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Electric Vehicle Motors and Controllers

Richard R. Secunde
National Aeronautics and Space Administration
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Work performed for
U.S. DEPARTMENT OF ENERGY
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Prepared for
Fifth International Workshop on Rare Earth—
Cobalt Magnets and Their Applications
Roanoke, Virginia, June 7-10, 1981

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ABSTRACT

The goal of DOE's Electric and Hybrid Vehicle Program is to promote and accelerate the development and public use of vehicles that use electricity as the principal source of propulsion energy. Successful achievement of this goal will ultimately result in significant petroleum savings to the nation. However, the design, performance, and cost of propulsion components must be improved before commercially attractive electric vehicles can be built. Improved and advanced components being developed under the NASA-managed propulsion portion of the DOE program include electronically commutated permanent magnet motors of both drum and disk configurations, an unconventional brush-commutated motor, and ac induction motors and various controllers.

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The work reported herein is part of the U.S. Department of Energy's Electric and Hybrid Vehicle Program.

Test results on developmental motors, controllers, and combinations thereof indicate that efficiencies of 90 percent and higher for individual components, and 80 percent to 90 percent for motor/controller combinations can be obtained at rated power. The simplicity of the developmental motors and the potential for ultimately low cost electronics indicate that one or more of these new approaches to electric vehicle propulsion may eventually displace presently used controllers and brush commutated dc motors.

INTRODUCTION

The goal of the Electric and Hybrid Vehicle Program of the U.S. Department of Energy (DOE) is to promote and accelerate the development and public use of vehicles that use electricity as the principal source of propulsion energy. Attainment of the goal would result in a significant number of electric and hybrid vehicles finding their way into the marketplace and will ultimately result in significant petroleum savings to the nation. The DOE has delegated project management responsibility for the propulsion system technology development part of the program to the NASA-Lewis Research Center.

Present day electric vehicles are mostly conversions of conventional internal combustion engine-powered cars. A few specially designed electric vehicles have appeared recently, either as low performance vehicles, experimental demonstration vehicles, or high cost, few of a kind production vehicles. All these vehicles are too costly and/or generally lack the performance necessary for broad public acceptance. A major reason for this is the high cost of components to the vehicle manufacturer, commonly referred to as the Original Equipment Manufacturer cost (OEM cost). The OEM cost of the motor and controller together can vary from $2,000 to $5,000. Before commercially successful electric vehicles can be built, the design, performance, and cost of propulsion components must be improved.

It is recognized that no single approach to propulsion components will be best for the broad range of potential vehicle missions, and that many potentially good solutions to a particular need exist. Therefore, during the first stages of most developments, multiple parallel efforts are being pursued. As development efforts progress, the number of supported approaches will be narrowed to those with the greatest potential for low cost and attractive performance.

Electronically commutated permanent magnet motors are an attractive alternative to the conventional dc brush type motor because of their potential for higher efficiency, simpler construction, lower cost and lighter weight. Induction motors driven by inverters are also attractive because of their high state of development and low cost. Semiconductor devices for commutation and inversion for these two alternatives are presently costly, but industrial market forces are expected to bring these costs down in the future. With the emphasis on motors, this paper describes propulsion system components being developed as part of the DOE Electric and Hybrid Vehicle Program. These include electronically commutated permanent magnet motors of both drum and disk configurations, ac induction motors and controllers, a dc brush-commutated motor, and a dc controller.

As the electric vehicle market develops, motors and controllers will be needed in substantial quantities. The simplicity of the developmental motors and the potential for ultimately low cost power electronics indicate that one or more of these new approaches to electric vehicle propulsion will eventually displace presently used brush-commutated dc motors.

GENERAL TOPICS

Terminology

In this paper two developmental time frames are used. These are mid-term and far-term. The mid-term implies readiness for commercial production in the late 1980's. Technology which is available and proven in other fields, such as aerospace, is used, but components are being designed specifically for electric vehicles. The far-term implies the use of technologies which are now new or not well established and a readiness for commercial production in the 1990's.

There are several hardware phases in these developments. The first is the proof-of-principle model. This is usually a small scale demonstration of the idea and applies mostly to the far-term components. Next is the functional model which is a full-rated assembly intended for test and evaluation in a laboratory environment. It would not normally be intended for use in a vehicle. The engineering model is the next step beyond the functional model. It would be designed for test and evaluation under normal use conditions in a vehicle. The prototype model is one designed with volume production in mind.

Goals

The goals of the DOE/NASA electric vehicle propulsion component developments, relative to what is commercially practical today, are as follows:

Motors:

- 5 percentage-point efficiency gain (at rated power)

- 60 percent weight reduction

- 50 percent cost reduction

Controllers:

- 2 percentage-point efficiency gain
- 50 percent weight reduction
- 40 percent cost reduction

Performance Requirements

The rating, or ratings, of a propulsion system component for electric vehicle application cannot be specified explicitly at this time. As an analogy, consider the difference between a 150 HP automobile engine and 150 HP truck and bus engines. Each has evolved to satisfy its particular application. A way remains to be developed to consistently specify the power of an electric vehicle propulsion system. Therefore in these developments, we instead specified that the components be designed to meet the duty cycle shown in figure 1. The indicated cyclic power requirements are those needed at the motor output to drive a 1450 kg gross weight vehicle over the SAE J227a, Schedule D driving cycle. One gear ratio change was allowed during the acceleration portion of the cycle if the motor design would benefit from it. Also specified was the capability to cruise at a constant speed of 55 miles an hour and climb a 10 percent grade at 30 miles an hour as indicated in figure 1. Cooling was to be by means of natural convection or forced air. Liquid or other cooling mediums were allowed if the contractor could show that the overall vehicle would benefit.

COMPONENT DEVELOPMENTS

Electronically Commutated PM Motors

Table I shows a summary of the four electronically commutated permanent magnet (PM) motors which are under development as parts of the multiple parallel component development approach being used in the Electric and Hybrid Vehicle Program. Two are of a drum configuration and two of a disk configuration. Each has potential for low cost in volume production (100,000 units per year) because of simplicity of construction and/or light weight (minimized use of raw materials). Their efficiencies are generally higher than those of present day motors used in electric vehicles. Permanent magnet drum motor technology has been demonstrated in other applications such as aerospace, therefore, these two motors are considered mid-term developments. The design approaches for the disk motors are more advanced and therefore these motors are intended for the far-term. The weights and speeds shown in Table 1 should not be taken as representative of particular types of motors. The designs of these motors in their present state of development reflect each contractor's interpretation of the performance requirements and the needed margins for overload, reliability, and safety.

