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**Urban Mass
Transportation
Administration**

Inverter-Controlled ac Induction Motor Propulsion System

Volume I: Executive Summary

March 1989
Final Report

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16. Abstract

An inverter-controlled ac induction motor propulsion system for rail transit cars was designed, developed, and tested to verify projected benefits and applicability of ac over conventional dc cars. Two New York City Transit Authority (NYCTA) R-44 dc subway cars were retrofitted with prototype ac propulsion equipment based on mature, low-risk ac propulsion technology. The program showed that propulsion systems using ac motors can provide greatly improved reliability and reduced maintenance, with significant reductions in life-cycle cost. The prototype ac propulsion system conserves energy through regenerative braking, returning energy to the line when the network is receptive. The equipment consists of a control unit incorporating solid-state integrated circuits and two essentially independent truck drives. For each truck, a single inverter unit powers two totally enclosed, self-cooled, squirrel-cage ac induction motors, each motor driving one of the two axles per truck. Each pulse-width-modulated, voltage-fed, thyristor-controlled inverter is forced-air cooled by a blower, which also cools the resistors used to dissipate dynamic braking energy when the line is not receptive. Demonstrated on the NYCTA, the ac propulsion system improved acceleration and braking performance with good electromagnetic interference and acoustic noise control and was fully compatible with the existing trainlines, NYCTA signalling and supervisory equipment, and dc cars. The report explains how the latest technology would be applied in future production equipment to result in even more benefits to the rail transit industry.

Volume I contains the executive summary; Volume II contains final report Sections 1 through 5.

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Ac traction motor
Dc chopper
Inverter drive unit
Power conversion unit
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PREFACE

The subsystem technology application to rail systems (STARS) program was sponsored by the U.S. Department of Transportation (DOT) Urban Mass Transportation Administration (UMTA). The UMTA organizational team was the driving force of the DOT effort to demonstrate the applicability of ac propulsion equipment to the U.S. transit industry. Credit also is due the American Public Transit Association (APTA) and its car equipment liaison board for its support during the entire program.

Work on this STARS program was conducted under DOT/UMTA Contract DTUM60-82-C-71144, initiated on March 31, 1982. Under this contract, the AiResearch Los Angeles Division of Allied-Signal Aerospace Company, teamed with Oy Stromberg Ab of Helsinki, Finland, designed, developed, fabricated, tested, and delivered a prototype inverter-controlled alternating current (ac) induction motor propulsion system for transit vehicle application. The system was demonstrated on two New York City Transit Authority (NYCTA) R-44 subway cars on the NYCTA transit system.

The program was truly a combined effort of administrative ability (DOT, UMTA) and technical initiative and creativity (AiResearch and its team member, Stromberg) resulting in a successful operational demonstration conducted with the support of the NYCTA, without whose help the program would not have been completed. Specifically, AiResearch acknowledges the NYCTA assistance in the areas of engineering support, test vehicle preparation and transport, electromagnetic interference (EMI) test support and supply of signalling equipment, and the maintenance of the nonpropulsion equipment on the R-44 test/demonstration vehicles. The availability of the NYCTA facilities, test track, and revenue service operation is appreciated. The DOT Transportation Systems Center of Cambridge, Massachusetts, also is recognized as a major contributor to the overall success of this STARS project, especially in the area of EMI and signalling testing. The following individuals are recognized for their specific contributions to the program.

- Ron Kangas, Chief, Technology Division, and Steve Barsony, Director, Office of Systems Engineering, DOT/UMTA, Washington, D.C.

European transit market, enabled satisfactory completion of hardware qualification testing, R-44 implementation, and integration of three complete sets of hardware (two installed car sets and one set of spares) and culminated in a lengthy, successful operating program on our nation's most demanding transit system, the NYCTA. The entire program was accomplished within the DOT/UMTA STARS contract budget.

It is acknowledged that the demonstrated system does not represent present-day technology such as the new developments in gate turn-off (GTO) devices that replace thyristors and thus eliminate commutation circuitry, or the latest advancements in microprocessors and software, but to incorporate this technology at the risk of program delays and possible failures was deemed unnecessary because the **system concept** and **application to a real environment** were the main priorities. Continually modifying proven equipment to incorporate the latest technological advances could not have guaranteed the STARS program success and, in fact, would undoubtedly have resulted in program delays and, consequently, financial hardships inconsistent with the STARS goals. Now that ac propulsion has been demonstrated as a viable replacement for outmoded dc equipment, new requirements can be met with the latest-technology systems.

The STARS program success is evident by current "on-the-street" requests for proposals by several U.S. transit authorities, including the NYCTA, for ac propulsion equipment or vehicles operating with ac propulsion. The Southeast Pennsylvania Transit Authority (SEPTA) currently is introducing ac propulsion equipment on its Norristown line. The STARS program was closely monitored by many U.S. transit properties interested in the industry shift from dc equipment to ac, and it has stimulated the widespread acceptance now being shown.

The executive summary, Volume I of this final report, provides an overview of the entire STARS program, including background information on electric rail transit and major program milestones. Volume II presents more detailed information on the activities of each phase of the two-phase program, including representative samples of significant recorded test data and summaries of test results.

- Ray Wlodyka, UMTA Project Engineer and Program Monitor, DOT, Transportation Systems Center, Cambridge, Massachusetts, and Dr. Ross Holmstrom and Mike West, EMI Support, Transportation Systems Center, Cambridge, Massachusetts
- Chuck Edelson, UMTA contract EMI support
- Richard Goodlatte, Chief Mechanical Officer, NYCTA
- Jack Rogg, New Car Engineering, NYCTA, and his STARS engineering staff, Oscar Rosenes and Arpad Frank; Al Dzingelis, NYCTA Phase I Project Manager
- Steve Shooman, Signal Department, NYCTA

The AiResearch program was under the direction of Charles Weinstein, product line manager of the electrical power and rapid transit systems group. Phase I program manager was Gabor Kalman, and the Phase II program manager was Jim Clemence. The AiResearch technical team was headed by Bob Rudich and Rudy Van Eck, and the NYCTA test program was under the direction of Keith Vasak of AiResearch. Stromberg's technical expertise and on-site support is acknowledged, especially that of Arto Issakainen.

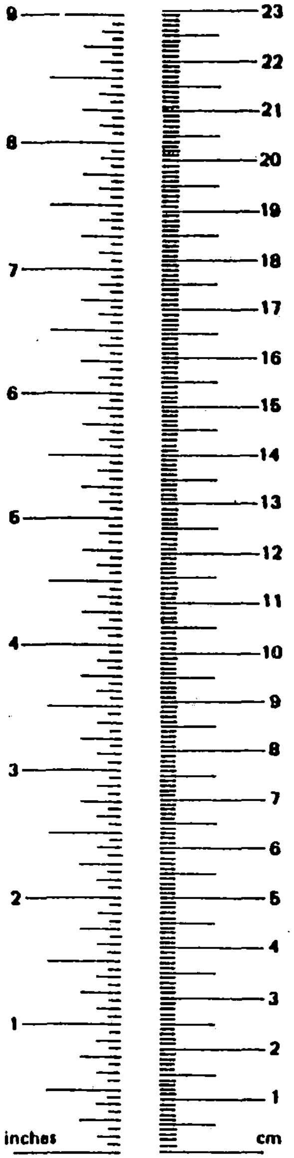
This document summarizes the design, laboratory testing, manufacturing, R-44 car installation, and car test program of the ac propulsion system applicable to a U.S. operating transit system. The program rationale promoted by the UMTA program organization was that the conversion from current dc onboard propulsion to ac will result in improved reliability and reduced maintenance and is compatible with existing transit practices. The introduction of ac induction motors, which have no commutators or brushes to service, is the key to this goal. Improved energy efficiency with elimination of series resistors and the ability to use regenerative braking, reducing electrical energy consumption by up to 37 percent, are additional benefits.

The key to the success of the STARS program as evidenced through the Phase I and Phase II efforts was the initial team decision by AiResearch and Oy Stromberg to use a **proven** ac propulsion concept tailored to the requirements of STARS. The use of this system, already developed and operational in the

METRIC CONVERSION FACTORS

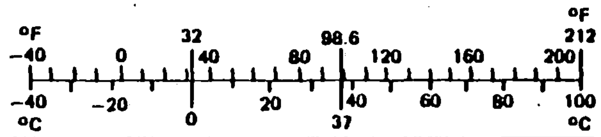
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.

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LIST OF ABBREVIATIONS

APTA	American Public Transit Association
ATO	Automatic train operation
CMOS	Complementary metal-oxide semiconductor
DOT	Department of Transportation
EMI	Electromagnetic interference
GTO	Gate turn-off (thyristor)
LCC	Life-cycle cost
LCE	Line control equipment
LED	Light-emitting diode
MDBF	Mean distance between failures
NYCTA	New York City Transit Authority
PWA	Printed wiring assembly
PWM	Pulse-width modulation (modulated)
STARS	Subsystem technology application to rail systems
TSC	DOT Transportation System Center
TTC	Transportation Test Center
UMTA	Urban Mass Transportation Administration

EXECUTIVE SUMMARY

INTRODUCTION

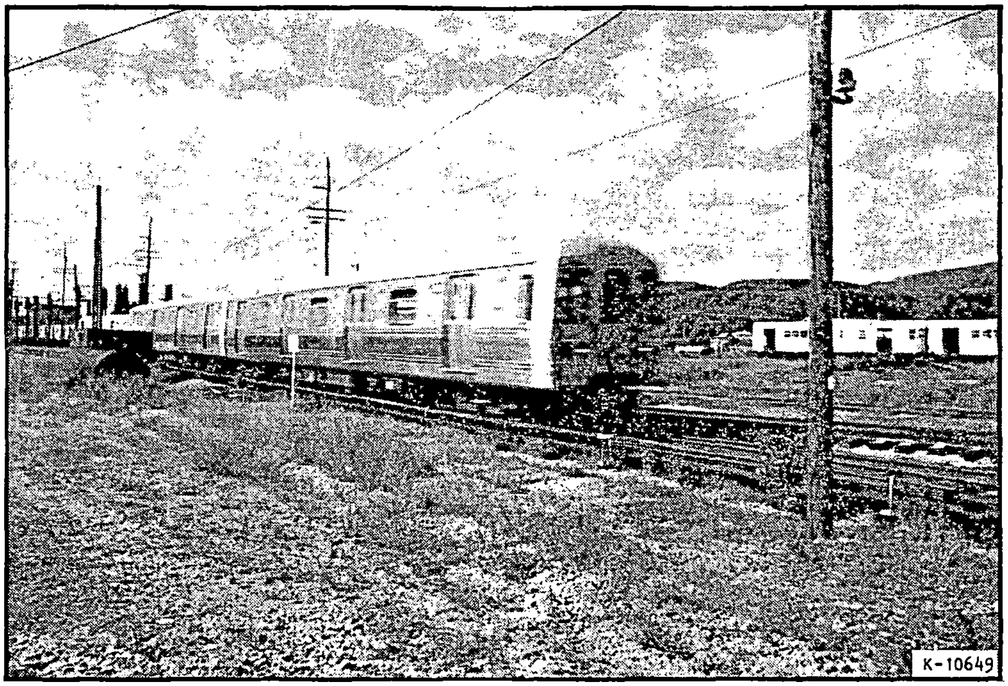
The DOT/UMTA-sponsored inverter-controlled alternating current (ac) induction motor propulsion system program has successfully demonstrated that ac propulsion systems offer significant, achievable near-term benefits to the rail transit industry.

The prototype ac propulsion system (Figures 1 and 2), built by an international team--AiResearch Los Angeles Division of Allied-Signal Aerospace Company in the United States and Oy Stromberg Ab of Helsinki, Finland--incorporates low-maintenance, totally enclosed ac traction motors together with thyristor-based power conditioning circuits and solid-state controls. The system was installed in place of the original direct current (dc) equipment in upgraded self-propelled R-44 subway cars of the New York City Transit Authority (NYCTA), and successfully demonstrated in New York in one of the world's most demanding rail transit applications.

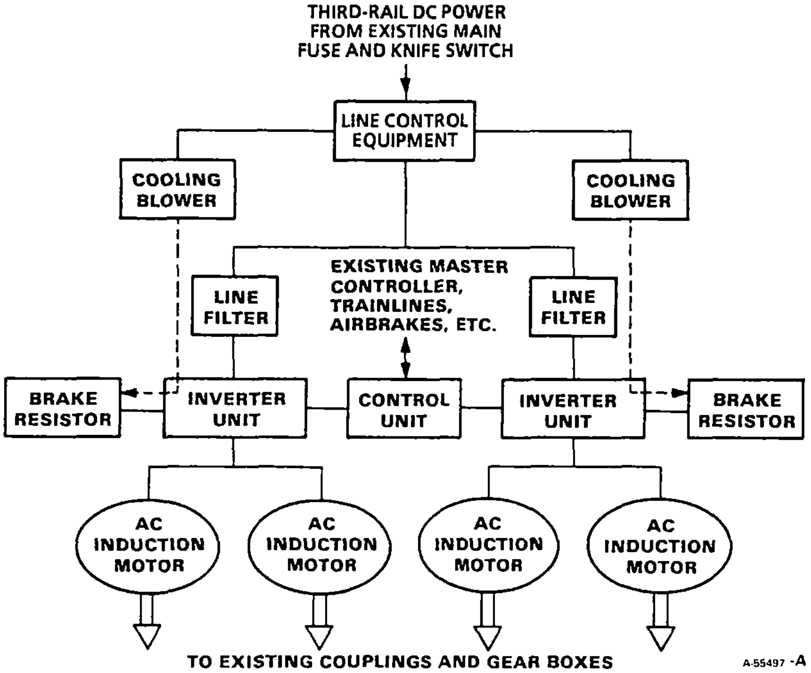
This executive summary provides an overview of the entire STARS program effort, including some background information on electric rail transit and the rationale for considering conversion to ac propulsion systems. The STARS program history is reviewed, program accomplishments are discussed, and the ac propulsion system and components are described. Significant test results are summarized. Volume II provides more details, including design information, pertinent data collections, and reduced test results.

DOT/UMTA STARS Program

The DOT/UMTA subsystem technology application to rail systems (STARS) program, of which this ac propulsion system program is an important element, was established to benefit the U.S. rail systems industry by encouraging the application of the latest technological developments to rail systems.



