mode SCRs to protect the DSAS device. Additional development work is required if this system is to be used on an operational vehicle.

In summary, the remaining motoring mode problems are of a second order nature involving refinements necessary to improve operational characteristics or operational reliability.

Braking Mode Problems

Those problems primarily affecting dynamic braking mode operation and the status of their solutions are summarized as follows:

1. The voltage ratings of the cycloconverter SCRs and DSAS devices were inadequate. In laboratory testing the problem was circumvented by disconnecting the cycloconverter from the motor when conducting dynamic braking tests at high motor speeds. Additional development is required, either to find a more practical solution for an operational system, or to incorporate modifications using SCRs or contactors to accomplish the disconnect function.
2. The voltage rating of the original brake module SCRs was inadequate. This problem was mitigated by replacing the original SCRs rated at 1800 V with devices rated at 2700 V. The replacement devices are adequate unless greater reserve voltage margins (derating) are desired, in which case devices rated for even higher voltages are available in a slightly larger physical size.
3. There is a noise problem in the brake module SCR gate drive circuit. As a result, braking module SCRs randomly turn on at speeds over approximately 3500 r/min. The problem is apparently the result of a ground loop in the gate drive circuit. In the laboratory, the problem was circumvented. Time did not permit its investigation and solution.
4. The dV/dt suppression circuits in the brake module were inadequate. As a result, SCR degradation or failure was possible. This problem was solved by the addition of suppression circuits having a maximum voltage rating of 3000 V.

In summary, the problems of brake modules SCR voltage rating (item 2. above) and dV/dt suppression (item 4. above) were solved as part of the developmental work performed. Time did not, however, permit resolving the more serious problems of overvoltage on the cycloconverter SCRs during braking (item 1. above) and the brake module SCR gate drive noise (item 3. above). These problems were circumvented in order to obtain dynamic braking performance data over the full speed range but these solutions are not directly applicable to an operational system. Additional development work is therefore required.

SECTION VI
FINAL CONFIGURATION

This section of the report contains a description of the changes made (or considered to be still required) to the propulsion system Test Article configuration, the status of the final configuration and the activities still required in order to arrive at a system configuration suitable for transit service.

6.1 CONFIGURATION CHANGES AND STATUS

The Test Article (TA) configuration refers to the configuration of the ASDP propulsion system hardware prior to changes which were made due to problems and deficiencies uncovered during the system level testing discussed in subsection 5.3. The configuration of the hardware at the end of the program is referred to as the "final" configuration.

Extensive modifications have been made to many parts of the propulsion system as a result of system level test effort. These modifications were made in electronic circuits, in electronics packaging, in the traction motors, and in the cooling system. Additional modifications are still required to make the system suitable for transit application.

Some of the changes, such as in the case of the motors, have been developed to a point suitable for vehicle service tests. Other changes, such as those made to the inverter, cycloconverter, and brake control modules, are of a configuration adequate for continued laboratory development work but are not adequate, in terms of mechanical integrity, for vehicle service testing. In still other areas, such as circuit modifications to the motor control electronics (MCE), there are extensive make-shift modifications. In such cases, repackaging is recommended prior to any further development work.

The status of the equipment drawings and specifications, like the status of the hardware, varies from component to component.

The mechanical design drawings and specifications have not been updated to reflect changes to the Test Article configuration, except in the cases of the truck-mounted equipment. Electrical schematics, however, have been updated to incorporate the changes made during system level testing and do reflect the "final" configuration. A complete drawing list is included in Appendix C of Volume III of this report.

The changes made, and the status of the final configuration of each major component of the system, are summarized in the following paragraphs.

6.1.1 ELECTRONIC CONTROL UNIT (ECU)

Very extensive circuit development work was carried out in the Motor Control Electronics (MCE) portion of the ECU. In contrast, little was done with the Train Control Electronics (TCE). The TCE was functionally verified but the signal interfaces between it and the MCE were not. Also, system level closed loop control was not verified. As a result it is not known what TCE circuit design and electronics packaging changes, if any, may be required. In the case of the MCE, even though extensive circuit redesign was accomplished, more is required. Furthermore, a complete redesign of the electronics packaging is felt to be required, both to accommodate additional circuits which have been added, and to reduce susceptibility to noise.

6.1.2 POWER CONVERTER ASSEMBLY

The PCA chassis was not modified during the test program. Changes would eventually be required, however, particularly if the system were to be considered for production. One reason is that changes to the inverter, cycloconverter, brake control, and field supply modules may require that the size of these units be increased. Another reason is that the raceway area available for hydraulic and electrical interconnects is marginal.

The changes made (or considered to be required) to the modules which comprise the power converter assembly are summarized as follows:

6.1.2.1 Inverter Module

The most significant change to the TA inverter module was the redesign of the SCR gate drive circuits. Also, the interconnect wiring from the circuit component board in the inverter to the SCR gate leads was changed to twisted pairs. Since the packaging density is very high, it is recommended that the unit be partially redesigned to improve serviceability.