Drum Motors

Figure 2 shows a cutaway model of the AiResearch drum motor. The internal configuration of the VPI/Inland motor shown in figure 3 is similar. As indicated by the number of terminals, the VPI/Inland motor uses various numbers of turns per pole, externally selected, to minimize current at low speeds. Compared to the conventional brush type dc machine in which the armature must rotate to effect commutation, these motors are of an "inside-out" construction in which the permanent magnet field is on the rotor and the armature is stationary. Commutation is achieved electronically. A number of important advantages result from having the winding stationary. The teeth and slots of the magnetic steel laminations become larger than in the conventional construction. The teeth can carry more magnetic flux and the slots can carry more copper. The net effect is that the resistance of the winding can be decreased improving the efficiency. At the same time, the heat dissipation area of the winding is increased. A higher power output, thus, can be achieved for the same temperature rise. The essential features of electronic commutation are shown in figure 4. An inverter is gated by a shaft position sensor coupled to the shaft of a synchronous machine. The inverter provides the power switching function, and its operation is analogous to brush commutation in a conventional dc motor. The dc-dc converter (chopper) controls the voltage supplied to the inverter, thereby permitting the speed to be controlled as in a conventional dc motor. With suitable feedback circuitry, the chopper is able to control the motor current and, thereby, its developed torque. Transistors or thyristors can be used in the chopper and inverter.

The AiResearch and VPI/Inland motors use Samarium-Cobalt ($SmCo_5$) permanent magnets. Functional models have been built and tested and engineering models are being constructed. The present weights and measured efficiencies shown in table I are for the functional models. The 26,000 rpm speed of the AiResearch motor results in its very low weight. It has been estimated that gearing to provide shaft speeds compatible with present automotive technology and mounted in a housing integral with the motor would result in a weight increase of about 2 to 4 kg. Figure 5 is a photo of the functional model AiResearch motor, and figure 6 shows the breadboard version of its commutation and control electronics. The electronics appear large in the present form, but when properly packaged, they will be suitable for automotive installation. The commutation electronics for all of the electronically commutated motors will be similar since they are all basically three-phase inverters. AiResearch uses thyristors as the commutating switches whereas VPI uses transistors. Transistors generally allow simpler circuits, but are more expensive than thyristors at present. The efficiency of the electronics will typically be above 90%, resulting in combined motor/electronics efficiency above 85% over a broad operating range. In comparing the electronically commutated motors to other approaches, it must be kept in mind that the commutation and control electronics contain virtually all of the control functions likely to be required for motor operation in an electric vehicle. Electronically commutated drum type motors for electric vehicles are described in greater detail in references 1 through 4.

Disk Motors

Unlike the drum motors, the two developmental disk motors are significantly different from each other. Figure 7 shows a cutaway model of the AiResearch disk motor. This can be considered a homopolar construction. The rotor consists of a single central donut-shaped permanent magnet and two multi-fingered pole pieces. An ironless stationary armature is located between the tips of the pole pieces. The motor is intended to be self-cooled by the air pumping action of the rotor. The housing is aluminum, serving no electromagnetic function. The electronic commutation for this motor will be similar to that for the drum motors. Development efforts are presently concentrated on the functional model of the rotating machine. Functional model tests indicate that the electromagnetic performance of the machine is as predicted, but that the open spaces between fingers on the rotor cause excessive windage losses. Design modifications to minimize windage loss are under way. The single 15-cm diameter magnet used in the AiResearch motor is rare-earth-cobalt. In its present form, it is a mosaic of several smaller magnets and has presented some handling and magnetization problems.

Figure 8 shows a cutaway model of the PM disk motor being developed by General Electric. Here also, development is presently concentrated on the rotating machine and electronic commutation will be similar to that used for the drum motors. This motor uses multiple permanent magnets in an aluminum rotor and stationary armature windings on each side. It was originally intended that the magnets used would be of the manganese-aluminum-carbon type. However, these magnets are still in the developmental stage and a sufficient quantity was not available to build the functional model. Furthermore, it has been determined that the low Curie temperature of approximately 300 C for the manganese-aluminum-carbon magnets makes them questionable for use in electric vehicle propulsion motors. Tests of the first functional model which was designed to use Alnico-8 magnets resulted in some trouble because momentary shorts in the electronic commutation circuitry caused gradual de-magnetization of the magnets. This motor is now being redesigned to use samarium-cobalt, which will allow the motor to be smaller and lighter and eliminate the demagnetization problem.

References 2, 4, and 5 provide further details on the disk motor developments.

Induction Motors and Controllers

Table II shows a summary of the induction motors, controllers, and combinations thereof which are under development as part of the Electric and Hybrid Vehicle Program. These developments are for the mid-term and all three contractors are using motor and inverter technology which has been proven in other fields such as aerospace and industrial motor drives.

Similar to the permanent magnet motors, the ac squirrel cage induction motor is of simpler design and construction than the dc motor. The rotor is solid, it has no brushes or commutator, and it operates at much higher speeds. These features provide attractive weight and size advantages. This is illustrated pictorially in figure 9 which shows the GE ac induction motor with integral gear box on the left and an equivalently rated brush-type dc motor on the right. Both are designed to provide the performance shown in figure 1. The dc motor weighs about 98 kg with a shaft speed of approximately 5,000 rpm. The smaller ac motor weighs about 46 kg including gear box and also has a maximum output shaft speed of 5,000 rpm. Induction motors are amenable to automated mass production, and thus have a significant cost advantage over equivalently rated dc motors.

Also like the permanent magnet motor, power electronics are needed to control and operate an induction motor in variable speed vehicle applications. These electronics take the form of a variable frequency, variable voltage, polyphase inverter. Motor speed and torque is controlled by controlling the frequency and voltage output of the inverter. Input to the inverter is dc. The theory of variable speed ac drives is covered extensively in the literature.

Figure 10 shows the engineering model of an ac induction motor/controller system being developed by Gould. The central item in the figure is the inverter, the small box is logic, and the motor is a modified high efficiency Gould production motor. The only changes to the production motor are a lower voltage winding, better rotor balance, removal of part of the rotor fins, and better bearings. The inverter uses thyristors as power switching elements. This inverter is not as efficient as one which uses transistors because of thyristor turn-off requirements. However, suitably rated thyristors can be obtained for $35 to $40 each, whereas equivalent transistors now cost $350 to $400 each.

Figure 11 shows a close-up of the engineering model inverter/controller developed by the General Electric Company. It is designed to operate the small ac motor shown in figure 9, which is specially designed and built for use with an inverter. This motor has laminations which are thinner than those used in conventional motors and copper rotor bars to reduce losses. The motor maximum speed is 15,000 rpm, but the gear box maximum output speed is 5,000 rpm, which is compatible with present day automotive transmissions. Because of these special features, the GE motor is more efficient than the Gould motor, but also more costly. The GE inverter uses developmental GE power transistor modules as power switches and therefore its efficiency is higher than that of the thyristor inverter. However, the currently used transistor modules are still very expensive and in short supply. There are, however, market forces at work in the transistor industry related to efficient industrial control and variable speed drives. These forces are expected to accelerate the development of lower cost, power transistors. Electric vehicle ac controllers will undoubtably benefit from the increasing availability of these lower cost transistors.