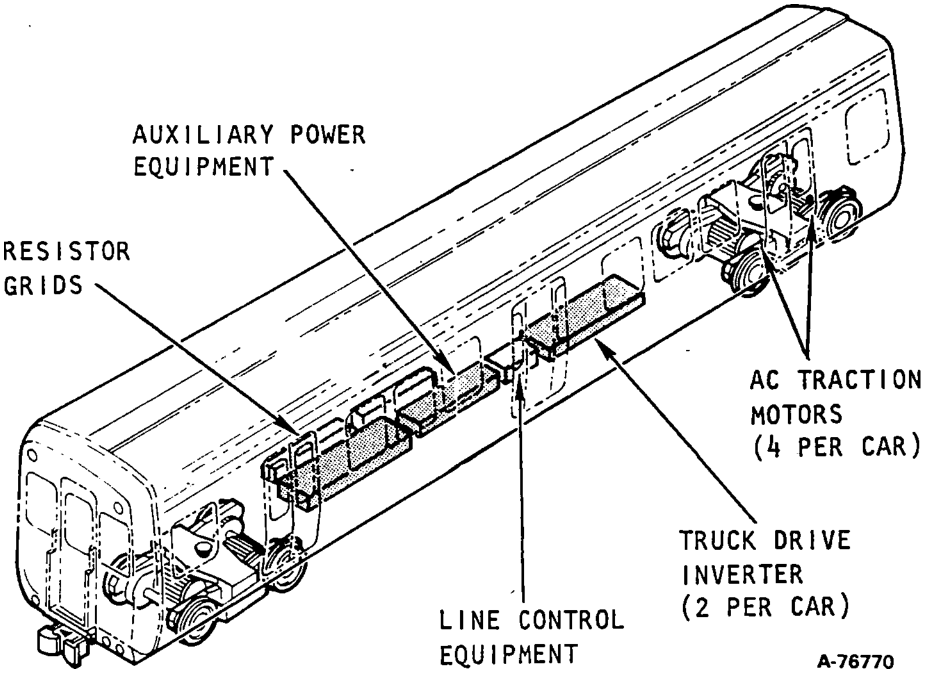
a. R-44 TEST/DEMONSTRATION CARS



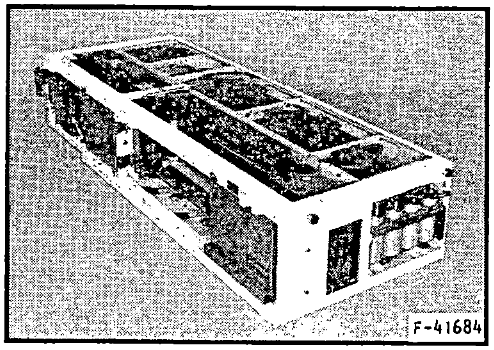
b. AC PROPULSION SYSTEM BLOCK DIAGRAM

F-56381

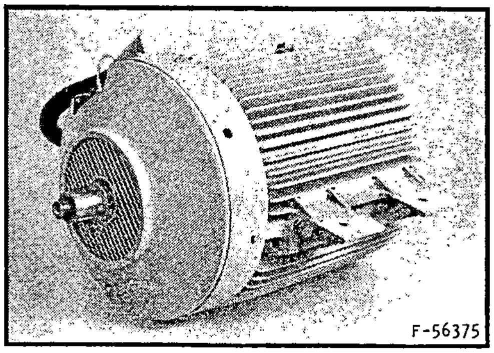
FIGURE 1. AC PROPULSION SYSTEM AS DEVELOPED FOR R-44 CAR



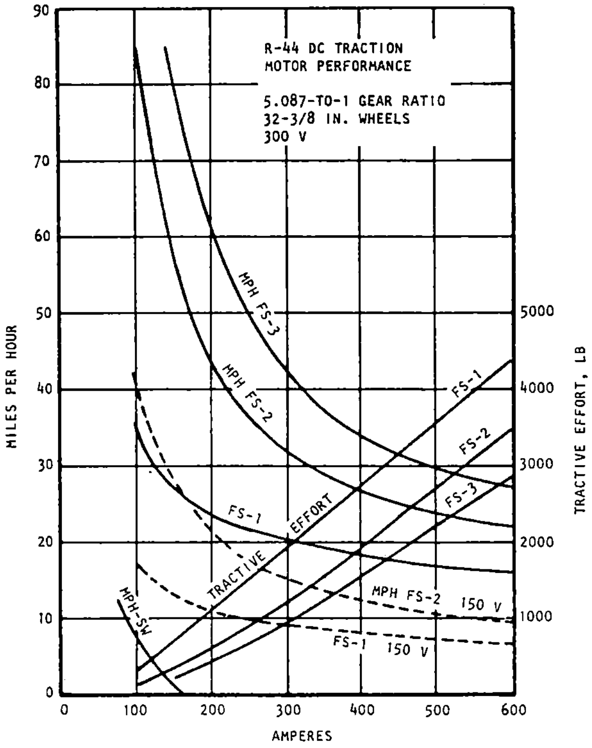
a. TYPICAL R-44 INSTALLATION



b. INVERTER



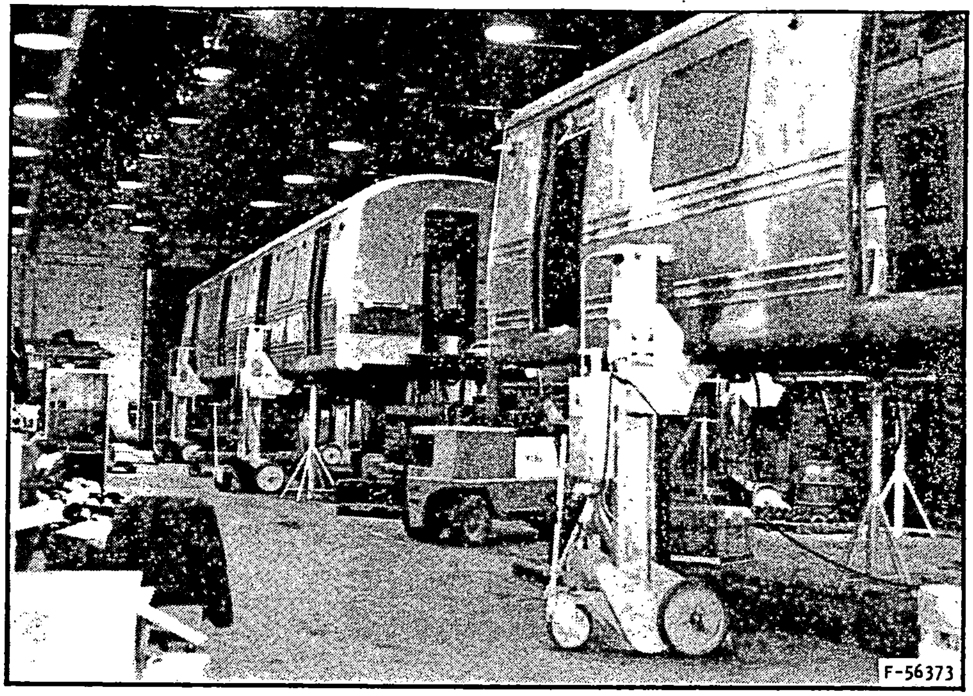
c. AC MOTOR



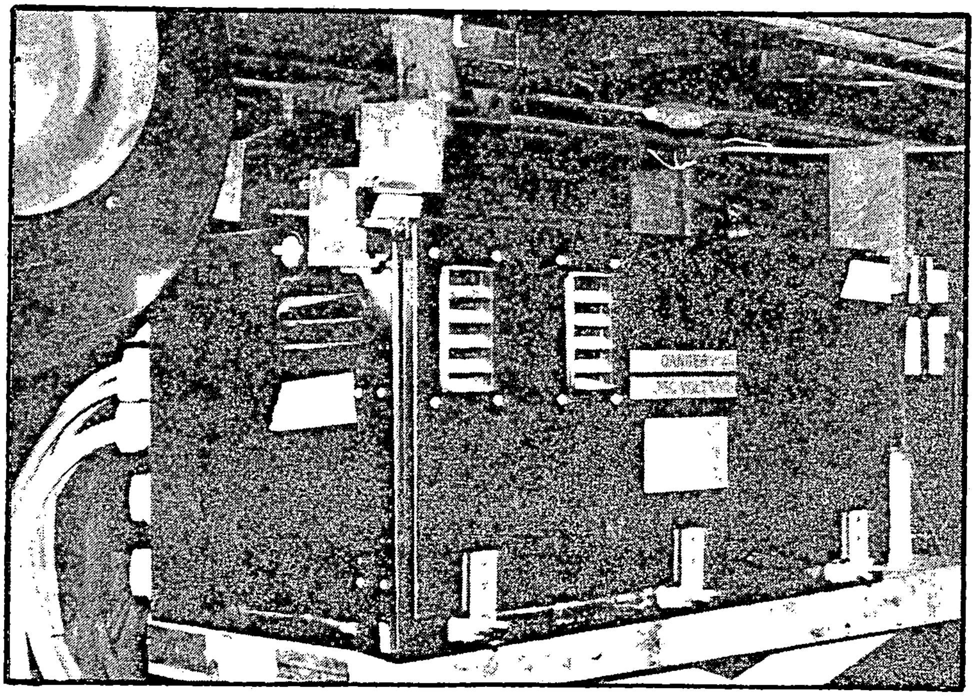
d. DESIGNED TO MATCH R-44 DC PERFORMANCE

F-56378

FIGURE 2. AC PROPULSION SYSTEM EQUIPMENT AND LAYOUT IN R-44 CAR



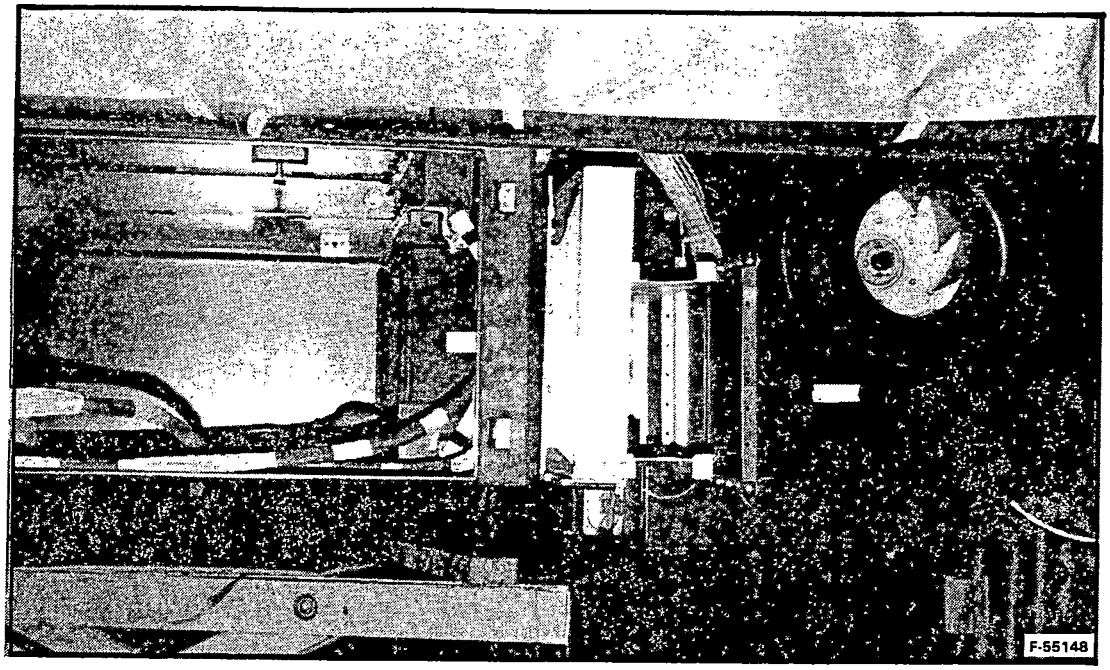
a. R-44 STARS CARS UNDERGOING REFURBISHMENT AT MORRISON-KNUDSEN FACILITY, HORNELL, NEW YORK



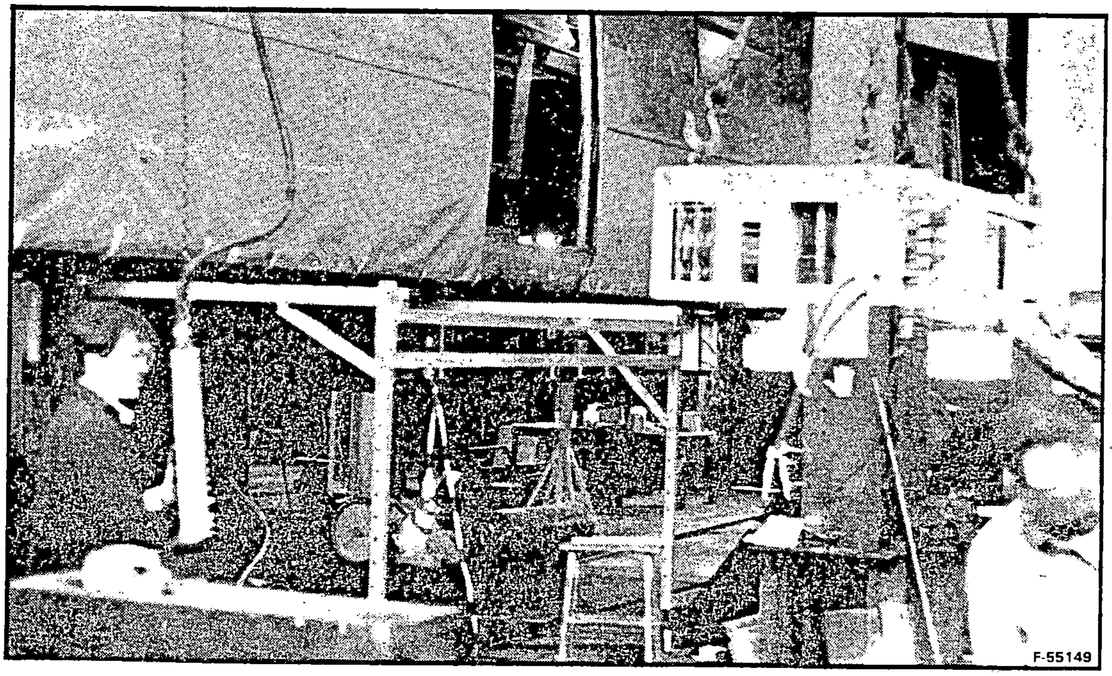
b. LINE CONTROL EQUIPMENT INSTALLATION (SHOWS SAFETY HANGING FEATURE)

F-56376

FIGURE 2. (CONTINUED)



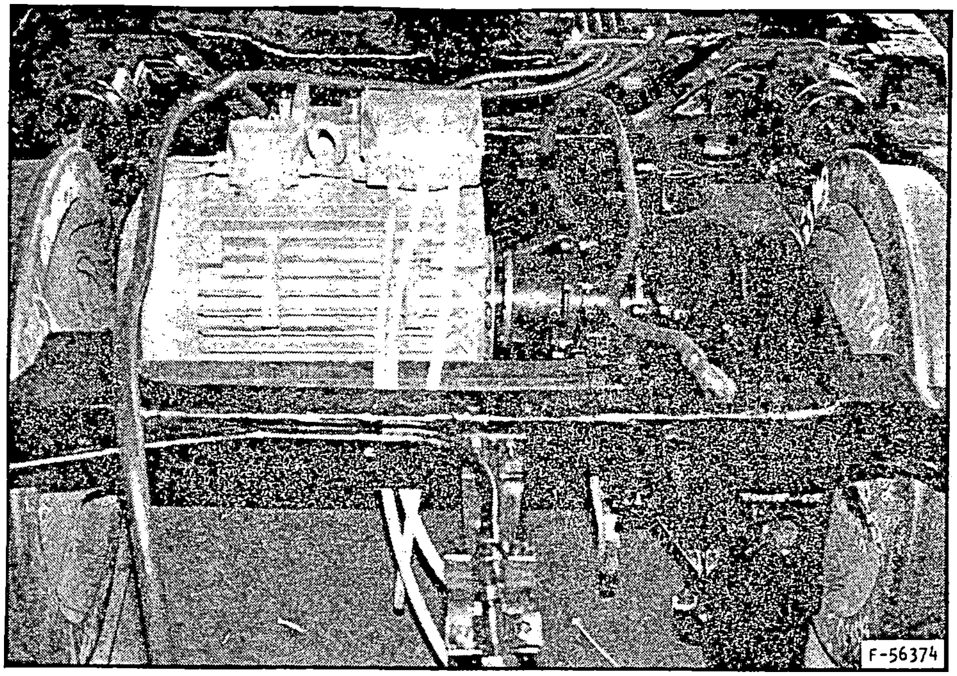
a. INVERTER ENCLOSURE AND COOLING AIR BLOWER



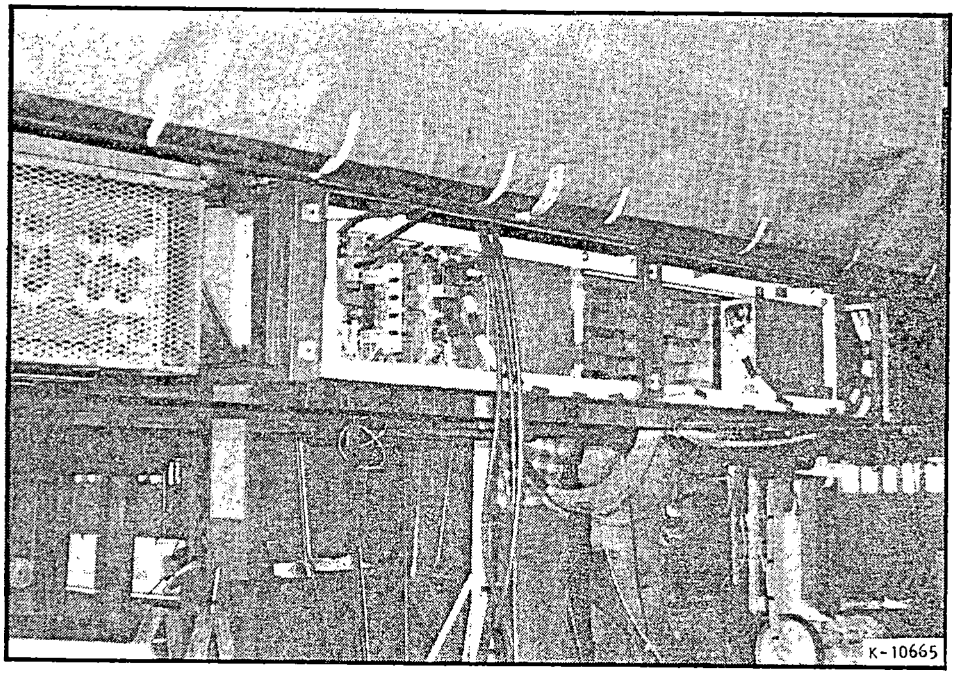
b. LOWERING INVERTER INTO RACK

F-56524

FIGURE 2. (CONTINUED)



a. AC MOTOR INSTALLATION IN R-44 CAR



b. BRAKE RESISTOR AND INVERTER INSTALLATION IN R-44 CAR

F-56379

FIGURE 2. (CONTINUED)

DOT/UMTA has sponsored numerous programs to foster the development of advanced systems for the U.S. rail transit industry. In previous programs, ac induction motor propulsion was identified as the most suitable system developed to date for transit applications, primarily because of the desirable characteristics of the induction motor. Important benefits expected to accompany a conversion from systems using conventional dc traction motors to systems using the less expensive, lower maintenance squirrel-cage ac induction motor include:

- Lower operating costs
- Reduced maintenance
- Improved reliability
- Energy savings

The 3-phase ac squirrel-cage induction motor, unlike conventional dc traction motors, has no brushes or commutator to wear out--there are no insulated windings on the cast-aluminum rotor. Its simple, brushless construction makes it easier and less costly to manufacture, and it is nearly maintenance-free. With no insulated wire on the rotor, rotor temperature is not a major concern, and the motor can be completely sealed to prevent dirt and water from getting inside. The motor can be cooled effectively by a built-in fan to provide airflow over the external finned surface. With no brushes or commutator to wear, periodic maintenance is limited to relubricating the bearings once every 3 or 4 years and occasionally washing off the outside of the motor with a hose.