6.1.2.2 Capacitor Module

No changes were made to the TA capacitor module and no need for changes is foreseen.

6.1.2.3 Cycloconverter Module

Changes made to the TA cycloconverter module were as follows:

- The SCR gate drive circuits were extensively modified and the gate drive transformers were replaced with redesigned units that were larger in size.
- The interconnect wires between the gate drive circuits and the SCR gate wires were replaced with shielded, twisted wires and were rerouted for minimum length.
- To implement the above wire routing change, it was necessary to remove side reinforcing structure of the module.

These changes have resulted in a configuration not suitable for use other than in laboratory tests. Redesign is therefore required.

6.1.2.4 Field Supply Module

The failure of the field supply transformer required modification of the windings for improved cooling. It also indicated that continuous flow of coolant through the module is necessary. In the TA configuration the module acted as a stand-pipe sump in the coolant loop. The loop flow did not pass through it.

6.1.2.5 Brake Control Module

Several major hardware changes were made to the TA configuration brake control module. High voltages encountered during braking resulted in the addition of insulation barriers around some of the bus strips and all of the terminal feedthroughs. New SCR gate drive and dV/dt circuits were also added.

In order to accommodate the dV/dt resistors and capacitors a deeper enclosure was made. Also, as with the cycloconverter, support structures were removed. Prior to any vehicle service tests, repackaging of this module would be required.

6.1.3 INPUT LINE FILTER/POWER CONTROL SWITCHGEAR

In an early test, it was found that the turn-on current surge through the input filter inductor caused a voltage transient which exceeded the 1200 V rating of the input filter capacitance located in the power control switchgear. Possible solutions were postulated; however, the existence of higher priority developmental problems led to a decision to disconnect the input filter inductor from the system for all testing. As a result, none of the proposed solutions was incorporated into the filter design or verified in system testing.

6.1.4 RESONATING INDUCTOR MODULE

As a result of a component level test which indicated a poor inductor quality factor (Q), the internal support structure of the resonating inductor module was changed from aluminum to an inert fiberglass material. Also a change was made in the location of the fuses at the input to the inverter to correct an original circuit design error. This resulted in an extensive revision of the interconnect between the resonating inductor and the inverter module. Following these changes, the performance of the resonating inductor was satisfactory and no further changes are considered to be required.

6.1.5 COOLING SYSTEM

Two improvements to the cooling system were incorporated during the TA test program. First, a reservoir was added in the laboratory configuration to permit coolant flow through the field supply module, which previously had served as the reservoir. Second, sound dampening acoustic foam was placed in appropriate areas within the cooling assembly interior to absorb fan and pump noise.

6.1.6 TRACTION MOTOR

Changes made to the traction motor were discussed in paragraph 5.3.3.

6.1.7 GEAR DRIVE AND AXLE COUPLING ASSEMBLY

Changes made to the gear drive and axle coupling assembly were discussed in subsection 5.2.

6.2 ACTIVITIES REQUIRED TO DEVELOP A PRODUCTION CONFIGURATION

The development of a production configuration requires, in general, the completion of the laboratory development and system qualification tests followed by a series of vehicle service tests. The remaining laboratory development tests consist of the following: (1) solving the previously discussed problems and completion of the open-loop characterization of the system for both the motoring and braking modes; (2) integration of the MCE with the TCE and verification of closed loop control of the system for both the motoring and braking modes; (3) verification of mode to mode transitioning and control; (4) resolution of previously identified cooling system and packaging problems; and (5) completion of simulation studies supportive to the development of a closed loop motoring and braking control capability.

Upon completion of laboratory development, qualification tests must be conducted to verify that the equipment meets the established design and performance requirementd and to provide a degree of assurance that it is suitable for integration into the modified-SOAC. Some of these tests would be conducted at the major component or assembly level; however, the primary means of qualification would be through system level tests of an integrated propulsion system.

The vehicle service tests would consist of engineering evaluation and acceptance tests of the equipment as installed on the modified-SOAC. These tests would be carried out at the HSGTC at Pueblo, Colorado.

6.2.1 LABORATORY DEVELOPMENT

Specific background and tasks relative to completing the laboratory development phase of the remaining effort is discussed in this paragraph.

6.2.1.1 Motoring Mode Development Required

The remaining motoring mode development work is summarized as follows:

- The development and verification of solutions to the previously discussed motoring mode problems
- The verification and characterization of motoring mode open loop characteristics and capabilities when the input voltage is varied over the specified range of 450 – 750 V.

- The verification of closed loop motoring mode control. This involves placing the inverter VCO under the control of the TCE microprocessor, closing the feedback loop indicating motor output power, and controlling the system via a simulated P-signal. If the microprocessor is verified in a simulation, as discussed in subsection 5.5 of Volume II of this report, little difficulty is foreseen in this development area.
- The verification and characterization of system operation when subjected to transients and step changes in input voltage.