Figure 12 shows a model of an ac propulsion system being developed by Eaton. The controller (inverter and logic) shown behind the motor is similar in size and appearance to that by Gould. The Eaton controller uses power Darlington transistors which is a significant contributing factor to its high efficiency. The Eaton induction motor is oil-cooled and has a maximum speed of 9,000 rpm. The motor is coupled directly to the transaxle from which it obtains cooling oil flow.

References 4, 6, and 7 provide further

details on induction motor and controller developments.

Brush-Commutated Motor and Controller

Electric vehicles being built today, and those now contemplated for the near future and mid-term, almost universally use brush-commutated dc motors for propulsion. These motors are controlled in two major ways, armature voltage control and/or field voltage control. The wide understanding and acceptance in industry of systems with brush-type dc motors tends to indicate that these systems will continue to be used until the performance, light weight, and reliability of the more advanced systems described previously in this paper become well established and their cost in volume becomes competitive with or lower than that of dc motor systems. The Electric and Hybrid Vehicle Program includes two advanced components for dc systems. These are a wound field, unconventional disk motor and a high efficiency controller. These two components are summarized in table III.

Figure 13 shows a cutaway model of the brush-commutated dc motor being developed by Westinghouse. It is a version of the classic gramme ring configuration which, though not new, presents the possibility for low cost manufacture. The rotating armature can be adapted to automated machine winding. In the Electric and Hybrid Vehicle Program this motor is being considered for the far-term because of its need for advanced technology to allow low cost fabrication of the armature core. Also, to reduce cost to as low a value as practical, it may be possible to eliminate the separate commutator in this motor by spot hardening sections of the armature winding. Commutation could then be achieved by running the brushes on the winding of the toroidally wound armature. The functional model of the Westinghouse motor had a maximum speed of 4,800 rpm and therefore was somewhat heavy, about 88 kg. The engineering model is being designed for a maximum speed of 7,200 rpm and is expected to weigh about 52 kg.

One of the most direct and effective means of controlling dc motor speed and torque for an electric vehicle propulsion system is by varying motor armature voltage by means of an electronic chopper. Such a chopper is simply an electronic switch in series with the armature, which varies the average armature voltage by controlling the on and off times of the switch. Chopper controllers are widely used in the electric lift truck industry, and this technology is being applied to electric vehicles. Both thyristors and transistors are used as the switch with controller switching frequency limited by available semiconductors to usually around 500 Hz, but in some cases as high as 2,000 Hz. These frequencies result in increased losses in the motor and batteries because of the rms currents created by the switching action.

The Chrysler Corporation is developing a high frequency chopper designed for either a compound or a shunt wound dc motor. This controller is shown in figure 14 with its cover removed. Its measured efficiency is around 95 percent. It's a transistor chopper operating at 10 kHz and therefore is very quiet. The 10 kHz operation allows the additional benefit that a small filter can be used to make the ripple currents, and losses due to them, in the battery and motor very low. In the present model, the rms ripple current is about 5 amperes. At the present time this controller is considered for the mid- to far-term period because it uses costly, but very efficient power transistors. Reference 8 provides further detail on this controller development.

Costs

As mentioned previously in this paper, the present OEM cost of a motor-controller combination varies from $2,000 to $5,000. The developmental components which have been described herein all have features which should result in significantly lower cost when fully developed and in volume production. Presently, of course, their cost is high because of the use of newly developed devices and very low volume.

Mass produced induction motors for electric vehicle propulsion should have an OEM cost of $150 to $250 which is less than half the cost of a conventional brush-commutated dc motor. The more efficient permanent magnet motors will be somewhat more expensive than the induction motors. Present estimates indicate that if the price of cobalt and rare earth stabilizes at present levels, the OEM cost of a permanent magnet motor should be between $200 and $300 when production volume reaches 100,000 units per year.

The electronics are, without question, the most expensive part of induction motor and electronically commutated motor propulsion systems. However, it must be kept in mind that these electronics contain virtually all of the control functions that are likely to be required for motor operation in an electric vehicle. The OEM cost of these electronics has been estimated at $1,400 to $1,650 for the thyristor versions. The transistor electronics cost is considerably higher now, but is potentially less expensive due to the less complex circuitry required. There has been an increased interest recently in low cost, high power transistors on the part of many transistor manufacturers. If power transistors were to become available at a price of $0.15 per ampere, a figure within the goals of a number of transistor manufacturers, transistor electronics for the induction and permanent magnet motors could be produced for an OEM cost of about $600 per unit. The total OEM cost of the propulsion system would then be under $1,000, not including batteries or transmissions.

The eventual low cost of the developmental dc brush-commutated motor and controller should also result in a propulsion system OEM cost of under $1,000. The dc motor will probably be more costly than an induction motor, but the controller for it is simpler than the electronics used with induction and permanent magnet motors.

Therefore, at the present it is not practical to predict which approach will be lowest cost. Hardware developments are planned to continue to the point where designs are at a suitable level which will allow realistic prediction of cost and performance.

CONCLUDING REMARKS

Ongoing electric vehicle propulsion system component technology developments are aimed at improving performance and reducing cost. Permanent magnet and induction motors both offer potential advantages over presently used brush-commutated dc motors in the areas of efficiency, weight, size, and cost. Relative to the induction motor, the permanent magnet motor should be more efficient because it does not need an external source of excitation. The induction motor, however, should be less costly because it uses less costly materials. For similar speeds, the size of these two motors should be similar. The inverters needed to drive and control these two motors are very similar, and ultimately will be equivalent in cost, efficiency, and weight. Because of its simplicity of control, the brush commutated dc motor will maintain its appeal for electric vehicle propulsion for some time. A lower cost disk design will enhance ores appeal as will a high efficiency dc controller.

Results of technology development on these components to date have shown promise of significantly improved performance and ultimate low cost. The most significant cost problem at present is that of the power electronics needed for operation of induction and permanent magnet motors. Market forces other than the electric vehicle are working to reduce the cost of power electronics. The long term relative advantages of induction motor, permanent magnet motor, and brush-type motor propulsion systems remain to be determined. Therefore, technology development related to promising concepts is planned to continue until such a determination can be made.

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TABLE I. - DEVELOPMENTAL ELECTRONICALLY COMMUTATED MOTORS

Contractor	Construction	Maximum, rpm	Weight, kg*		Efficiency at 15 kW, percent*	
			Now	Predicted	Now	Predicted
AiResearch	P. M. drum	26,000	15**	15**	93	93
VPI/Inland	P. M. drum	8,000	40	27	93	95
AiResearch	P. M. disk	14,000	20	22	72	90
GE	P. M. disk	11,000	58	48	83	90

*Without electronics.
**Requires external fan, approximately 2.7 kg additional.