The open-frame construction of the typical dc traction motor and its exposed, electrically "hot" brushes/commutator surfaces are eliminated, along with the brushes/commutator "flashover" and maintenance problems.

Electric Rail Transit Background

In the past two decades, developments in power conditioning and controls devices and circuitry have made the ac induction motor propulsion system a practical alternative to dc systems for rail transit application. Fast-acting switching and control circuits using solid-state electronics now can make ac propulsion systems feasible and competitive with dc systems.

One reason dc motors were used instead of ac motors in the earliest rail transit electric propulsion system applications is that it was easier to provide variable speed from dc motors. Although the superior attributes of ac motors were recognized at that time, the difficulties encountered in developing ac power control circuitry that would operate satisfactorily on-board moving rail vehicles made the use of ac motors impractical.

The induction motor torque/speed characteristic is only suitable for transit applications when a variable-frequency, variable-voltage supply is available, and until the advent of high-speed, high-power solid-state switching devices, suitable power supplies could not be developed. The mechanical contactors, relays, etc. used in dc systems were not suitable because they would not provide the extremely rapid, precisely timed switching action needed for variable-frequency ac control, nor were rotating motor-alternators suitable for providing variable-frequency ac power.

The advent of the thyristor, a solid-state device capable of rapidly switching large electrical currents, made it possible to develop dc-to-ac inverter power supplies suitable for induction traction motors.

One of the first applications of thyristors was in dc propulsion systems for so-called dc "chopper" regenerative braking systems. In regenerative braking, the traction motors function as generators driven by the wheels, and the generated electrical energy is returned to the third-rail power network. The motors, acting as generators, place a load on the driving wheels and thus act as electrical brakes. The chopper circuit allows the generated voltage to be increased to a level above that of the line, so power can be returned to the line during periods of line receptivity. When the line is not receptive, another thyristor circuit, a braking chopper, controls power dissipated in braking resistors during dynamic braking. The result is reduced operating costs by reducing overall energy consumption.

Although dc-chopper regenerative braking has made a significant impact in reducing energy consumption, the dc propulsion systems used predominantly in U.S. electric rail transit vehicles appear to have reached a level of development beyond which continued improvements are limited by the dc motor's inherent high maintainability requirements. The necessity for frequent inspection, servicing, and replacement of the brushes and commutator is the primary limitation of the conventional dc traction motor design. The commutator, and the brushes that must make electrical contact with the rotating current-carrying segments in the commutator, are both subject to wear and erosion by friction and electrical arcing.

1. Direct-Current Traction Motors

When electric propulsion systems for rail transit were first developed over 100 years ago, the dc motor was the obvious choice because of the ease of speed control using the methods available at the time, mechanical contactors.

Its wound rotor/separately wound stator (field) construction and operating characteristics permitted relatively simple step-wise speed control by using a system of manual or electropneumatic cam-operated mechanical switches (contactors) and resistor banks, which was within the capabilities of the existing control technology. In addition, dc motors were compatible with dc primary power transmission systems, which avoid the difficult commutation problems encountered when ac power is used.

The dc motor speed is adjusted by inserting various resistances in the power circuit and by reconnecting units in different series, series-parallel, and parallel configurations. This can be accomplished with mechanical switching devices or contactors. With its wound-rotor construction, however, a dc motor requires brushes and a commutator to carry the high armature current. Despite improvements in materials and design over the years, the mechanical wear and electrical arcing associated with the brushes and commutator necessitate frequent maintenance.

2. Alternating-Current Traction Motors

In the squirrel-cage ac induction motor, speed is controlled by varying the frequency of the ac supply--not feasible using mechanical contactors, but now readily accomplished using fast-acting solid-state electronic switching circuits.

In the squirrel-cage induction motor, the rotor rotates under the influence of the rotating magnetic field generated by the alternating currents in the stationary stator winding--thus no brushes or commutator are required. Maintenance is limited primarily to infrequent bearing relubrication.

3. Power Conversion Equipment

To make a change from dc to ac propulsion possible within the existing transit networks, the dc primary power must be converted into suitably conditioned ac for the ac traction motors.

It was not until fast-acting, high-power solid-state switches (thyristors) became available that it became practical to convert the primary dc power into the variable-frequency ac needed for ac propulsion systems. By using thyristor-based inverters to convert dc into quasi-sinusoidal ac power, ac traction motors could be used in the existing dc transit systems.

Such systems have been operating in revenue service since the early 1970's, especially in Europe. The fast action of the high-power solid-state "switches" and powerful computational capabilities of digital microprocessor units now make it feasible to properly control the ac power frequency and voltage to effectively regulate the speed and torque of ac traction motors.

4. NYCTA dc Cars

The inverter-controlled prototype ac induction motor propulsion system was designed to be installed in place of the dc equipment on two NYCTA R-44 subway cars for demonstration purposes.

The NYCTA cars are self-propelled electric rail transit cars powered by four dc traction motors installed in two 2-axle trucks. The R-44 dc propulsion system is shown in the block diagram of Figure 3. Each motor drives a separate axle through a flexible coupling and a speed-reducing gearbox with a gear ratio of 5.087:1. The cars have contact shoes to collect power from the NYCTA third-rail current source, which supplies nominal 600 vdc. The cars are designed to operate as a married pair or in trains with other cars, all controlled from one car.

The NYCTA cars are controlled by the motorman's five-position master controller, which includes:

(a) Minimum power

(b) Series

(c) Parallel

(d) Coast

(e) Braking

(f) Express (when installed)--corresponds to "Stromberg Mode" (80 mph) on the ac system

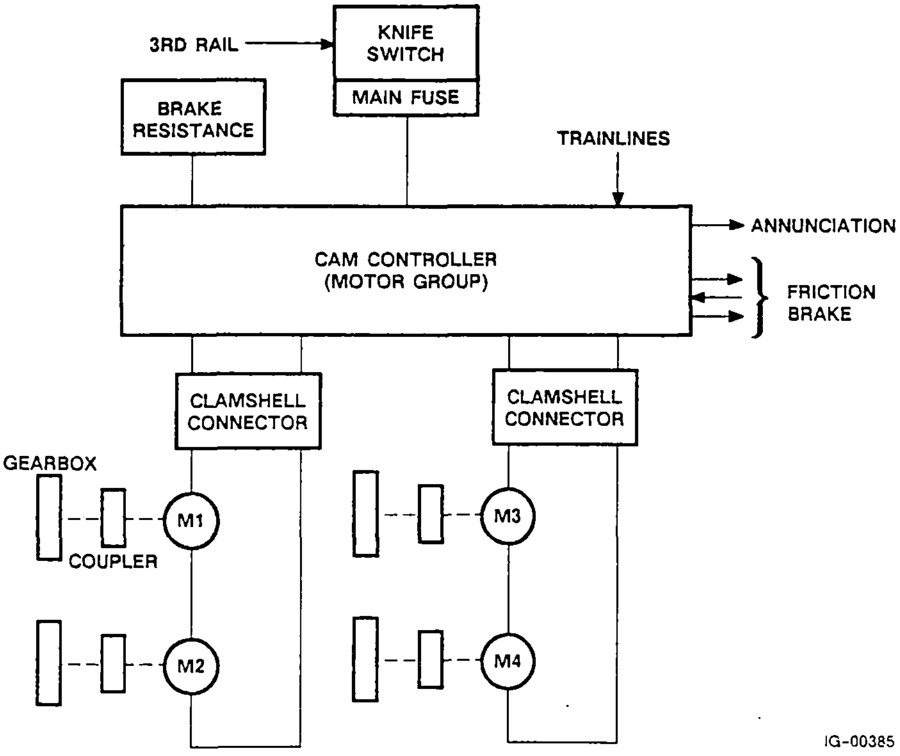


FIGURE 3. R-44 DC PROPULSION SYSTEM BLOCK DIAGRAM

In the minimum power position, the traction motors are connected in full series with maximum field resistance; in the series/parallel positions, the resistance is progressively removed in nine steps and the motors reconnected. In coast, power to the motors is removed, and dynamic braking is enabled. In dynamic braking from high speed, the motors function as dc generators supplying current to resistor banks that dissipate the dynamic braking energy. At low speed, the electropneumatically actuated friction brakes take over. Pneumatic braking is used in emergency braking.

The dc cars are designed to provide an acceleration rate of up to 2.5 miles per hour per second (mphps) and selected rates of deceleration between 1.5 and 3.0 mphps for empty and fully loaded cars.

PROTOTYPE AC PROPULSION SYSTEM PROGRAM

As one of the DOT/UMTA STARS programs, the inverter-controlled ac induction motor propulsion system program was intended to demonstrate the potential benefits of ac propulsion to the rail industry.

The program goals, system specifications, and major accomplishments are summarized in following paragraphs. Also presented is a brief program history, together with a discussion of some of the key technical issues that were addressed.

Program Goals

The primary goal of this program was to demonstrate and verify the projected performance improvements and operating and maintenance cost reductions obtainable with the inverter-controlled ac induction motor propulsion system.

By demonstrating such benefits, it was expected that this program would help pave the way for greater application of ac propulsion systems in the U.S. rail industry and provide needed improvements in electric rail transit. The transfer of technology developed in European ac propulsion systems contributed greatly to this goal, in line with DOT/UMTA STARS program strategy.

System Requirements

The ac propulsion system program statement of work and specification called for two car-sets of ac propulsion equipment installed in two upgraded NYCTA R-44 cars in place of the dc propulsion equipment.

The ac equipment was required to operate from the existing NYCTA 600-vdc third-rail power, using the existing R-44 current collection equipment, main switch, and fuses. Each car set of ac equipment was to consist of:

- Four squirrel-cage induction motors to be installed on the existing R-44 trucks using existing motor mounting provisions and gearboxes
- One or two static inverters to convert the dc power into quasi-sinusoidal ac power suitable for the ac motors
- An electrical regenerative braking system to conserve energy by using the ac traction motors as generators during braking and returning energy to the line
- A propulsion system control unit that will interface with the ac propulsion system equipment and existing train controls and signals, handling common tractive effort between trucks, blending of electrical and friction brakes, gap and dead rail detection, and safety features
- Associated mechanical and electrical equipment including all equipment required to interface with the vehicle

Major Accomplishments

The accomplishments in this program are especially noteworthy in light of the constraints imposed on an acceptable ac replacement for conventional dc propulsion systems.

The establishment of dc propulsion as the U.S. rail transit industry standard places additional restrictions on competitive ac systems. For successful introduction into and widespread acceptance by the rail industry, the ac system must be compatible with the existing transit authority dc primary power and associated control, signalling, trainline systems, etc. that have been set up for dc propulsion.

Significant accomplishments during program Phase I included the following:

- System analysis results:
  - Railroad line profile established for 37 stations, 17.64 mi, 63-min run
  - Electromagnetic interference (EMI), signalling capability preliminary report prepared
  - Energy study prepared
  - R-44 interface/Stromberg design
- Laboratory system test--3-month comprehensive program (equivalent to 15,000 miles) completed without failure
- R-44 equipment layout and weight-balance study
- Completed reports:
  - Life-cycle cost summary
  - Maintainability
  - Reliability/safety study
  - Energy analysis
- Test program plan

Major accomplishments of Phase II of this program included:

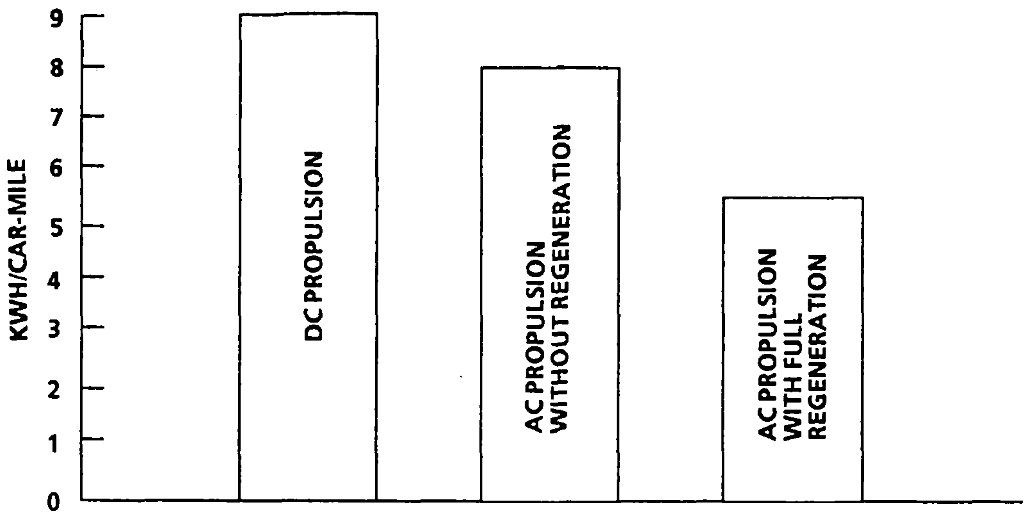
- Demonstrated acceleration, braking, and maximum speed performance equal to or better than that of the R-44 dc system
- Demonstrated the capacity for system braking regeneration within line receptivity levels
- Demonstrated EMI levels and compatibility with trainlines and the NYCTA signalling circuits and subsystem equipment
- Established basis for greatly improved reliability projections, reduced maintenance requirements
- Projected significant improvement in life-cycle cost
- Generated an ac propulsion procurement specification in cooperation with the NYCTA

1. Performance

The ac propulsion system demonstrated acceleration performance and maximum speed exceeding that of the dc system. Maximum deceleration during braking was equal to that of the dc system.

The ac system's fully regenerative braking capability was demonstrated, as was brake blending (regenerative plus dynamic braking), under conditions of full, partial, and zero line receptivity.

Figure 4 presents an energy consumption comparison showing that the ac propulsion system with full regenerative braking would be expected to use 37 percent less energy than the dc propulsion system under equivalent operating conditions. Even without regenerative braking, the ac system is more efficient, using 10 percent less energy than the dc system.



AC PROPULSION WITH FULL REGENERATIVE BRAKING
YIELDS 37 PERCENT ENERGY SAVINGS OVER DC PROPULSION

a. ENERGY CONSUMPTION SUMMARY

(100 - CAR FLEET IN OPERATION, 30 YEARS, PRESENT WORTH)

COST ITEM	DC PROPULSION ($1,000)	AC PROPULSION ($1,000)
PROPULSION SYSTEM PRICE	225	225
ENERGY COSTS (FULL REGENERATION)	263	166
MAINTENANCE COSTS	88	17
COST OF REQUIRED SPARE CARS	146	46
NEW TECHNOLOGY INTRODUCTION	--	2
PRESENT WORTH PER CAR (1987)	$722	$456

b. LIFE-CYCLE COST SUMMARY

EG-03059*

8-14579

FIGURE 4. ENERGY AND LIFE-CYCLE COST COMPARISONS

2. Life-Cycle Cost

Estimated life-cycle cost for the ac propulsion system is significantly less than that of the dc system.