6.2.1.2 Braking Mode Developing Required

The remaining braking mode development work is greater in extent and more difficult to define than that for the motoring mode. Several interrelated reasons for this are as follows:

- There are two modes of operation to control: dynamic braking and regenerative braking. In addition, the potential exists for a hybrid mode in which both types of braking are employed simultaneously.
- It is necessary to transition between the dynamic and regenerative modes without interruption of the braking effort.
- There are two means of controlling braking torque in both the dynamic and regenerative modes: motor field control and braking SCR phase gating control. The criteria for the interrelated use of the two control methods has not been fully defined. Each has certain advantages and limitations.
- The specific development testing required depends to some degree on the specific solution selected for previously discussed braking mode problems.

The development tasks required to complete the laboratory phase of the braking mode development effort are listed below somewhat in sequence, but they are highly interrelated and as a result, considerable iteration will be required.

- Develop and verify solutions to the braking mode problems discussed in paragraph 5.3.3.
- Verify operation in the regenerative braking mode in a manner similar to the verification of the dynamic braking mode of operation.

- Complete the characterization of the system for both the dynamic and regenerative braking modes. The specific system characterization data needed are as follows:
  - For the dynamic braking mode: Torque versus Speed versus Field Excitation Current versus Phase Delay.
  - For the regenerative braking mode: Torque versus Speed versus Field Control versus Phase Delay versus Input (3rd rail) Voltage.
- Determine the system response times for the dynamic and regenerative modes using both field control and phase delay control.
- Using the characterization data and the dynamic response characteristics, simulate the braking mode in a hybrid computer simulation similar to that for the motoring mode.
- Using the simulation, develop control algorithms for both the regenerative and dynamic braking modes. These algorithms would determine the relative use of field control versus SCR phase delay gating control.
- Develop software, program the TCE microprocessor, and verify the braking mode including mode transitioning on the simulation.
- Program the microprocessor in the system to duplicate the simulation and verify system level dynamic and regenerative braking mode operation.

6.2.1.3 Mode Transitioning and Operational Sequence Verification

A series of integrated system laboratory tests are required with the objective of verifying sequencing of the system through simulated operational profiles. Key elements will be verification of the capability to transition between the motoring and braking modes and verifying the control of jerk rate throughout the sequences. These tests depend on the completion of the previously discussed motoring mode and braking mode development tests, and on integrated operation of the system under the control of the TCE microprocessor.

6.2.2 LABORATORY QUALIFICATION TESTS

Qualification testing of the ASDP propulsion system must be accomplished to assure that the equipment will meet the design and performance criteria established in Boeing Specification D239-10000-1. Qualification would be accomplished primarily by subassembly and system laboratory tests and in some cases by analysis and/or similarity to equipment presently used in transit car environments. The ASDP propulsion system qualification matrix is shown in Table 6-I.

The general approach would be to qualify the majority of the components and subassemblies at the system level using dynamometer simulation. This approach eliminates complex simulated interfaces with other subassemblies, reduces test duplication, and more comprehensively verifies subsystem integration. Testing to verify performance characteristics would be accomplished using dynamometer equipment described in paragraph 5.3.1 to simulate transit car operation.

The system testing would cover the following:

- Acceleration and Braking Performance
- Continuous Speed and Coast Performance
- Regenerative Braking Capability
- Operation at 400, 450 and 750 Vdc Line Voltage
- Operation Over Rail Gaps
- System Thermal Capability
- System Control, Functional.

6.2.3 PUEBLO TEST UPDATE

Completion of the modifications and tests discussed in this section will provide a system ready for simulated transit service testing at the Pueblo HSGTC Test Track. This will also represent a system that is close to a production configuration. Remaining effort will involve the incorporation of modifications required to solve problems uncovered in the field testing and the incorporation of changes and refinements to improve producibility, maintainability, reliability, etc.

Test Hardware Requirements	Performance Characteristics	Thermal	Vibration and Shock	Acoustic Noise	Transients	EMI-RFI
Electronic Control Unit	SL	S	S	NA	SL	VS
Power Control Switchgear	SL	SL	A	NA	SL	VS
Resonating Inductor	SL	SL	A	Sa	SL	VS
Power Converter Assembly	SL	SL	Sa/A	NA	SL	VS
Traction Motor	Sa/SL	Sa/SL	Sa*/A	Sa	SL	VS
Line Filter Inductor	SL	SL	A	NA	SL	VS
Brake Resistor	SL	SL	S	NA	NA	NA
Cooling Assembly	SL	SL	A	Sa	NA	NA
Speed Sensors	SL	SL	S	NA	NA	NA
Truck Connector Box	S	SL	S	NA	SL	NA
Motor-Gearbox Coupling	SL	SL	S	NA	NA	NA

VS - Vehicle Systems Tests
SL - Propulsion System Laboratory Tests
Sa - Subassembly Test

S - Similarity
A - Analysis
NA - Not Applicable

* Generated Vibration only.

Table 6-I. Propulsion System Qualification Matrix