TABLE II. - DEVELOPMENTAL INDUCTION MOTORS AND CONTROLLERS

Contractor	Component	Weight, kg		Efficiency, at 15 kW, percent,	
		Now	Predicted	Now	Predicted
Gould	3-ϕ inverter, (thyristor)	69	50	85	90
	Motor, 9000 rpm	53	53	85	89
GE	3-ϕ inverter, (transistor)	69	50	93	94
	Motor*, 15,000 rpm	46	46	93	95
Eaton	3-ϕ inverter, (transistor)	60	45	92	93
	Motor**, 9000 rpm	67	59	90	93

*Motor includes integral reduction gearing to provide 5000 rpm maximum output speed.
**Motor is oil cooled.

TABLE III. - DEVELOPMENTAL DC MOTOR AND CONTROLLER

Contractor	Component	Weight, kg		Efficiency, at 15 kW, percent	
		Now	Predicted	Now	Predicted
Westinghouse	Gramme ring 7200 rpm disk motor	88.5*	52	92	90
Chrysler	10 kHz chopper arm. and field controller (transistor)	36	32	97	97

*Weight for functional model, 4800 rpm maximum.

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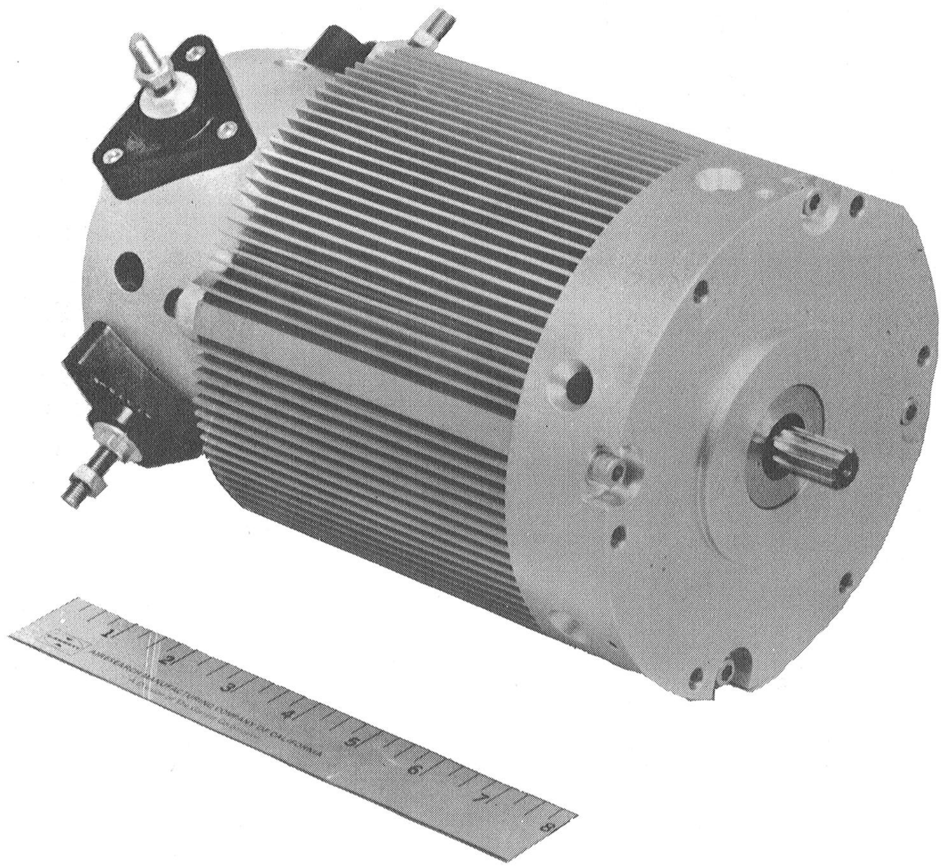

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Figure 5. - Functional model hardware-AiResearch drum motor.

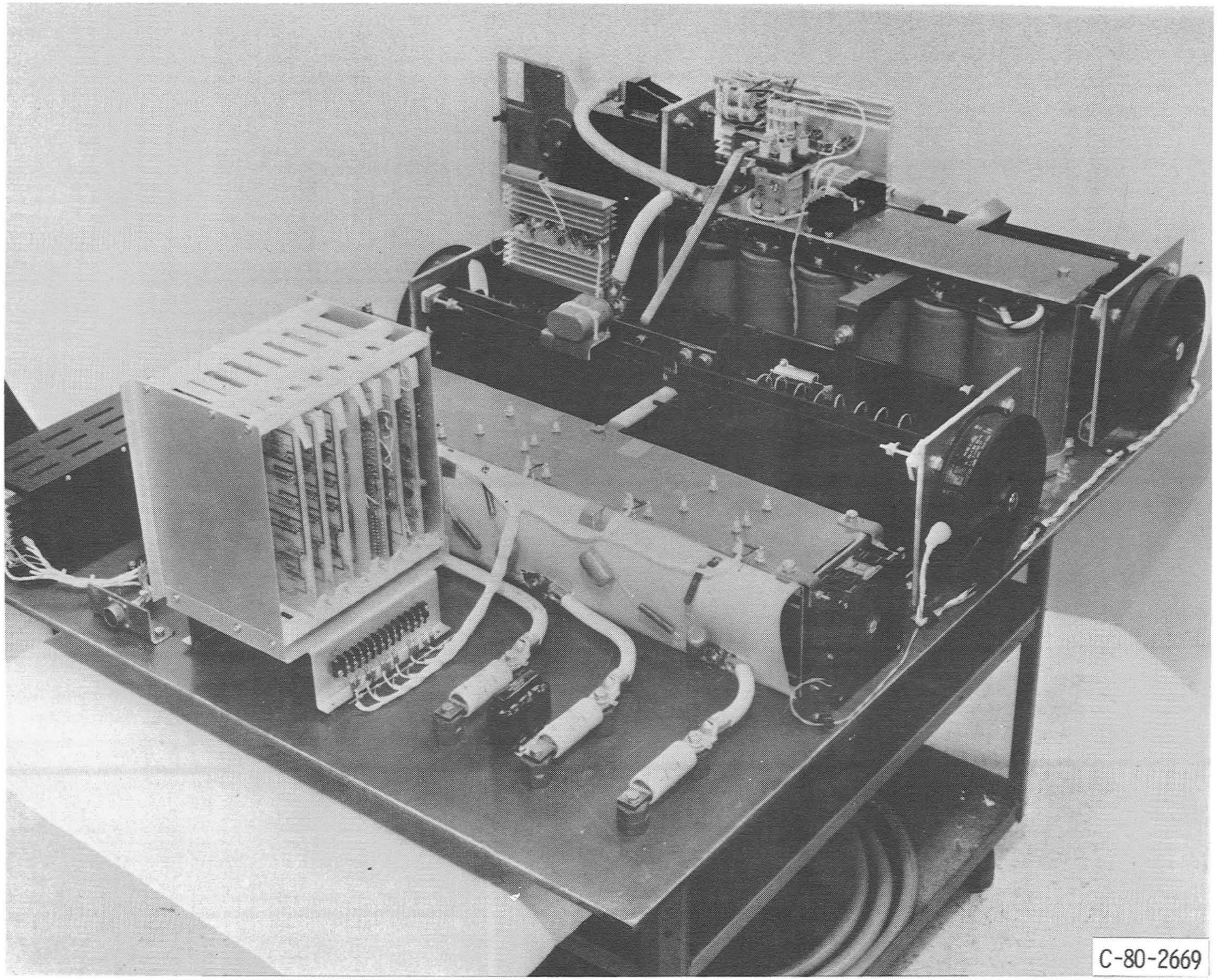

Figure 6. - Breadboard version of thyristor commutation and control.