The life-cycle cost summary of Figure 4, based on present-worth-1987 calculations, shows an overall savings of up to 37 percent for cars equipped with ac propulsion and regenerative braking; operating under conditions of full line receptivity. Of this savings, 37 percent is related to energy costs, 36 percent to spares, and 27 percent to maintenance. The first costs of the dc and ac systems were considered equal, although a penalty was assessed the ac system to account for the introduction of new technology with probable initial adjustments required. The cost comparison is for a property-specific application, assuming 100-car fleets in operation over 30 years in NYCTA service.

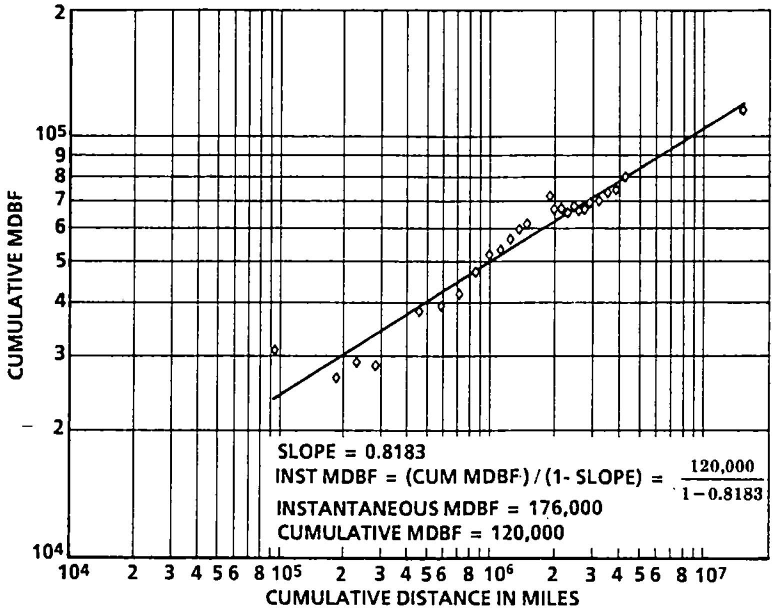
3. Reliability

The ac propulsion system is projected to be far more reliable than the dc system.

The STARS ac propulsion system is based primarily on equipment produced for the Helsinki Metro system, which started track testing in 1977 and entered revenue service in 1982. Helsinki Metro kept careful reliability records on this ac propulsion system equipment, which demonstrated excellent reliability growth curves.

As shown by Figure 5, the control unit demonstrated an instantaneous mean distance between failures (MDBF) of 176,000 mi and a cumulative MDBF of 120,000 mi after 16.5 million car miles of operation, and the equivalent distances for the inverter are 612,000 and 410,000 mi. The ac traction motor had only 3 failures in 66 million motor miles, for a motor MDBF of 22 million miles. The following table shows a calculated Helsinki Metro system MDBF (per car) of 91,000 mi. The R-44 dc system records, in contrast, indicate a MDBF of only about 18,300 mi.

HELSINKI METRO CONTROL UNIT RELIABILITY GROWTH 5/82 THROUGH 6/86



SLOPE = 0.8183

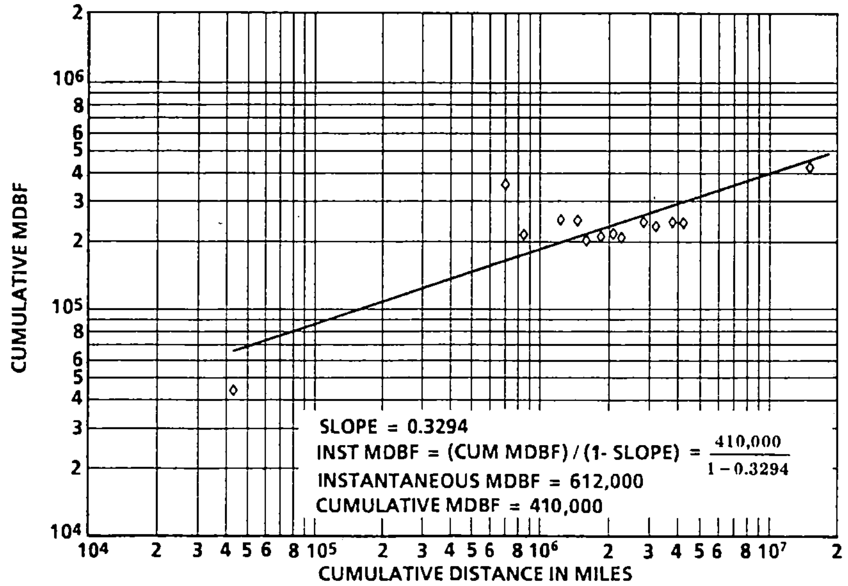
INST MDBF = (CUM MDBF) / (1- SLOPE) = $\frac{120,000}{1-0.8183}$

INSTANTANEOUS MDBF = 176,000

CUMULATIVE MDBF = 120,000

X-12044

HELSINKI METRO INVERTER UNIT RELIABILITY GROWTH 5/82 THROUGH 6/86



SLOPE = 0.3294

INST MDBF = (CUM MDBF) / (1- SLOPE) = $\frac{410,000}{1-0.3294}$

INSTANTANEOUS MDBF = 612,000

CUMULATIVE MDBF = 410,000

X-11984

FIGURE 5. RELIABILITY GROWTH CURVES

Component	MDBF, mi
Controller	120,000
Inverter	410,000
Motors (4)	5,500,000
Total system	91,000

The STARS ac propulsion system reliability is projected to equal that of Helsinki Metro, based on the similarity of equipment.

Program History

The inverter-controlled ac induction motor propulsion system program, initiated on March 31, 1982, was expanded to 76 months duration from the 46 months initially planned.

The ac propulsion system program (Figure 6) was originally proposed as a 46-month effort to culminate in simulated revenue service testing at the DOT Transportation Test Center (TTC) in Pueblo, Colorado. During the course of the program there were some program modifications that affected both the schedule and scope of work. Having particular significance to the results of this program was the decision to change the test site to the NYCTA system in New York and to use upgraded R-44 cars as the demonstration vehicles.

The ac propulsion system originally was to be installed in two standard R-44 cars and subjected to simulated revenue service tests at the TTC controlled test track in Pueblo. The initial system design efforts in Phase I of the program were in line with this objective, and the equipment built for development testing was tailored to such a test program.

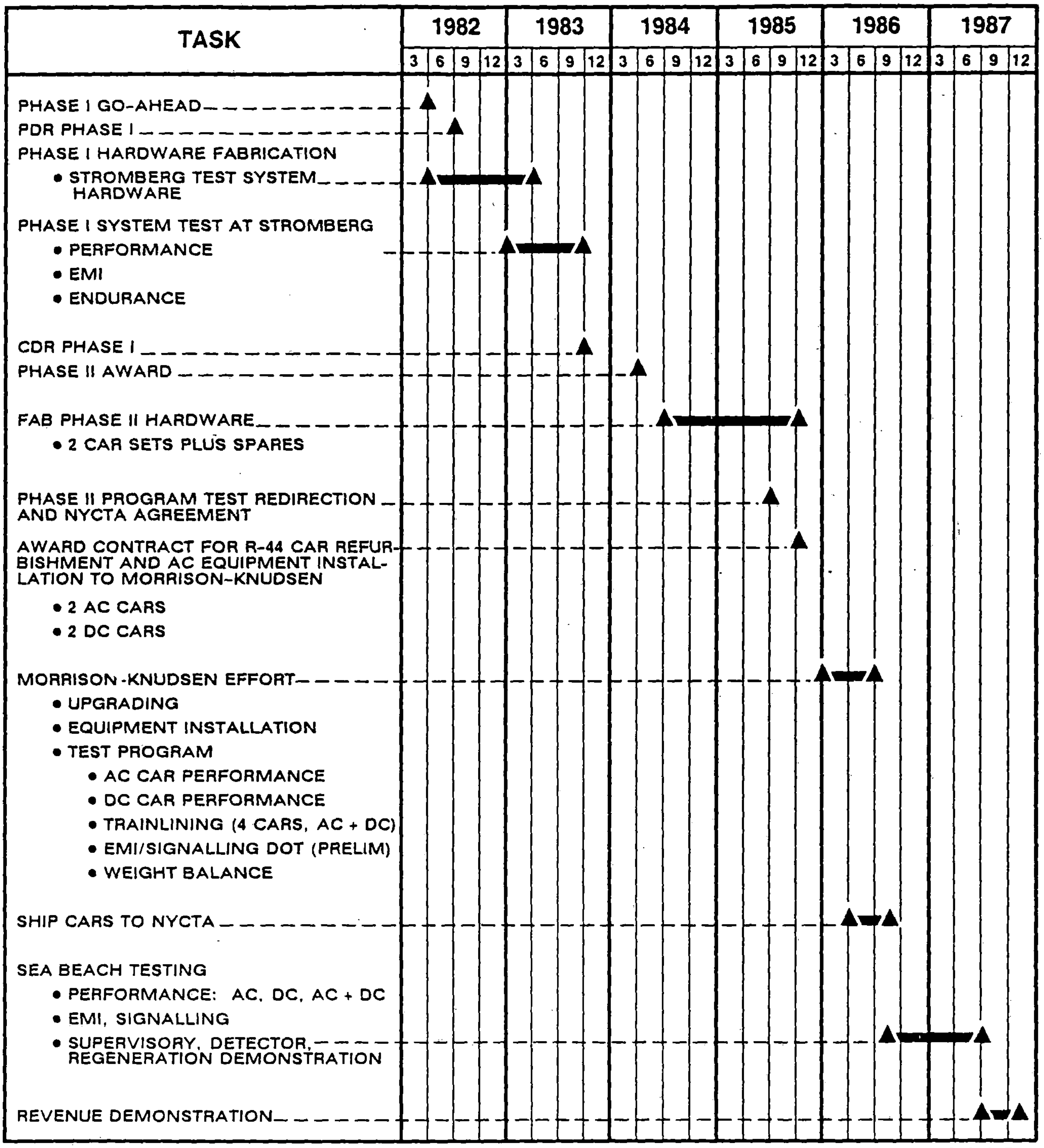


FIGURE 6. INVERTER-CONTROLLED AC INDUCTION MOTOR PROPULSION SYSTEM PROGRAM MILESTONES

Later, during the early part of Phase II, DOT/UMTA, AiResearch, and the NYCTA agreed to conduct Phase II testing on NYCTA property in New York using two upgraded R-44 cars and, in conjunction, two upgraded dc cars for comparison testing. The change of test site had two important impacts on the program: (1) it provided an opportunity for more realistic testing in actual transit service, and (2) it resulted in a significantly more stringent development test program.

Although the TTC tests were planned to simulate revenue service in a typical transit application, the actual testing would have been done in an environment allowing more careful control of test conditions and outside influences than was possible in New York.

The change in car configuration also had impact on the work, since the upgraded cars differed from the standard R-44's in several aspects, including the air brake system and master controller.

The R-44 car upgrading and ac equipment installation work was conducted by the Morrison-Knudsen Company of Hornell, New York, as a subcontractor to both AiResearch and the NYCTA.

Overall, the change in cars and test site had the effect of significantly increasing the scope of work--introducing unanticipated site-specific problems that were not directly related to the equipment performance but still had to be resolved--while, on the other hand, resulting in a more meaningful and convincing demonstration performed under actual revenue service conditions.

Test Activity Summary

Test activities for the ac propulsion system program included component tests performed before installation in the R-44 demonstration cars, initial system testing done at the Morrison-Knudsen facilities in Hornell, New York, and demonstration testing performed at the NYCTA Sea Beach facilities.

Individual components of the ac propulsion system were thoroughly tested at the manufacturer to verify acceptability prior to delivery to Hornell for installation in the two ac propulsion demonstration vehicles and service as spares.

1. Test Program at Morrison-Knudsen Facility

Initial system testing was performed at the system installation site of Morrison-Knudsen Company in Hornell, New York, where facilities were available to allow thorough "shakedown" testing to verify correct and safe car operation with the ac propulsion system installed.

Tests were performed on the ac cars, operating individually and as a married pair as well as during operation with dc cars, to fully establish proper car functioning. The following list summarizes the Morrison-Knudsen test program:

- Tests of ac cars
    - Acceleration (AW0 and AW3 loading simulated, 30 mph)
    - Deceleration (AW0 and AW3 simulated)
    - Electric brake fade (below 5 mph)
    - Jerk limit operation (drive-brake-drive)
    - Emergency brake operation
    - Regeneration simulation
    - Spin/slide demonstration
    - Safety, fault isolation system checkout
    - Preliminary signal circuit EMI tests and radiated EMI test program (ac and dc)
- Tests of ac cars coupled to dc cars
    - Trainline compatibility
    - GE controller operation vs STARS R-44 specifications
    - Performance runs

2. Test Program at NYCTA Sea Beach Facility

After demonstrating satisfactory operation at the Hornell site, the demonstration cars were transferred to the NYCTA Sea Beach facility for the remainder of the test program on an operating railroad line.

The NYCTA Sea Beach activities included:

- A comprehensive performance test program
- An EMI-signalling test program
- A substation supervisory circuit interference test program
- A power consumption test program (for "A" line service)
- A ripple detector demonstration program (for "A" line service)

The performance testing was structured to provide complete characterization of the ac cars performance in "AB" married car pairs (designated AB(ac)), and in four-car trains consisting of two ac and two dc cars (designated ABBA). Tests of the two dc cars (designated AB(dc)) also were performed to permit accurate ac and dc car performance comparisions. As shown by the performance test plan flow chart in Figure 7, the tests were performed at two different car weights, AW0 (empty) and AW3 (fully loaded).

3. System Improvements Resulting from Test Program

The lengthy and comprehensive test program was successful in demonstrating its goal of ac propulsion integration into an operating transit system with no impact on existing "in-place" equipment or facilities. The benefits of regeneration and the reduction in car maintenance requirements were evident. The tests revealed areas of improvement for future designs.

As in any complex test program, some difficulties occurred; however, they did not alter the test program conclusions and only served to provide technical additions to future procurement specifications. Two noteworthy incidents that resulted in lengthy investigations were:

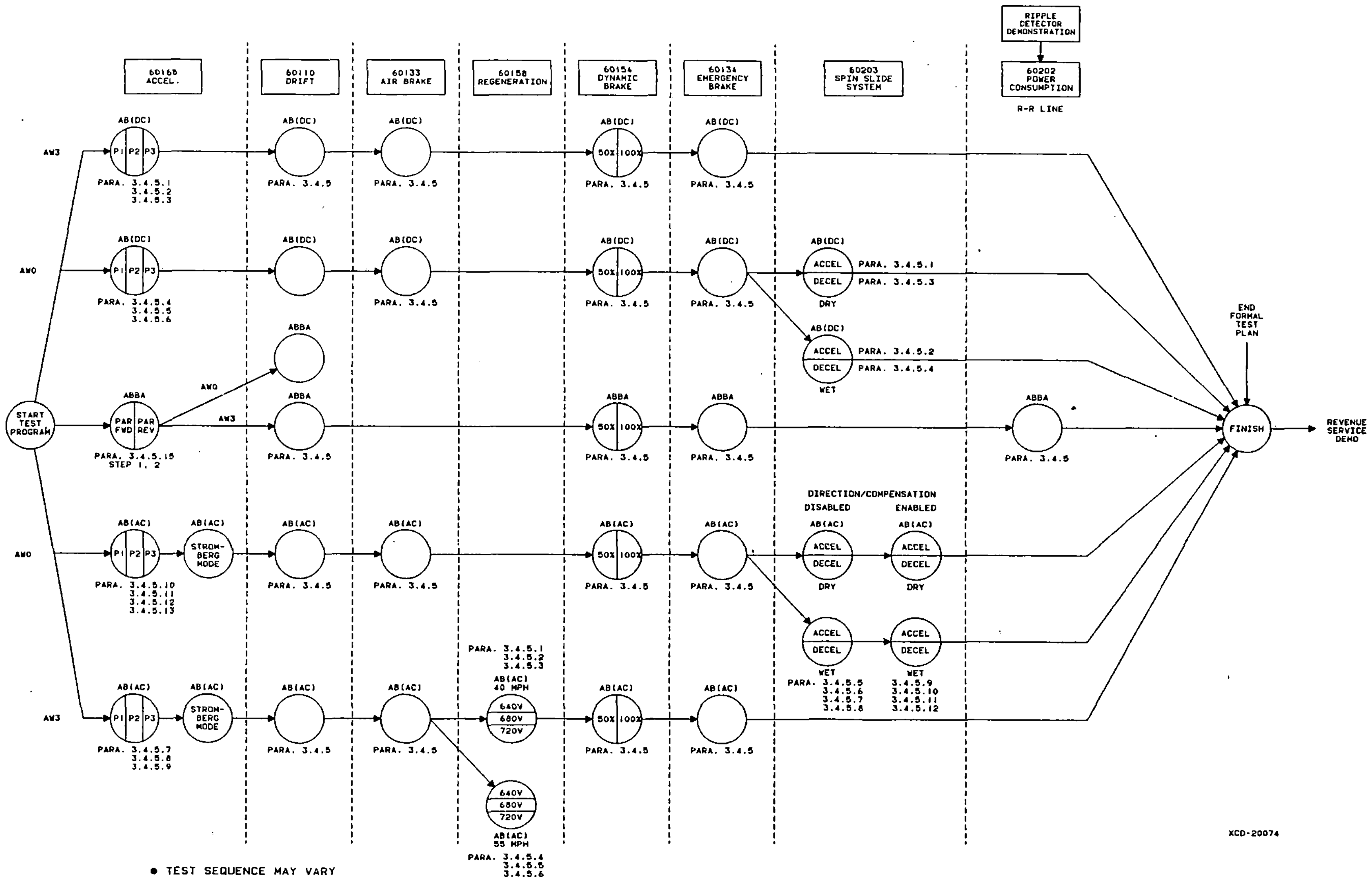
(a) Transfer of Braking Energy from Regenerative or Rheostatic to Friction, and Subsequent Wheel Lockup and Slide--During a demonstration run, the ac cars were placed in "full service brake" for regeneration testing. In the ac control unit, an optical isolator is used to limit braking rate and prevent wheel slide. In this test run, the wheels were locked and the isolator, sensing no relative axle motion, switched from regenerative brake to friction. Since the R-44 car onboard friction brake system was not equipped with a spin-slide circuit, the slide continued. Subsequent lengthy testing of both ac and dc cars showed that slides could be induced on a regular basis when friction brakes were suddenly applied. Considering the track conditions, wheel lockup was substantiated. In future systems, the ac propulsion would be designed for a longer "window" on electrical braking to allow for momentary wheel and axle-to-axle lockup before switching to the friction brake system from regenerative braking. It also is recommended that all friction brake systems be equipped with spin-slide controls. It is noteworthy that the ac car system appropriately functioned as designed to switch from regenerative to friction-only braking as a safety measure in response to any slide indication. It was also conclusively shown that there could be no overlap of electric and friction brakes.

(b) Several Power Device Failures of the Onboard ac Inverters During Regeneration and Power Consumption Testing in Conjunction with the Ripple Detector Tests--These device failures were traced to inadequate component grounding and shielding procedures. The R-44 utilizes the car itself as ground. This would be taken into consideration on future designs.

Technical Issues

The key to the use of an ac induction motor in rail transit applications is the availability of a controlled, variable-frequency, variable-voltage ac power supply, made possible through the application of solid-state electronics.

STARS PERFORMANCE TEST PROGRAM NYCTA TEST FACILITY



- TEST SEQUENCE MAY VARY
- EMI-SIGNALLING TESTS TO BE ON SEPARATE SCHEDULE

FIGURE 7. NYCTA SEA BEACH FACILITY PERFORMANCE TEST PLAN

1. Speed/Torque Control

The ability to electronically control the ac traction motor speed, torque, and direction of rotation is an important factor in achieving improved reliability and performance over cam-controlled dc propulsion systems.

The ac system eliminates the numerous maintenance-intensive electrical contactors and power-robbing series resistances required by the typical dc system.

By controlling ac frequency and voltage, motor speed and torque can be varied. The direction of rotation of a 3-phase induction motor such as used in traction motor applications can be easily reversed by interchanging two of the three stator connections. With thyristor circuitry this can be done electronically; no mechanical reverser contactor is necessary. Of importance in regenerative and dynamic braking systems, the induction motor operates as an induction generator when driven at a rotor speed above synchronous speed. Thus, simply reducing the frequency of the ac supply to reduce synchronous speed below rotor speed will initiate electrical braking action.

2. Wheel Diameter Variations

When two induction motors driving different axles are electrically connected in parallel and powered from a common inverter, some limits are placed on the allowable wheel diameter difference between axles.

If the inverter powers two parallel motors, which drive two axles having wheels of differing diameters, then the two motor speeds will be different. The motor driving the axle with the larger diameter (slower) wheels develops the larger torque; the average or effective torque is midway between the two axle torques. The slower motor, producing the greater torque, will demand more current from the inverter than the machine turning faster. In the brake mode, however, the axle with the smaller diameter wheels develops the higher braking torque. Hence, there is a compensating effect which tends to even out motor loading due to wheel diameter differences. The NYCTA requirement for the STARS program was to allow a 3/4-in. difference in diameter within a truck and anything up to new/fully worn variation on a car. Hence, separate inverters were selected for each truck with a medium slip motor characteristic to allow the 3/4-in. variation.

3. Electromagnetic Interference (EMI) and Signalling

Extensive analysis and test efforts showed that the ac propulsion system-generated EMI did not result in an increase in radiated emissions or track circuit relay activity over that from dc cars. Thus, no related adverse impact on transit property signalling would be anticipated upon conversion from dc to ac operation.

Extensive Phase I studies were conducted as part of a cooperative program between AiResearch/Stromberg and the DOT Transportation System Center (TSC). Additional studies were provided by the EMI technical working group (TWG), a DOT/UMTA-sponsored committee composed of senior engineers from propulsion system suppliers, representatives from the Government and universities, and consultants. The total effort consisted of:

- Characterization and cataloging of signalling equipment susceptibility (performed by TSC/TWG)
- Characterization of steel rail electrical parameters as a function of dc current (TSC/TWG)
- Derivation of train-to-signalling transfer functions (AiResearch/TSC/TWG)
- Prediction of drive emissions (AiResearch/Stromberg)
- Measurement of drive emissions as part of the Phase I laboratory system test of one prototype truck drive (AiResearch/Stromberg)
- Design for compatibility (AiResearch/Stromberg)

The study was to be further defined in Phase II and emission limits established for continued testing at the DOT Pueblo facility. When the Phase II test program shifted from Pueblo to the NYCTA test track, it was deemed necessary to establish track signalling circuit compatibility through actual testing on the NYCTA Sea Beach Line. A total of 18 track circuits (single- and double-rail, 25- and 60-Hz) were provided by NYCTA as representative of their signalling system, and tests were performed as shown by the following list.

GRS balancing reactor single rail--60 Hz	Circuit 1
US&S capacitor-type single rail--60 Hz	Circuit 12
GRS balancing reactor single rail--60 Hz	Circuit 2
GRS capacitor-type single rail--60 Hz	Circuit 4
GRS capacitor-type single rail--25 Hz	Circuit 6
US&S shielding reactor single rail--60 Hz	Circuit 10A
US&S single rail (no shielding reactor)--60 Hz	Circuit 10
GRS matching transformer single rail--60 Hz	Circuit 3
US&S balancing reactor single rail--60 Hz	Circuit 11A
US&S single rail (no balancing reactor)--60 Hz	Circuit 11
US&S matching transformer single rail (PV250 relay)--60 Hz	Circuit 14
US&S shielding reactor single rail--25 Hz	Circuit 17
US&S matching transformer single rail (PTV-42 relay)--60 Hz	Circuit 13
US&S shielding reactor single rail--25 Hz	Circuit 18
GRS balancing reactor single rail--25 Hz	Circuit 5
GRS rotary-type relay double rail--25 Hz	Circuit 7
GRS vane relay double rail--60 Hz	Circuit 8
US&S matching transformer double rail--60 Hz	Circuit 15

Two open-circuit configurations also were tested.

Numerous test runs were made for each track circuit. The test program included:

- Circuits tested with negative return isolated through the substation (an isolated return is considered worst case because all propulsion return current is returned through the track circuit)

- Circuits tested with nonisolated return

The signalling circuit test track is shown in Figure 8. In all, about 500 test runs of the ac cars were made with both visual monitoring and recordings made of circuit activity. The cars were maintained at AW3 load conditions (fully loaded) for the test, with all ac equipment operating. The results of this comprehensive program showed that the spectral signatures of the ac cars were in line with those of existing dc cars and resulted in no additional EMI-induced track circuit relay activity.

Conductive emissions tests then were performed on the AB(ac) cars and on the ABBA consist (with the ac cars driving) on the NYCTA Sea Beach Track E3. To simulate worst-case, the cars were fully loaded and operated with all auxiliaries turned on, headed in a direction toward the substation. Numerous test runs were made under varying modes of operation (acceleration, deceleration, regeneration, and nonregeneration), and no emissions with an amplitude sufficient to affect either power substation equipment or operation were observed.

AC PROPULSION SYSTEM DESCRIPTION

The prototype ac propulsion system utilizes squirrel-cage ac induction motors to drive each axle, supplied by variable-frequency, pulse-width-modulated, voltage-fed, solid-state inverters controlled by a propulsion system control unit using a combination of analog and digital microprocessor-based circuits. The system is capable of full regenerative braking subject to line receptivity.

In line with the decision to use mature, reliable components, the prototype system is a modification of the ac propulsion system used on the Helsinki Metro system, which began service in 1977. The system is designed for compatibility with automatic train control systems and telecommunications systems employed in the U.S. with regard to EMI, harmonics, and supply transients.

The ac propulsion system basically comprises two truck drives, each having two squirrel-cage induction motors to drive the two separate axles on

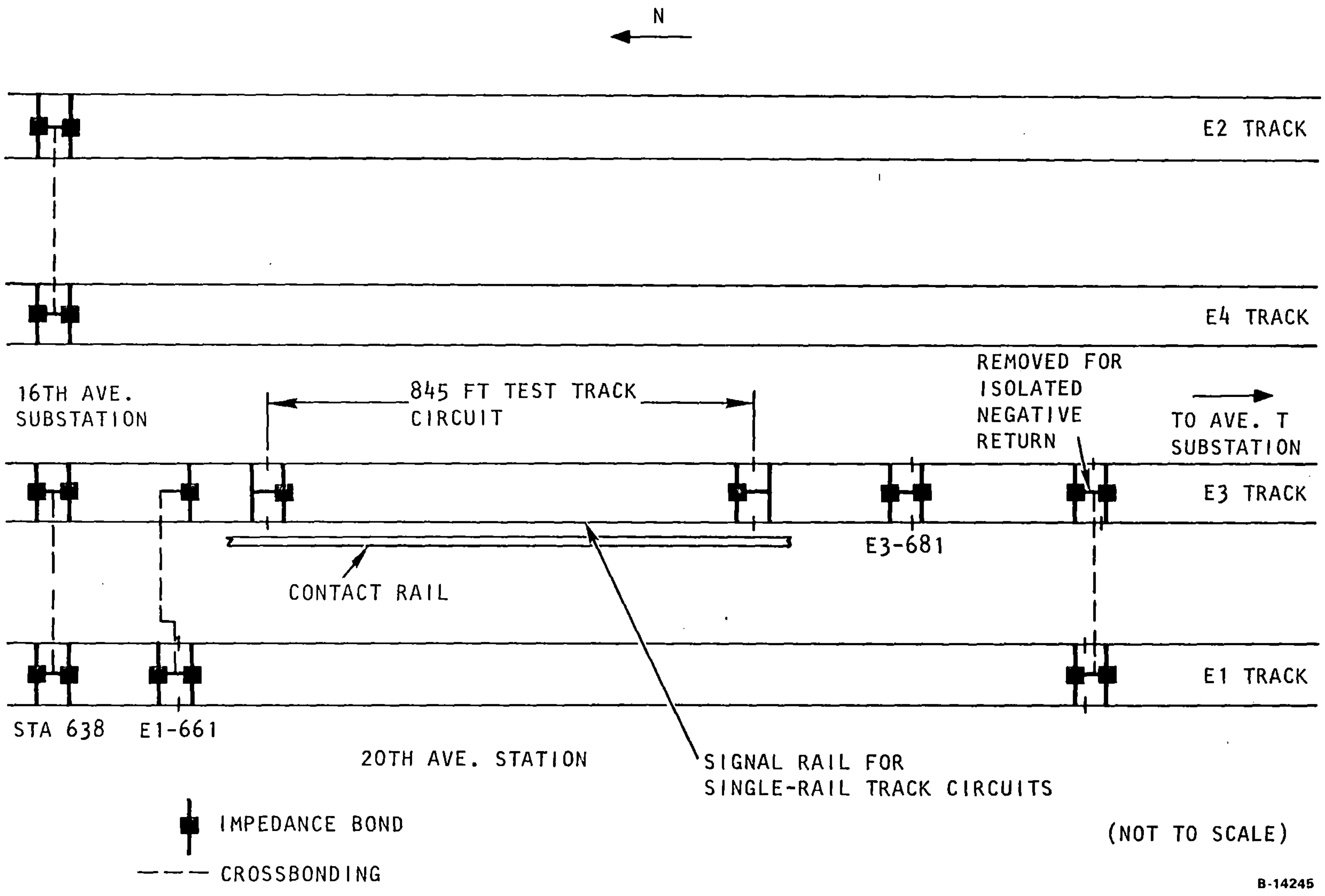


FIGURE 8. SIGNALLING TEST TRACK CIRCUITS AT SEA BEACH

each truck. Each pair of motors is driven by a single, solid-state, voltage-fed, pulse-width-modulated static inverter. Both truck drives (four motors and two inverters) are controlled by a single control unit. Other major components are the line control equipment (one per system), line filters (two per system), brake resistors (two per system), and inverter/resistor cooling blower units (two per system).

Design Features

Designed as a retrofit installation on existing upgraded NYCTA R-44 dc subway cars, the prototype ac propulsion system uses the existing dc motor mountings, gearboxes, and couplings and operates from the existing dc third-rail power, responding to all interfacing control signals in the same manner as would a conventional cam-controlled dc car.

The system is designed to provide the capability of operating the ac propulsion-equipped cars in-train with existing R-44 dc cars. Trainlining and other vehicle interfaces remain unaltered. The original master controller, pneumatic braking (p-signal) generator, main fuse and knife switch, and the "clam-shell" connectors are retained.

This approach affords a practical and realistic demonstration, representing one that could readily be phased into service to replace older dc systems. Some of the features of the ac propulsion system are listed below.

- Variable-voltage, variable-frequency ac traction motor drive
- Voltage-fed, pulse-width-modulated, forced-commutated thyristor static inverter
- Full regenerative braking capability over the entire speed range
- Induction traction motors designed to accommodate 3/4-in. wheel diameter differences when supplied from a single inverter
- Adaptive spin/slide control circuits
- Microprocessor-based inverter controls

- Control unit annunciators to aid diagnostics
- Tractive effort feedback controls with automatic current limits
- Undercar layout compatible with existing dc equipment arrangement
- Utilization of existing dc motor mounting points, flexible couplings, and gearboxes
- Proven electromagnetic compatibility in existing transit vehicles and with existing track circuitry
- Open-frame construction for inverter, filter, and control units housed in enclosures designed to facilitate equipment installation and removal
- Complete self-protection by built-in and external circuits
- Dead-rail protection and incorporation of a ripple detector to satisfy NYCTA specific requirements

The two drives share only those portions of the controls that are, of necessity, car-oriented. Provisions are made for both automatic and manual isolation of a malfunctioning truck drive.

The equipment furnished and its specifications (Table 1) were dictated by the intent to retrofit two NYCTA R-44 cars with service-proven ac traction motor propulsion while retaining the capability of operating these cars in-train with existing cam-controlled R-44's.

For each drive a single inverter unit powers two squirrel-cage induction motors in parallel. Each inverter is cooled by a dedicated blower, the exhaust air being used to cool the brake resistor. The traction motors are of totally enclosed, self-cooled construction.

TABLE 1

AC PROPULSION SYSTEM SPECIFICATIONS

Specified Service Conditions		
Line voltage	Nominal Range	600 vdc 425 to 720 vdc
Regeneration voltage limit		600 to 720 vdc, setable
Low voltage supply	Nominal Range	37.5 vdc 28 to 44 vdc
Wheel diameter range		31 to 34 in.
Wheel diameter difference		0.75 in. max. (between axles on same truck)
Ambient temperature		-20° to +110°F (-29° to +43°C)
Performance Requirements		
Initial acceleration		2.5 mphps
Time to 70 mph		90 sec
Service brake rate (linear brake taper)		3.0 mphps below 50 mph to 2.3 mphps at 80 mph
Jerk limit		Setable: 1.0 to 2.5 mphpsps
Maximum speed		80 mph
Maximum normal speed		70 mph (31 to 34 in. wheels)
Control		Match existing R-44 cars
Duty cycle		NYCTA RR line (AW3)

Notes: Unless otherwise indicated, performance is for 32-3/8 in. wheels and unloaded (AW0) to fully loaded (AW3) weight.