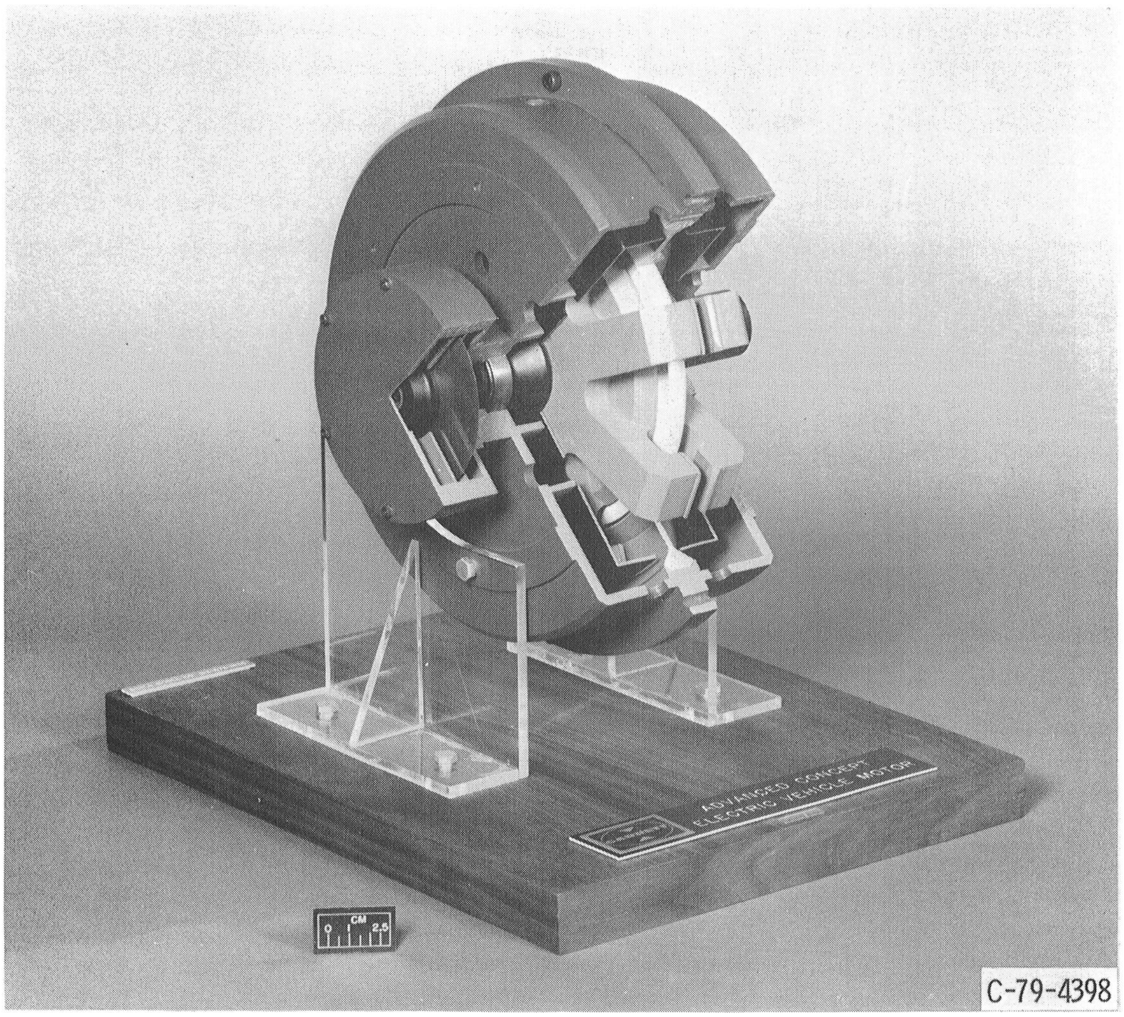

Figure 7. - AiResearch disk motor (without electronics).

Figure 8. - G. E. disk motor (without electronics).