AW3 is defined as:

87,025 lb	AW0 of car with dc propulsion
-10,491	Dc propulsion equipment (removed)
76,534	
+11,590	Ac propulsion equipment (added)
88,124	
+43,000	Maximum passenger capacity
131,124 lb	AW3 of car with ac propulsion

Installation

The ac propulsion equipment was installed in the R-44 cars in place of the dc equipment that was removed.

The ac propulsion system installation in the R-44 car involves:

- Control equipment
- Undercar equipment
- Truck equipment

The control equipment was installed in place of the removed dc automatic train operation (ATO) equipment on the "A" car and includes the propulsion control unit, load weigh unit, and miscellaneous equipment such as the low-voltage supply circuit breaker and blower circuit breakers (plus the associated equipment retained from the R-44 dc installation). On the "B" car, which has no cab, the control equipment was installed on the engineer's panel.

The undercar equipment (Figure 9) includes the line control equipment (LCE), line filters, inverters, cooling blowers and plenums, air filters, and brake resistors. The ac equipment is arranged to fit into the undercar space available after removing the dc equipment, which included the lighting inverter, control group, and associated resistors. The original knife switch, converter, brake operating unit, air supply reservoir, and battery box were retained, but relocated in the undercar area.

The undercar equipment is located essentially in two symmetrical groups about the car centerline, to maintain required balance. All of the equipment fits within the clearance lines, allowing good access and good airflow for all units.

The truck equipment consists of the ac induction traction motors and mounting hardware. The ac motors were designed to use the same mounts as the dc motors they replace, and the same couplings to the original gearboxes.

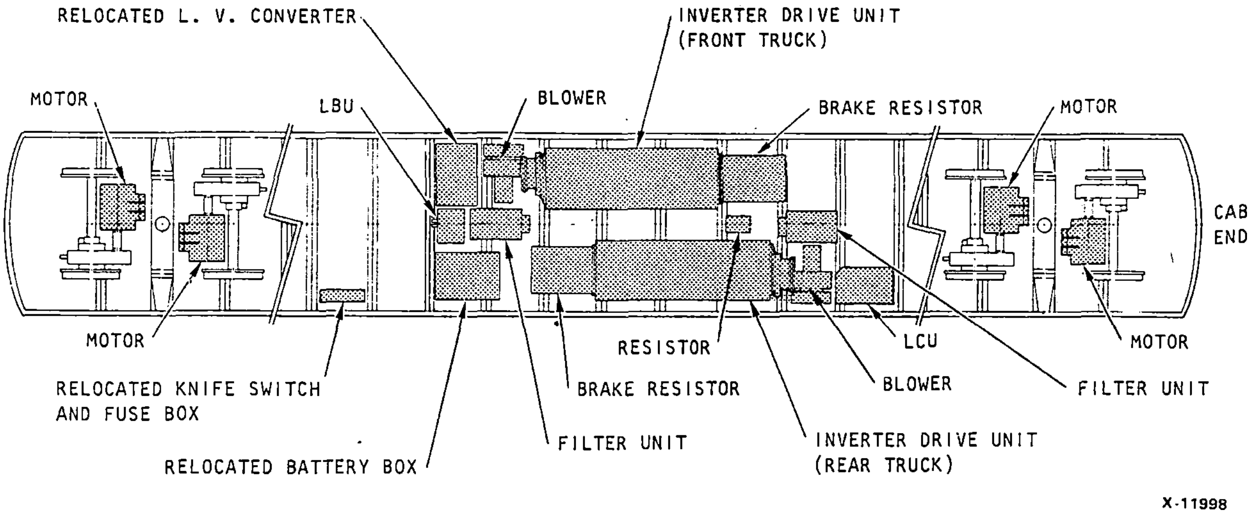


FIGURE 9. UNDERCAR EQUIPMENT ARRANGEMENT

Table 2 shows the weight breakdown for the ac propulsion system equipment. The comparative dc total weight is 10,441 lb.

Power Circuit

The power circuit for the ac propulsion system converts third-rail 600-vdc power into variable-frequency, variable-voltage ac suitable for the induction traction motors.

The main elements of the power circuit are:

- The knife switch and main fuse (existing R-44 equipment)
- The line control equipment
- Two identical truck drives, each consisting of:
  - One line filter
  - One inverter
  - Two ac traction motors

As shown by Figure 9, current drawn from the third rail flows via the knife switch and main fuse to the line control equipment (LCE). The LCE includes a fast-acting dc circuit breaker (MCB), a differential current relay (KDC), a contactor (KBL) for blower control, contactors (KIS) that switch power to the

TABLE 2

AC PROPULSION SYSTEM WEIGHT BREAKDOWN

Item	Qty	Weight, lb	
		Each	Total/Car
Traction motor	4	1331	5324
Line filter	2	750	1500
Line contactor	1	270	270
Inverter unit	2	1544	3088
Brake resistor	2	550	1100
Blower assembly	2	241	482
Blower ducting (plenum/filter)	2	80	160
Cab control unit	1	141	141
Surge limiting resistor	1	25	25
Line breaker unit	1	199	199
Total			12,289

two drives (also used to isolate a malfunctioning drive), and a contactor (KRS) that switches out the resistor (RSL) used to limit the in-rush current when the line filter capacitors are charging.

Each drive is isolated from the line by a line filter, which provides required inductive source impedance to the inverter input chopper and mitigates EMI. Each inverter consists of a dc-link (capacitor bank) and the following:

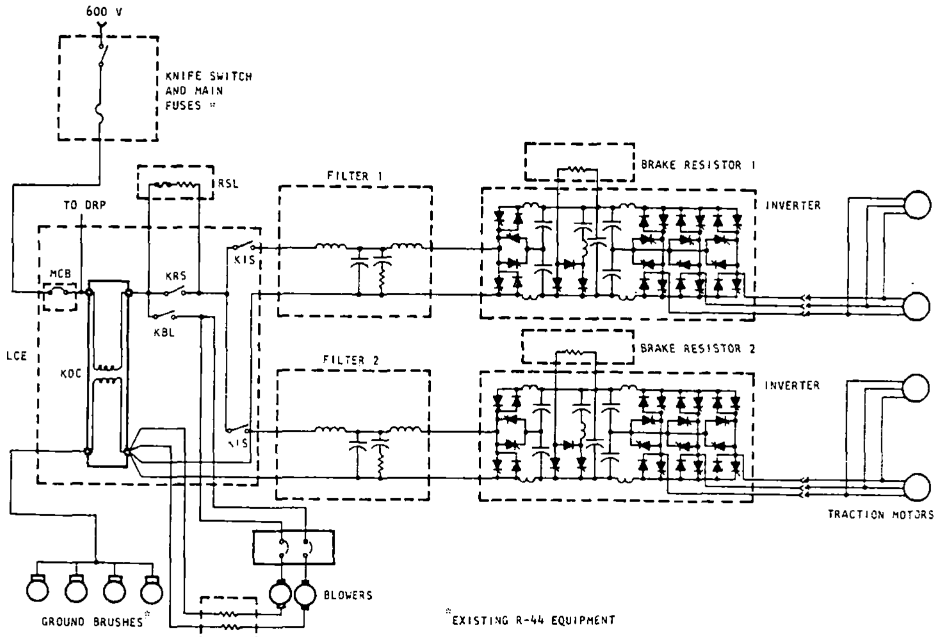
- A line chopper to provide the desired internal dc-link voltage regardless of line voltage fluctuations and to control the power returned to the line during regenerative braking.

- A three-phase inverter to convert the dc power to ac, and, in the regenerative braking mode when the motors function as induction generators, to rectify the generated ac for return to the third rail.
- A brake chopper to direct power that cannot be regenerated to the brake resistor instead. The resistor is sized to dissipate all of the dynamic braking energy under conditions of zero line receptivity.

Controls and Operating Modes

The ac propulsion system is designed to operate in a manner that closely matches the R-44 dc cars operation for compatibility with the existing NYCTA rail operations.

The propulsion control unit (located in the cab) interfaces with the trainlines and the line control equipment by means of optical couplers to provide high-voltage isolation. It receives the commands from the master controller (existing R-44 equipment) through the trainlines and provides the signals to the truck drives to obtain the desired propulsion system response.



*EXISTING R-44 EQUIPMENT

8-14246

FIGURE 10. AC PROPULSION SYSTEM POWER CIRCUIT

Normally, the controls are set to match the R-44 torque/speed performance characteristics and trainline command response. These performance characteristics are considerably less than the capability of the ac propulsion system. Consequently, an alternative full-performance mode is provided, which features continuous tractive control. The capability to respond to a spin-slide system also is provided.

In the braking mode, the ac propulsion system provides preferential blended electric brake control in the following order:

(a) Regenerative braking to the extent that the third rail is receptive

(b) Dynamic (resistive) braking when third-rail receptivity limits the amount of regeneration

(c) Smoothly blended friction braking at very low speeds (below 5 mph)

Regeneration can be switched off by a switch located in the cab, and provisions are made for both automatic and manual isolation of a malfunctioning truck drive. When one truck is cut out because of a malfunction, the other truck continues to provide its rated tractive effort in motoring; however, the system reverts to friction braking because friction brake control is not implemented on a per-truck basis in the R-44 car (thus no blending is possible).

Functionally, the control unit is divided into three sections, a car control section and two truck control sections. The car control section delivers load-weight-compensated motor torque requests to each of the two truck control sections as a function of trainline signals. The two truck control sections provide inverter frequency and voltage commands to the two truck drive inverters so that the sum of the two traction motor torques corresponds to the requested level.

Built-in Protection Measures

The ac propulsion system includes built-in measures to protect the system and its components against damage and malfunction and to prevent safety hazards.

The power and control circuitry includes protection against line voltage fluctuations that might result in overcurrent, overvoltage, or undervoltage conditions. Ground leakage protection also is provided, as is component overtemperature protection.

A "dead-rail" protection circuit prevents the possibility of energizing a dead section of the third rail during regenerative braking, avoiding a potential safety hazard. Although safe operating practices dictate that such "dead" sections must be safely isolated and grounded at the site of work to prevent electrical shock during rail maintenance or other work, the added protection provided by dead-rail-sensing and regenerative-braking-inhibit circuitry in cars equipped with regenerative braking is a desirable safeguard.

Of particular concern is the possibility that during regenerative braking, the vehicle, after passing an interruption of the supply (third rail gap), can energize a dead section of the third rail when regaining contact.

The ac propulsion system includes circuitry to sense dead rails and power gaps and shut off the current flow from the system to the line during braking. An antiregeneration relay in the line control equipment reacts rapidly to either a rail gap or dead rail, preventing regeneration by removing the triggering signals from the regeneration thyristors in the power circuits and initiating resistive braking instead.

To satisfy an NYCTA-particular requirement for disabling regeneration upon loss of third-rail power, the demonstration vehicles also are equipped with an AiResearch-designed "ripple detector," which measures third-rail voltage continually. When the power-station-generated 720-Hz ripple voltage imposed on the third-rail dc voltage decreases to a minimum level, the detector circuit disables the regeneration system on the car. Regeneration is inhibited until the circuit is again triggered on by sufficient third-rail ripple voltage. The ripple detector system can be adjusted to activate or deactivate at desired ripple levels. Obviously, a penalty in regeneration of electrical energy occurs with the ripple detector in operation, because the system will not regenerate with a low ripple voltage even though the line may be receptive. The ripple detector is independent of the rail gap detector.

MAJOR COMPONENTS

All of the major components in the ac propulsion system are based on mature technology and service-proven equipment.

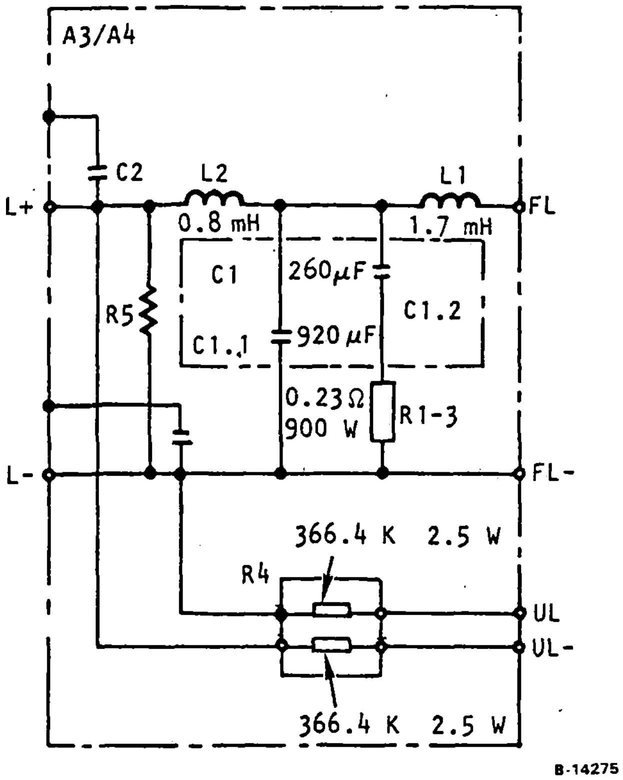
The inverter-controlled ac induction motor propulsion system includes the following major components. The paragraphs that follow provide component details.

- Two line filters, one for each inverter
- Two inverters, one for each truck drive
- Four ac induction traction motors, two per truck, one driving each axle
- A propulsion system control unit

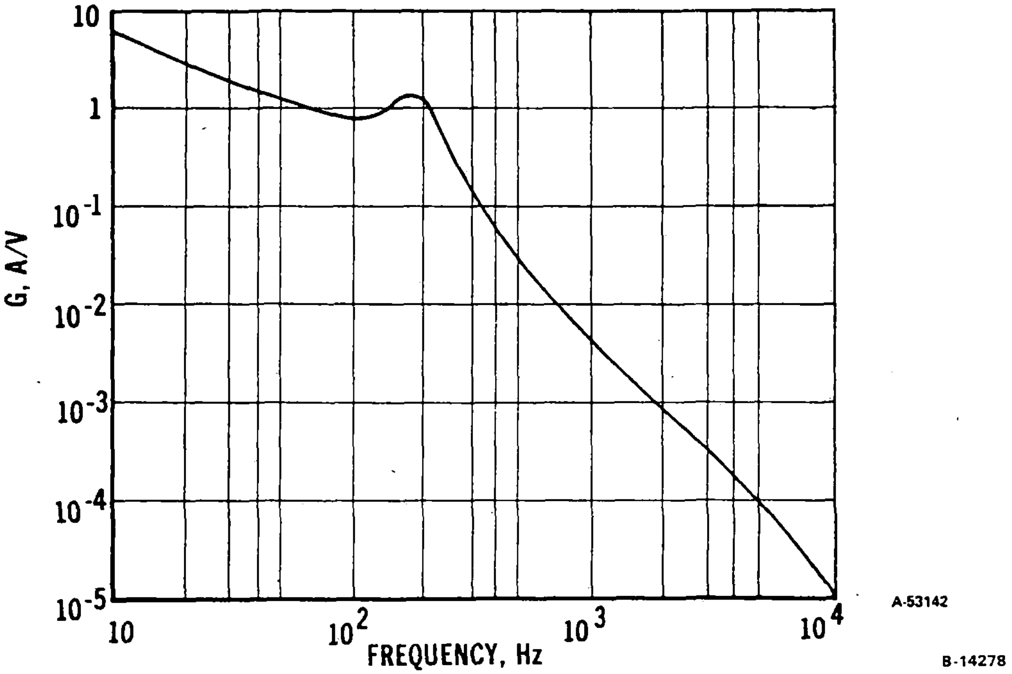
Line Filters

The line filters isolate each truck drive from the line and attenuate the line current harmonics generated by the line chopper (in the inverter) to prevent EMI to the signalling or track circuits. They also protect the inverter line choppers from surge voltages coming from the line.

As shown by Figure 11, each line filter circuit includes two dc reactors (inductors L1 and L2), a filter capacitor unit (C1), a damping resistor (R1-3), two radio frequency (rf) capacitors (C2, C3), a voltage divider resistor unit (R4), and a discharging resistor (R5), all mounted in a separate aluminum enclosure located under the car.



a. CIRCUIT DIAGRAM OF LINE FILTER



b. FILTERING CURVE OF LINE FILTER

FIGURE 11. LINE FILTER CIRCUIT AND RESPONSE

Inverters

Two voltage-fed, pulse-width-modulated (PWM), compound-commutated solid-state static inverters supply variable-frequency, quasi-sinusoidal, 3-phase ac power to the ac squirrel-cage induction traction motors.

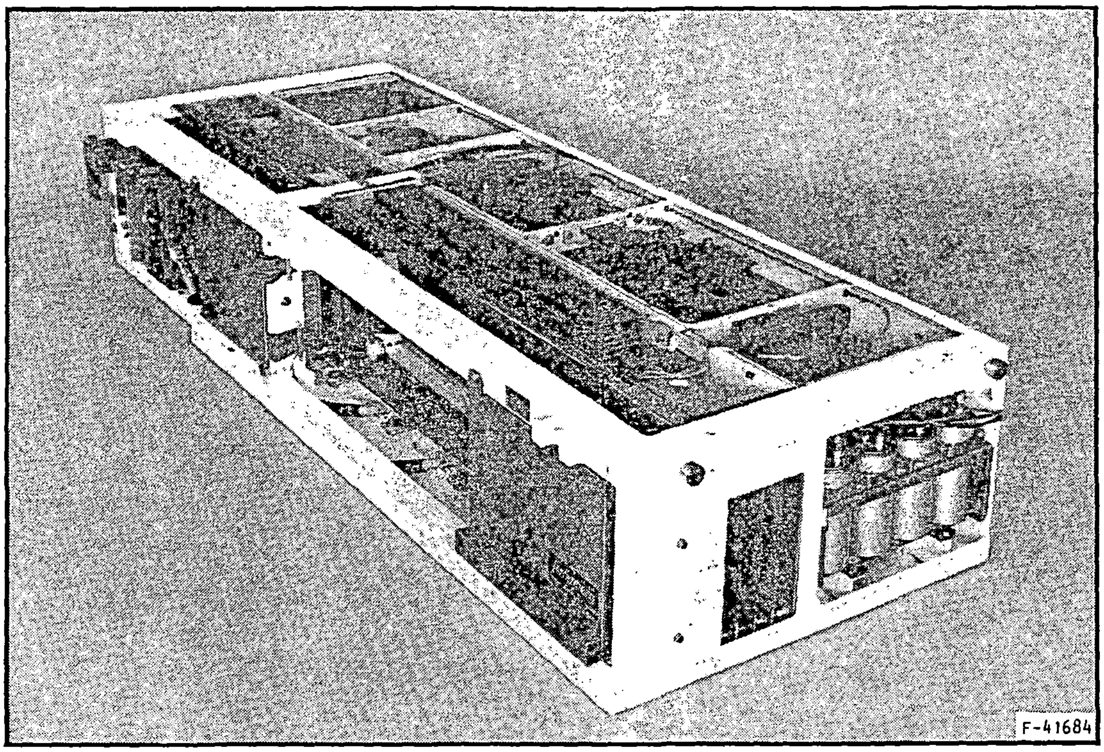
There is one inverter for each truck drive, each of which powers two ac induction traction motors electrically connected in parallel (Figure 12).

Located beneath the car, the inverters are forced-air-cooled by blowers (one per inverter) that provide clean filtered air to cool the electronics. Each inverter interfaces with the propulsion system control unit and operates from the low-voltage dc supply. Depending on the operating mode (traction or electrical braking) the inverter (1) converts dc received from the line filter into ac for the traction motors, or (2) receives ac from the motors (operating as generators) and transfers power to the line (regenerative braking) or to braking resistors (dynamic braking).

During traction operation, the inverter operates under control of the control unit to regulate ac frequency and voltage to achieve the desired motor speed and torque. Each inverter includes three subunits:

- A line chopper that regulates dc voltage obtained from the line filter so the dc link voltage supplied to the inverter and brake chopper is independent of line voltage variations
- An inverter that converts the dc-link power into variable-frequency, variable-voltage ac suitable for the traction motors
- A brake chopper that regulates the dynamic braking power dissipated in the braking resistors during conditions of inadequate line receptivity for full regeneration

Each of these subunits includes thyristor switching circuits based on forced-commutated thyristors with feedback diodes. The thyristors are triggered by signals from the control unit.



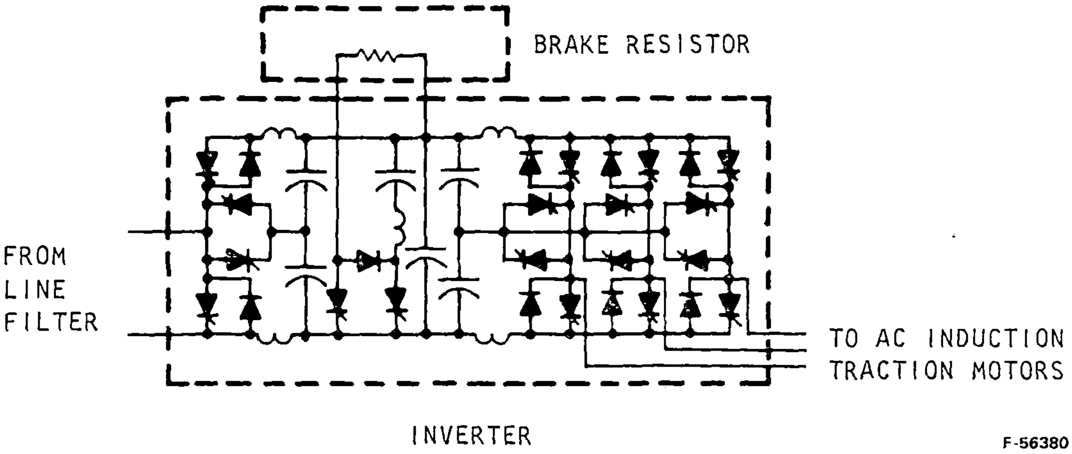


FIGURE 12. INVERTER AND SIMPLIFIED CIRCUIT DIAGRAM

Induction Motors

The STARS ac propulsion system is designed around and achieves many of its benefits from the minimum-maintenance, squirrel-cage ac induction traction motor.

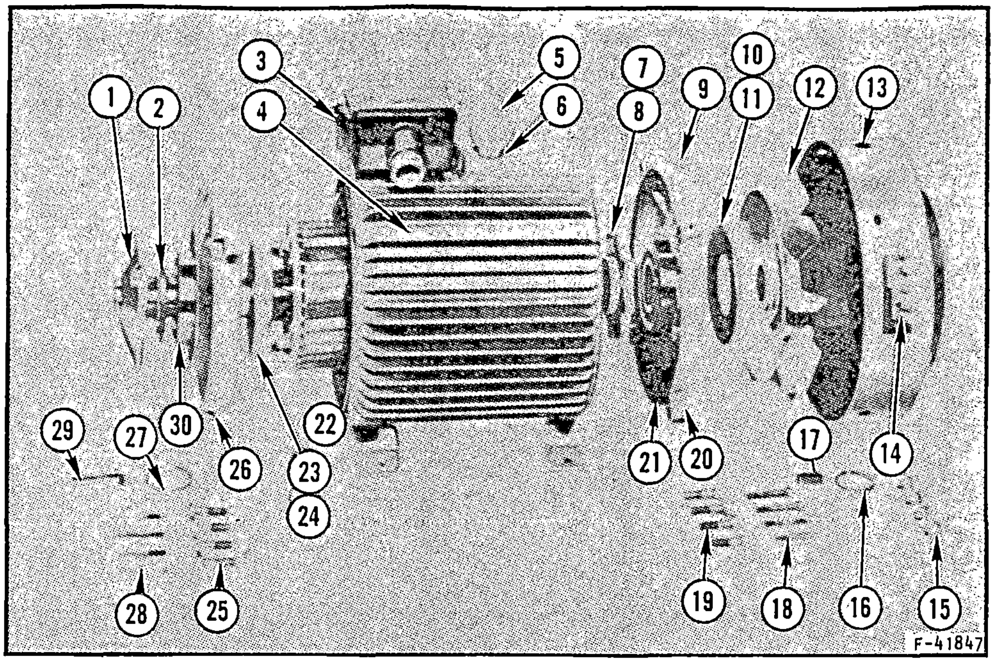
The high reliability and low maintenance benefits of the ac propulsion system are derived primarily from this brushless ac motor (Figure 13), which eliminates the inherent weak points of dc propulsion systems--the maintenance-intensive brushes and commutator in the dc motors.

The squirrel-cage ac induction motor does not have conventional windings but has interconnected rotor bars (the "squirrel-cage"), which turns in response to interaction of the rotating field created by the 3-phase ac current in the stator and currents resulting in the rotor; thus brushes and commutator are unnecessary.

For this application, a totally enclosed, fan-cooled motor is used. The ac motor features:

- Simple, rugged construction
- Lightweight, low-inertia laminated iron rotor with aluminum rotor bars
- Electrical parts not affected by environment
- No scheduled maintenance except infrequent bearing relubrication
- Mounting provisions and interfaces compatible with existing R-44 truck mounting points, couplings, and gearbox.

The motor has a steel housing with welded, widely separated cooling fins; a 4-pole, 60-slot stator with a single-layer diamond winding of class H insulated copper wire in double-delta 3-phase connection; a cast aluminum rotor cage; cast aluminum stator bars; and a laminated iron core to complete the magnetic circuit. The rotor is supported by two single-row deep-groove ball bearings equipped with relubrication pins. Motor specifications are:



TRACTION MOTOR PARTS LIST

(1)	OUTER BEARING COVER, DRIVE END
(2)	DISC
(3)	TERMINAL BOX, COMPLETE
(4)	HOUSING
(5)	EYE BOLT
(6)	WASHER FOR LIFTING LUG
(7)	INNER BEARING COVER, NON-DRIVE END
(8)	SEAL FOR INNER BEARING COVER, NON-DRIVE END
(9)	GREASE NIPPLE
(10)	WAVE SPRING WASHER
(11)	OUTER BEARING COVER, NON-DRIVE END
(12)	FAN
(13)	FAN COVER
(14)	NAMEPLATE
(15)	SCREW FOR FAN COVER
(16)	RETAINING RING FOR FAN
(17)	KEY FOR FAN
(18)	SCREW FOR BEARING COVER, NON-DRIVE END
(19)	SCREW FOR ENDSHIELD, NON-DRIVE END
(20)	ENDSHIELD, NON-DRIVE END
(21)	BEARING, NON-DRIVE END
(22)	ROTOR
(23)	INNER BEARING COVER, DRIVE END
(24)	SEAL FOR INNER BEARING COVER, DRIVE END
(25)	SCREW FOR ENDSHIELD, DRIVE END
(26)	ENDSHIELD, DRIVE END
(27)	RETAINING RING FOR DISC
(28)	SCREW FOR BEARING COVER, DRIVE END
(29)	KEY FOR SHAFT END
(30)	BEARING, DRIVE END

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FIGURE 13. SQUIRREL-CAGE AC INDUCTION MOTOR EXPLODED VIEW

Type	HXUR/E 562G2
Power	128 kW
Voltage	470 v
Connection	D2
Rated current	205 amp
Rated frequency	45 Hz
Rated speed	1325 rpm
Power factor	0.83
Protection class	TEFC
Insulation class	H
Weight	1336 lb (606 kg)

With no insulated windings on the rotor, the ac motor is able to operate at higher temperature, reducing the cooling requirements. With no brushes/ commutator and no internal cooling air passages required, the motor can be totally enclosed, improving reliability by providing protection from dust, dirt, rain, snow, etc. The motor is self-cooled by a built-in fan that forces cooling air over the outer finned surface of the stator housing. No special cooling air filters with attendant periodic replacement requirements are necessary.

The rotational speed of an ac induction motor depends on the frequency of the ac power supplied to it. The control unit and inverter act together to provide the required motor torque/speed and directional response in traction and during electrical braking modes. Unlike conventional dc traction motors, there is no need to electrically reconnect the motors for different operating modes--thus no main circuit contactors are needed. There are no switched resistances in the field circuit. No reversing contactors are needed--to reverse motor direction, the ac voltage phase sequence is electronically reversed. The transition from drive to braking mode is made by reducing the synchronous speed of the motor from slightly greater than to slightly less than shaft speed, whereupon the motors act as ac generators.

The combined effects of many of these features of the ac motors result in additional benefits to the ac propulsion system:

- No Brushes/Commutator--No costly brush examination/replacement or commutator grinding, no problems at higher voltage from arc-over, no exposed electrically "hot" surfaces
- Squirrel Cage--Allows higher operating temperature, higher speed, and less complicated cooling system; simpler construction reduces weight, resulting in less unsuspended mass, less rotating inertia, less wear for wheels
- Totally Enclosed, Self-Cooled Design--Eliminates complicated cooling systems, ducting, filters; provides additional protection against contaminants

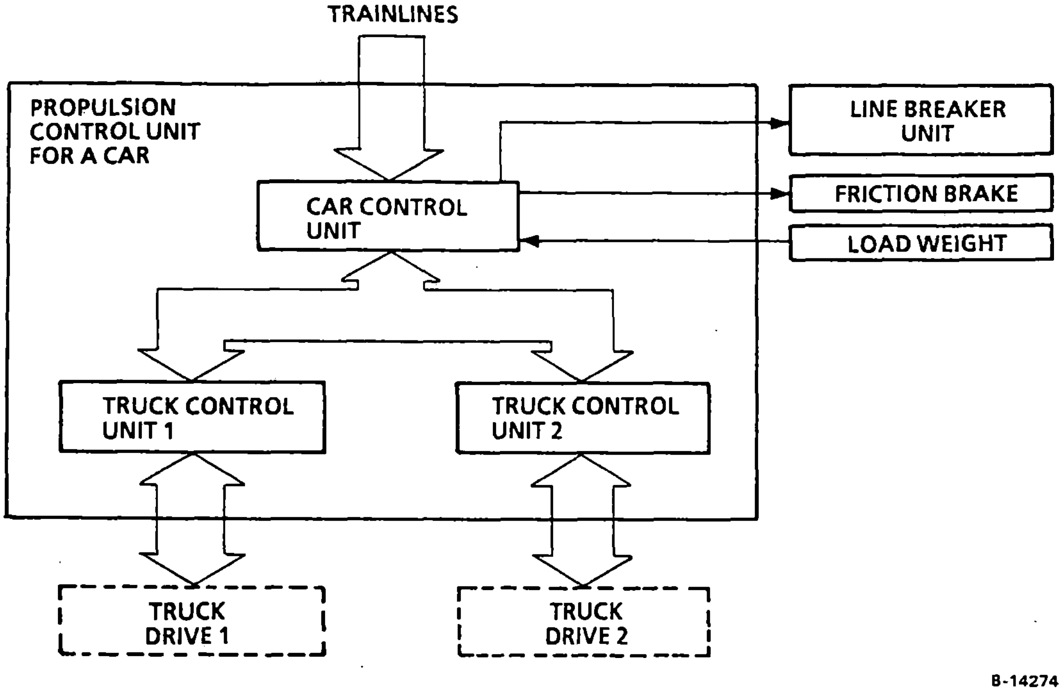
Propulsion System Control Unit

The control unit operates in conjunction with the inverters to control the ac frequency and voltage supplied to the ac induction traction motors.