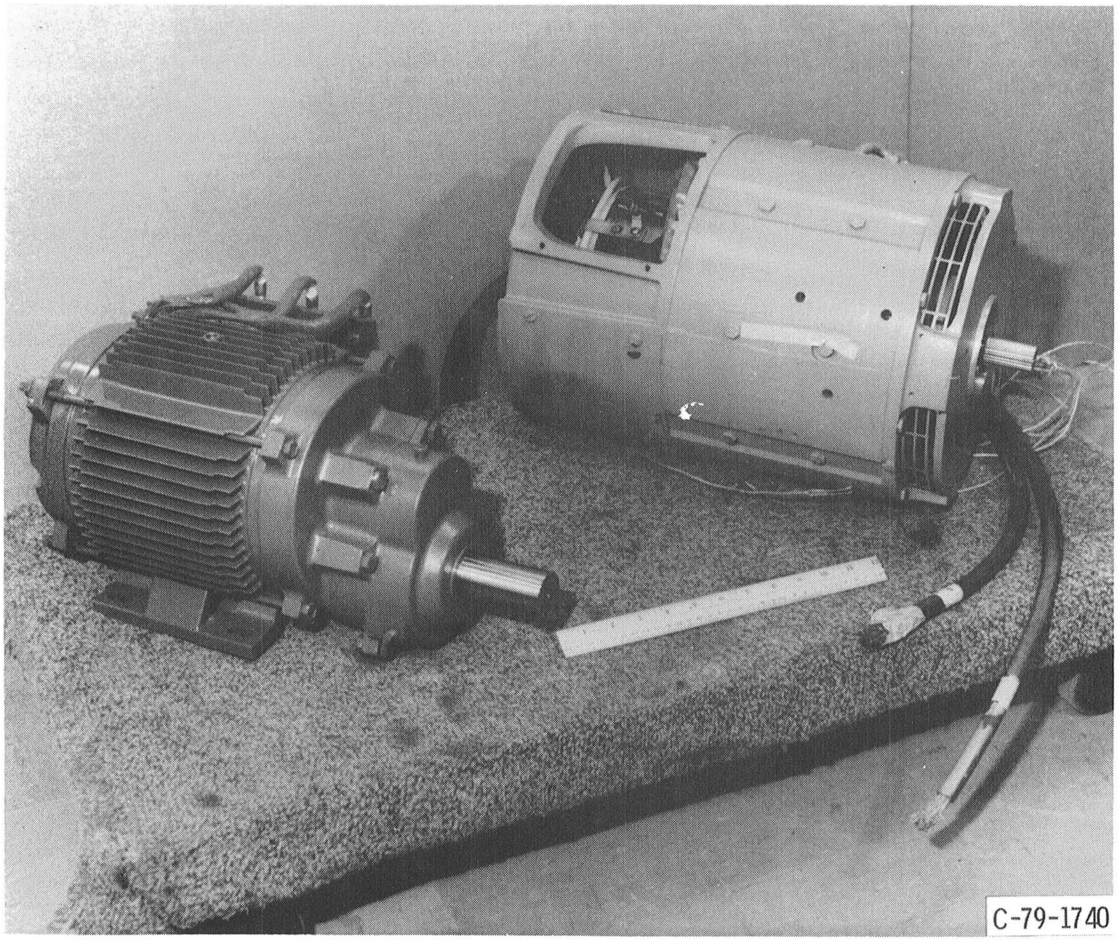

Figure 9. - Comparison - ac induction and dc brush-commutated motors.

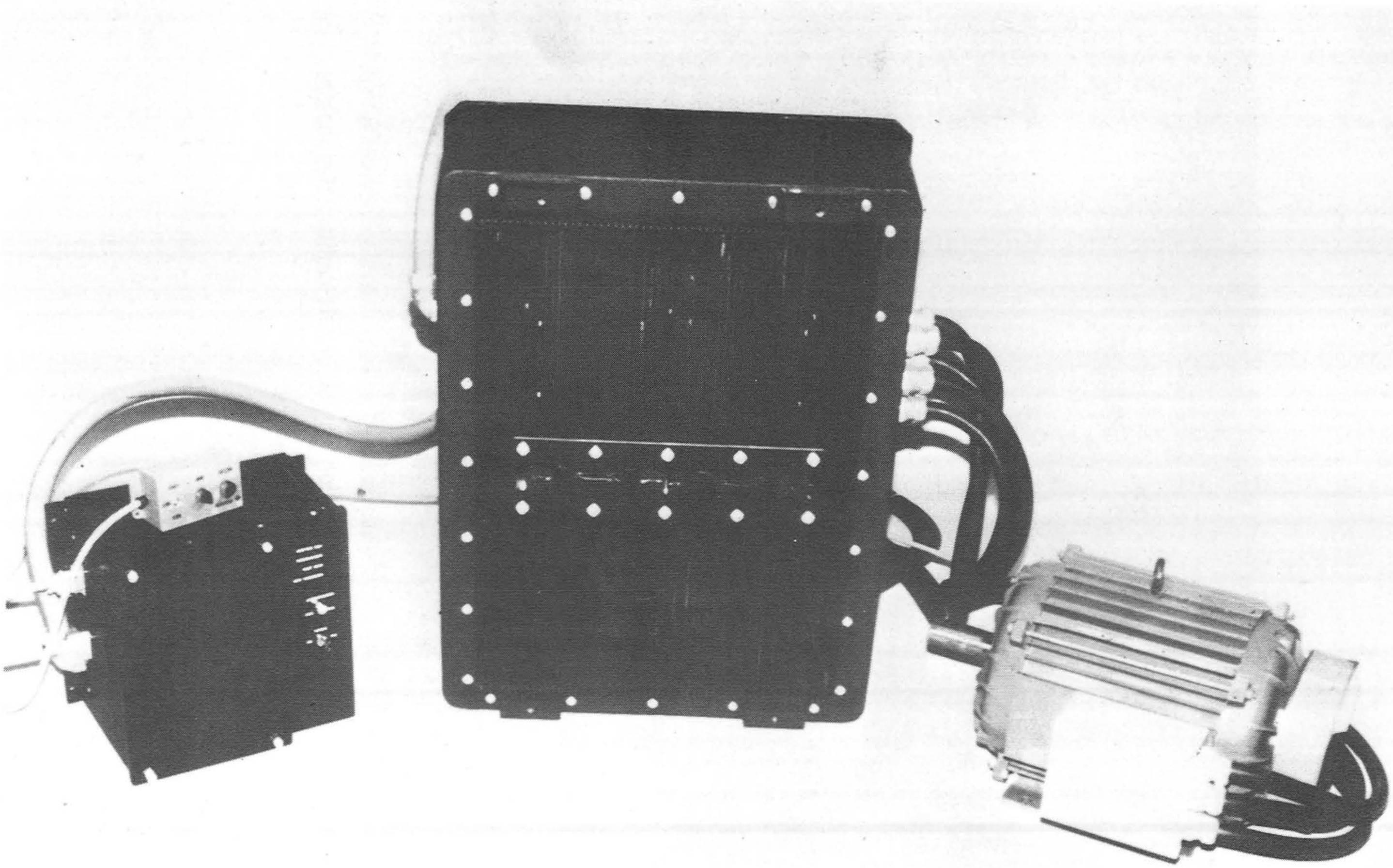

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Figure 10. - Gould induction motor/controller system.