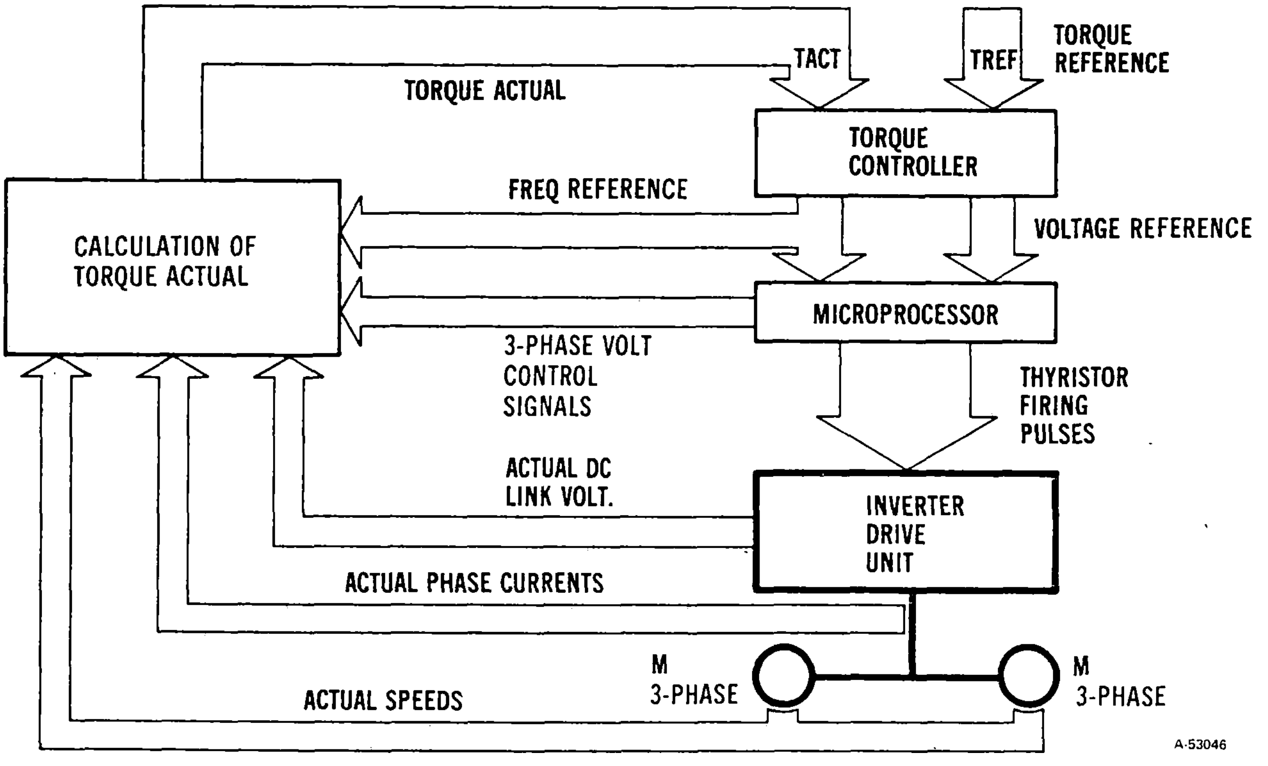
Operating in response to trainline commands and feedback signals, the controller provides the triggering signals to the thyristor switching circuits in the line filters and inverters. It is powered from the R-44 low-voltage supply and interfaces with:

- The master controller
- The line control equipment
- The ac traction motors
- The line filters
- The pneumatic friction brakes
- Sensors and transducers

The control unit performs the calculations necessary for ac motor directional control and torque control, and regenerative and dynamic braking. The control unit uses combined analog and digital circuitry with complementary metal oxide semiconductor (CMOS) and solid-state microprocessor devices (Figure 14). The electronics are contained on printed wiring assemblies (PWA's) installed in removable racks, and have built-in test connections for testing without removing PWA's. Light-emitting diodes (LED's) provide indications of normal/abnormal (failure) PWA conditions.



a. FUNCTIONAL HIERARCHY



b TORQUE CONTROL

FIGURE 14. PROPULSION CONTROL UNIT SIMPLIFIED BLOCK DIAGRAMS

The circuits are sectionalized according to function to comprise one car control section and two truck control sections, each in a separate PWA rack.

The car control section delivers the load-weight-compensated torque request to each of the truck control sections as a function of trainline signals.

The two identical truck control sections regulate inverter frequency and voltage to each truck so that the sum of the two traction motor torques corresponds to the level commanded by the master controller.

CONCLUSIONS

The DOT/UMTA inverter-controlled ac induction motor propulsion system program provides a sound basis for rail transit industry decisions to modernize their operations, improve performance, and reduce costs by using ac propulsion.

The ac prototype system performance shows that significant improvements are obtainable by ac retrofitting. Addressing U.S. rail industry concerns about increasing operating and maintenance costs and unsatisfactory experiences with prior introduction of unproven equipment, the AiResearch/Stromberg team provided a system that was based on revenue-service-proven hardware (primarily that of Helsinki Metro) suitably adapted for use in U.S. transit properties.

The energy consumption and life-cycle costs projections are significantly lower than for dc.

The reliability record of the ac equipment is much better than that of dc propulsion.

The system uses the existing 600-vdc third-rail power, is interchangeable with present dc propulsion equipment, requires minimum revision to current operating practices, and would be easily integrated into ongoing vehicle overhaul programs.

Even through the ac propulsion system equipment was not initially intended for operation in the severe New York environment and does not incorporate the most recent technology, it demonstrated a remarkably trouble-free operating record and clear benefits. Most of the problems encountered in the two-year test period were overcome through extensive testing and development effort; those related to hardware would be eliminated with today's technology and increased knowledge of the New York system.

RECOMMENDATIONS

The prototype ac propulsion system, based on mature, proven technology to minimize development risk when the program was proposed in August of 1980, provided ample proof of the ac propulsion system advantages. Newer technology now can provide even greater benefits.

The inverter-controlled ac induction motor propulsion system program successfully demonstrated the projected performance improvements and operating and maintenance cost reductions that can be realized by changing from dc to ac propulsion, and did so on schedule, in a demanding, real-life environment. The decision to base the prototype system on service-proven hardware rather than attempting to develop all-new, state-of-the-art equipment with more potential for development problems to resolve no doubt contributed to this success.

Since 1980, however, newer, more efficient technology, especially in the area of power electronics and controls, has been developed and proven and is available for new designs. AiResearch recommendations for a future production version of this ac propulsion system would include the following equipment upgrades:

- Gate turn-off (GTO) thyristor power control devices
- Fully digital microprocessor-based propulsion control
- Heat pipe cooling for power control equipment
- Modularized construction

The use of GTO thyristors rather than the older conventional thyristor circuits and the use of fully digital microprocessor-based controls offer dramatically reduced parts count, thus increased reliability. The induction motor reliability is already so high that little improvement is expected. The following table compares the Helsinki Metro component reliabilities with the predicted improvements possible with these technology improvements.

Component	MDBF, miles	
	Helsinki Metro	Future
Control unit	120,000	150,000
Inverter	410,000	500,000
Motors (4)	5,500,000	5,500,000
Total system	91,000	113,000

GTO Thyristors

Still a new development when the ac propulsion system program began, but now fully proven, the GTO thyristor combines, within a single unit, the current switching capabilities of the more complex multi-component conventional thyristor switching circuit used in the inverter.

The conventional thyristor turns on in response to a triggering signal, but requires an auxiliary commutating thyristor/capacitor circuit (with associated capacitor charging delay) to turn it off. GTO's turn off rapidly in response to a triggering signal, in the same way they are turned on, with limited additional circuitry required. The benefits:

- Reduced cost, volume, and weight
- Fewer parts, greater reliability
- Reduced switching losses
- Faster available switching response

The increase in available switching speed enables faster control loop response and allows the pulse-width modulation mode to more nearly generate a sinusoidal output. Motor losses are reduced and the application of torque is smoother.

Fully Digital Microprocessor Control

Digital microprocessors are now available with greatly increased capabilities and speed.

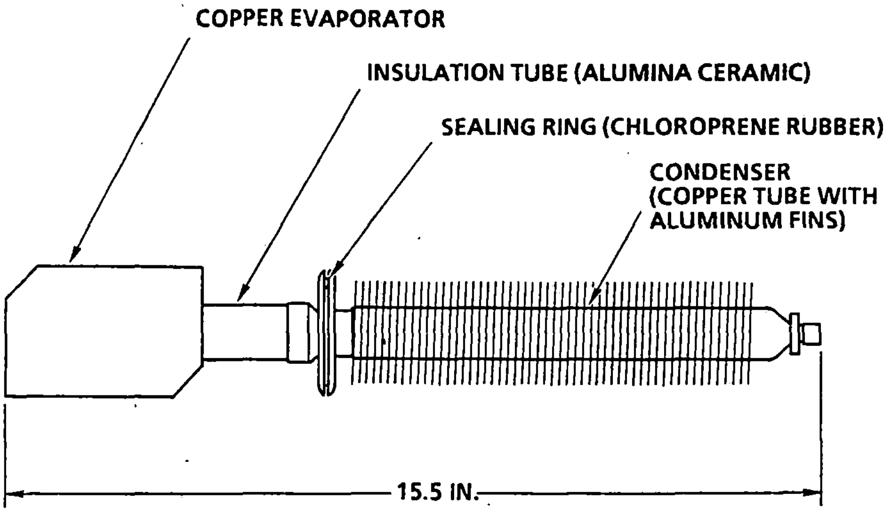
The new microprocessors can perform the functions that previously required many more components and offer built-in diagnostics and automatic malfunction indication to greatly simplify troubleshooting. At the same time, reliability is improved and cost reduced. Some of the benefits are:

- Extensive built-in test is practical, which simplifies troubleshooting, shortens turnaround time, reduces cost of maintenance.
- Parts count is dramatically reduced, thus reducing cost, space requirements, and logistics burden, while improving reliability.
- Control parameters are easy to modify through software (rather than hardware), which reduces development cost and widens product applicability.
- Event memories greatly facilitate trouble diagnosis.

Heat Pipe Cooling

Heat pipe cooling is an efficient method of cooling semiconductors that avoids the necessity for having cooling air (carrying potential contaminants) come into contact with any electrically live components.

Figure 15 shows a typical heat pipe. A hollow copper evaporator is joined to a finned copper tube (condenser) by a hollow electrically insulating section. A small amount of liquid Freon is introduced before sealing the heat



- **COOLING LIQUID: FREON II (2.8 OZ)**
- **TOTAL WEIGHT: 4.2 LB**

FIGURE 15. HEAT PIPE CONSTRUCTION

pipe. The fins on the condenser increase thermal efficiency, and the pipe is slightly inclined to make the evaporator the lowest point. The evaporator is clamped to the device to be cooled. Heat is conducted through the copper evaporator into the liquid Freon, which boils. The gaseous Freon rises up the tube until it condenses and gives up its heat before flowing back to the evaporator as liquid Freon again. Air may be blown over the condenser fins to increase cooling effectiveness without requiring airflow over the electrical device to be cooled.

Figure 16 shows a practical heat pipe inverter cooling package. Two semiconductors are double-side cooled using three heat pipes. All three condensers are located in a cooling air channel that runs through the center of the inverter box, isolating them from the electronics. Cooling air is blown down this channel.

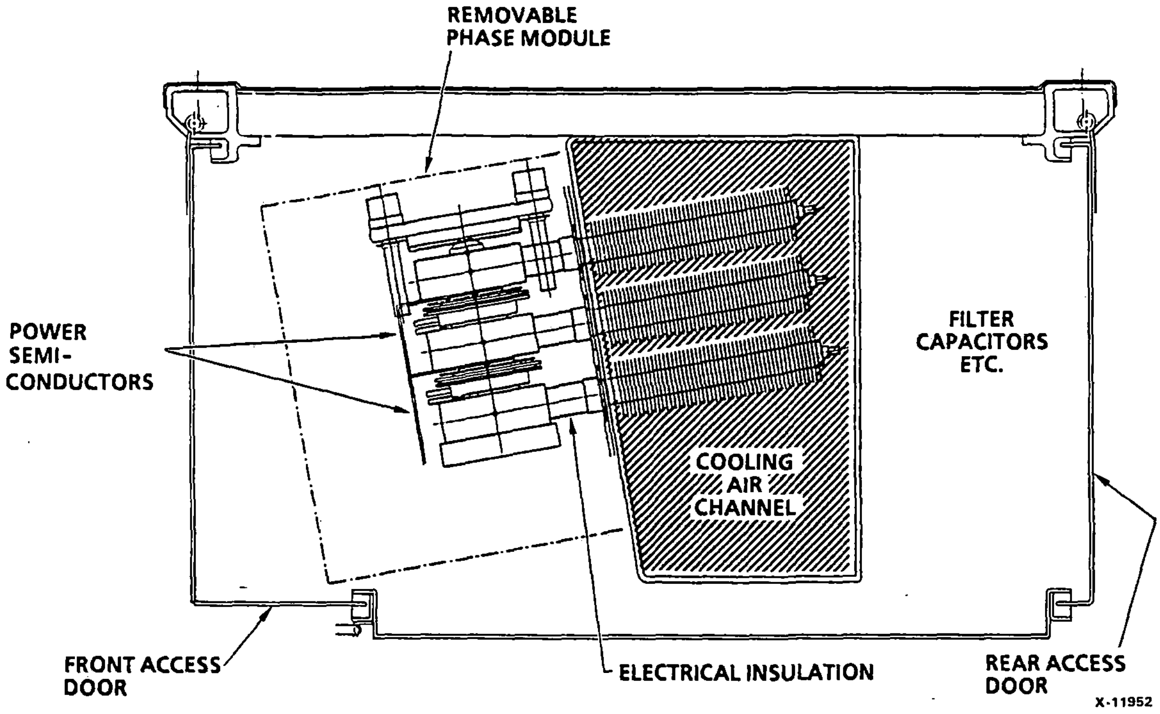


FIGURE 16. HEAT PIPE INVERTER PACKAGE

All semiconductors and gating components are readily accessible through the front access door, and filter capacitors are located on the opposite side of the air channel. No air is blown over any component other than the heat pipe condensers (which are electrically neutral), so there are no dirt buildup "tracking" problems. Cooling fins can be cleaned by blowing compressed air through the cooling channel with a hose.

Modular Construction

The use of GTO phase modules in the inverter offers advantages of ease of testing and servicing, which reduces maintenance time.

The modularized construction approach is demonstrated in Figure 17. By opening the front access door and loosening four bolts, a GTO phase module can be completely removed and replaced in minutes. Control and power connections are by plug and socket. A gasket between the module and cooling channel provides an airtight seal between the cooling air channel and electronics section.

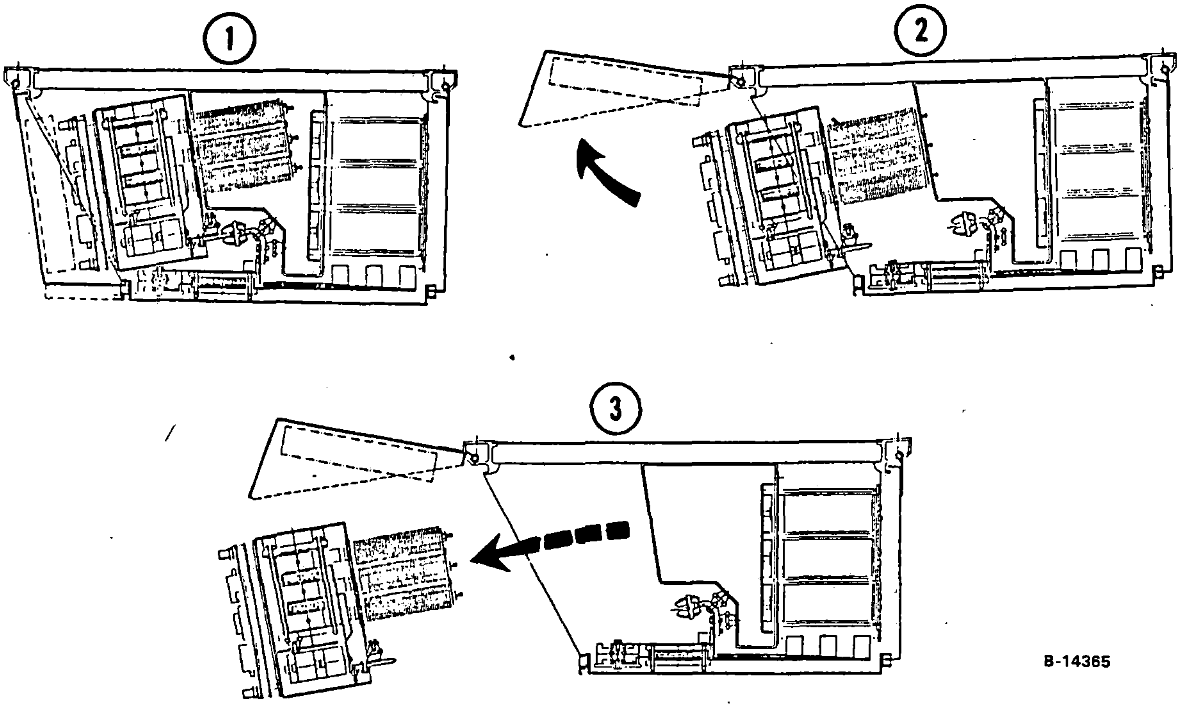


FIGURE 17. REMOVAL OF A GTO PHASE MODULE

Figure 18 shows a production GTO phase module that contains two GTO's for one phase, complete with three heat pipes and all gating components. Three such modules are required for an inverter.

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