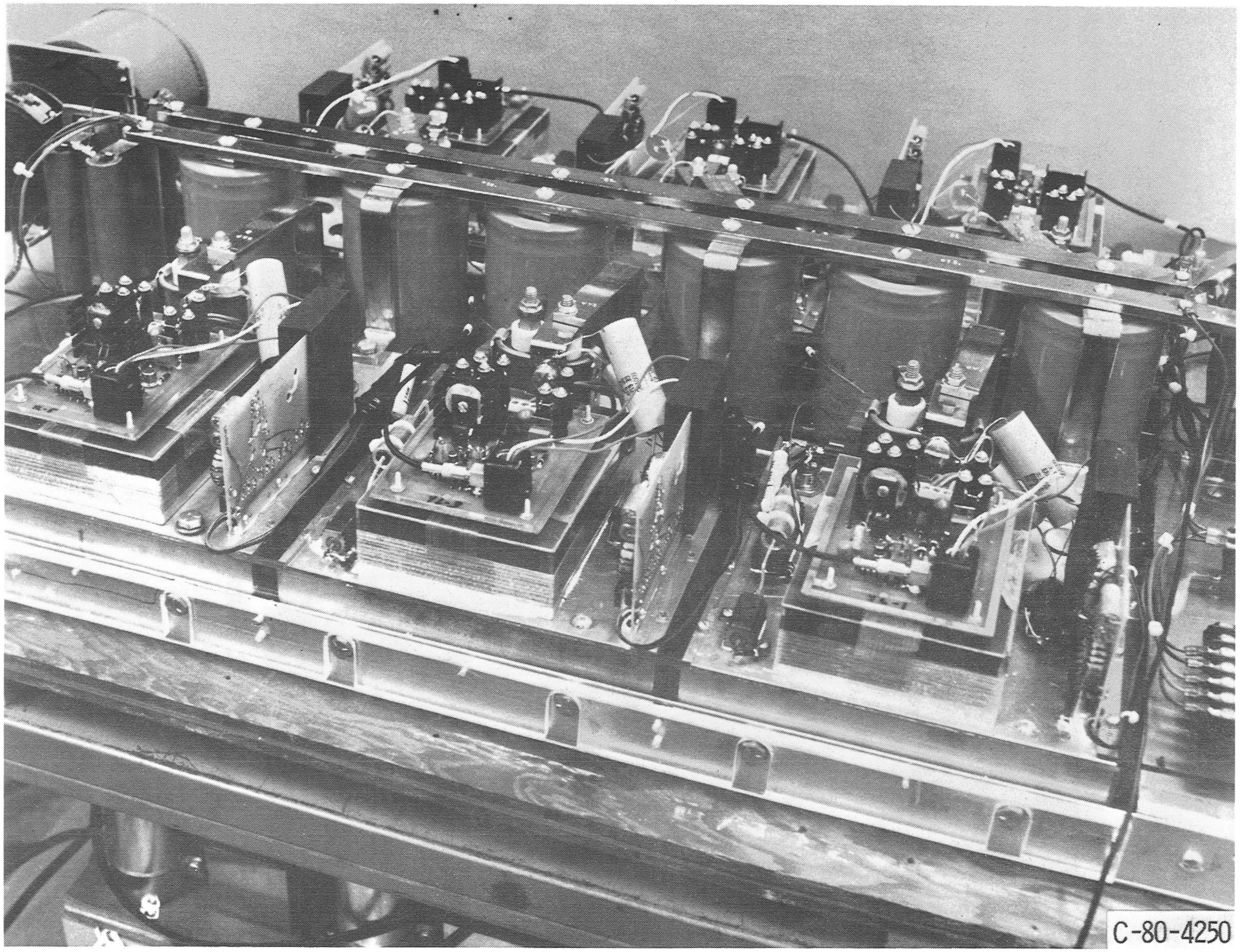

Figure 11. - G. E. inverter for induction motor-internal view.

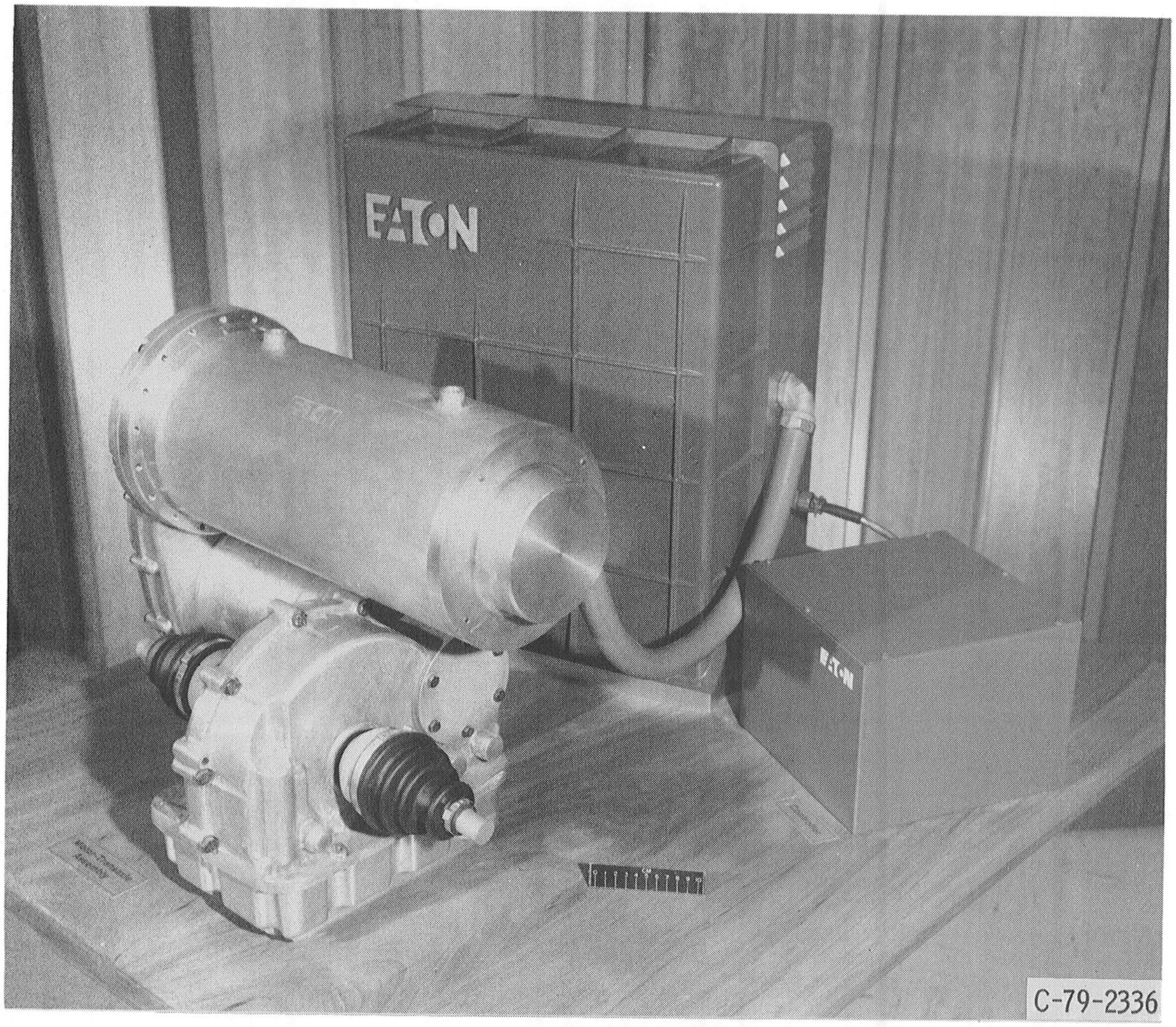

Figure 12. - Eaton ac induction motor propulsion system.

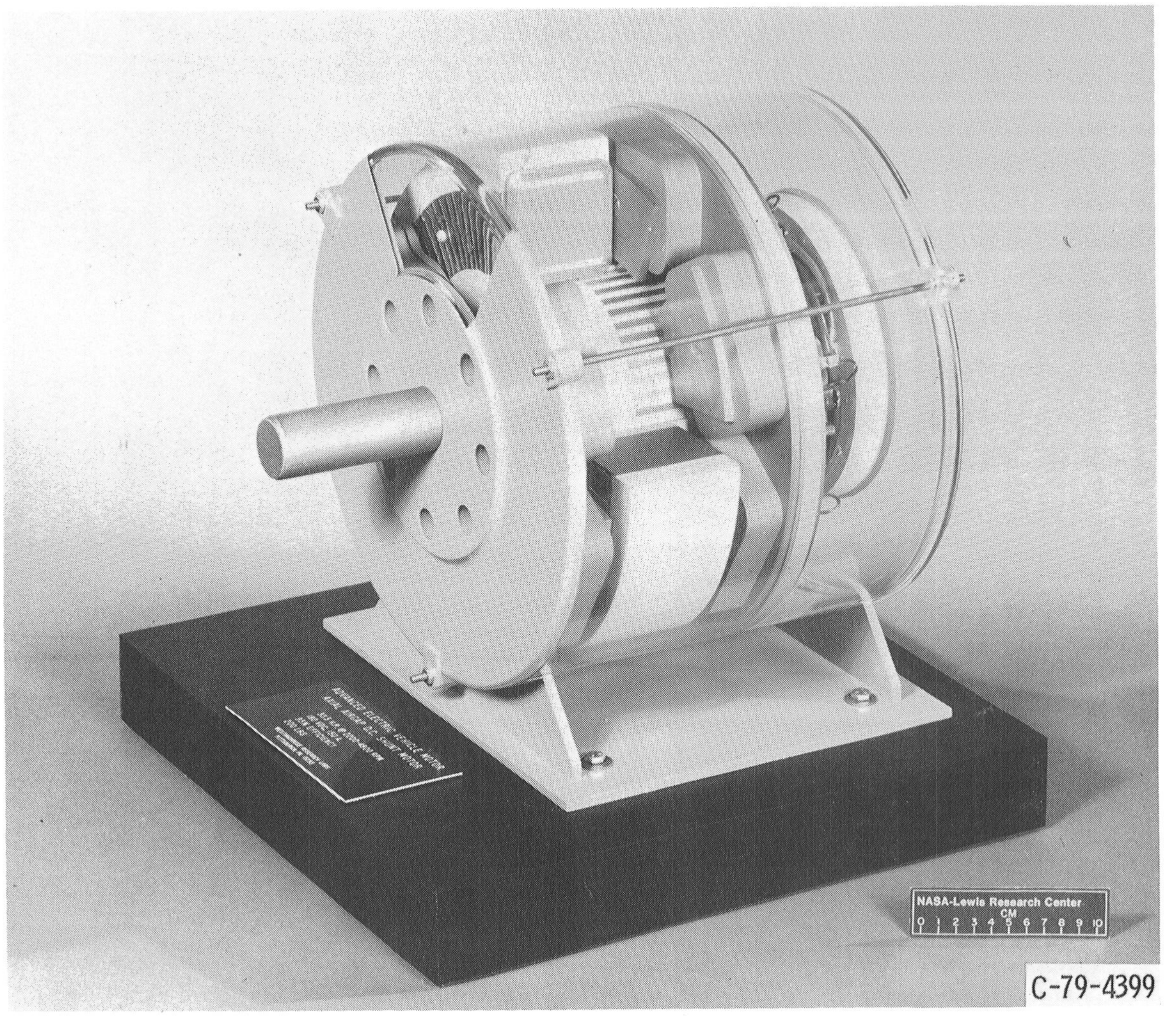

Figure 13. - Westinghouse brush-commutated disk motor.

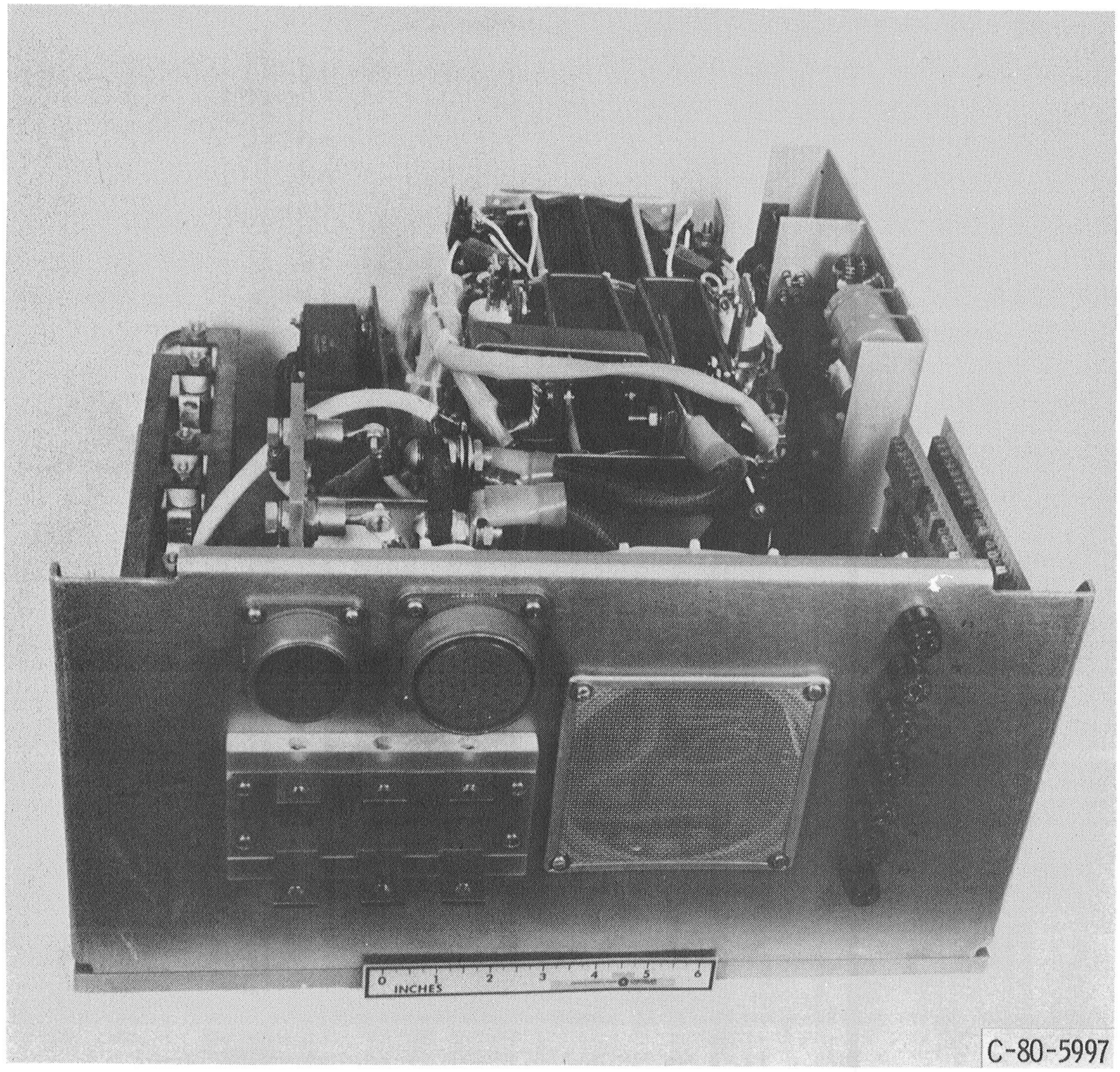

Figure 14. - Chrysler controller for dc brush-commutated motors.

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16. Abstract

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