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New Propulsion Components for Electric Vehicles

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National Aeronautics and Space Administration
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Work performed for
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NEW PROPULSION COMPONENTS FOR ELECTRIC VEHICLES

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ABSTRACT

The goal of DOE's Electric and Hybrid Vehicle Program is to advance technologies for electric and hybrid vehicles in order to enhance their potential as transportation options of national significance. 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. This paper describes improved and advanced component technology developed under the NASA-managed propulsion portion of the DOE program. This includes electronically commutated permanent magnet motors of both drum and disk configurations, an unconventional brush-commutated motor, ac induction motors, various controllers, transmissions and complete systems. 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 advance technologies for electric and hybrid vehicles in order to enhance their potential as transportation options of national significance. 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 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. The major reasons for this are the high cost of components to the vehicle manufacturer and very low production volume, both of the vehicles and the electric propulsion components. 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 the DOE-sponsored development of new propulsion components and systems for electric vehicles, multiple parallel efforts were pursued. As development efforts progress, the number of supported approaches should be narrowed to those with the greatest potential for low cost and attractive performance.

This paper (an update and expansion of a previous paper, "Electric Vehicle Motors and Controllers" DOE/NASA/51044-18, NASA TM-81760) describes propulsion system component technology developed as part of the DOE Electric and Hybrid Vehicle Program. Included are electronically commutated permanent magnet motors of both drum and disk configurations, ac induction motors and controllers, a dc brush-commutated motor, a dc controller, ratio changing transmissions, and complete ac and dc propulsion systems.

As the electric vehicle market develops, new, low-cost propulsion components 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

Goals

The primary goal of the DOE/NASA electric vehicle propulsion component technology developments, relative to what is commercially practical today, is a significant reduction in cost, while maintaining or improving performance. Implied by this goal is efficiency improvement and weight reduction. Propulsion components are interdependent among themselves as well as with the total vehicle. Lightweight, efficient propulsion systems for example will result in lower structural requirements on the vehicle and, thereby, lower battery requirements and vehicle costs.

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 design rated power of an electric vehicle propulsion system. Therefore in these technology developments, we instead specified that the components be designed to meet the duty cycle shown in Fig. 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 propulsion 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 Fig. 1. Cooling was to be by means of natural convection or forced air. Liquid or other cooling mediums were allowed if it could be shown that the overall vehicle would benefit. Components developed to provide this performance will verify the approach at a practical power level and should be scalable to other power levels as required.

COMPONENT DEVELOPMENTS

Electronically Commutated Motors

The essential feature of electronic commutation is an array of electronic switches (inverter) controlled by signals derived from a shaft position sensor which is directly coupled to the shaft of a synchronous machine, such as a permanent magnet (PM) motor. In some designs the voltage generated by the machine once it is rotating is used for control. The switches accomplish the sequencing of power to or from the synchronous machine, and their operation is analogous to brush commutation in a conventional dc motor. A dc-dc converter (chopper) can be used to control the voltage supplied to the inverter, thereby permitting the speed to be controlled as in a conventional dc motor. Transistors or thyristors can be used as switching devices in the chopper and inverter. The inverter electronics for all of the electronically commutated motors will be similar.

A brief summary of the five electronically commutated permanent magnet motors which have been brought to the full-rated test hardware stage is given in Table I. Three are of a drum (radial air gap) configuration and two of a disk (axial air gap) configuration. Each has potential for low cost in volume production (100 000 units per year) because of simplicity of construction and/or lightweight (minimized use of raw materials). Their efficiencies are generally higher than those of commercial motors used in present day electric vehicles. Permanent magnet, electronically commutated drum motor technology has been demonstrated in other applications such as aerospace, therefore, these three motors are considered mid-term developments (ready for volume use in the late 1980's). The design approaches for the disk motors are more advanced and therefore these motors would be for the far-term (volume use in the 1990's). The weights and speeds shown in Table I should be taken only as preliminarily representative of particular types of motors because the designs of these motors in their present states of development reflect each contractor's interpretation of the performance requirements and the needed margins for overload, reliability, and safety.

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. Also, as a comparison, present commercially available d.c. motors alone weigh from 60 to 90 kg in the power range of interest.

Drum Motors A cutaway model of a representative permanent magnet drum motor for electronic commutation is shown in Fig. 2. Compared to the conventional brush type d.c. 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 armature 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. Also, there are negligible losses in the permanent magnet rotor, eliminating the need for specific rotor cooling provisions. These features lead to a generally higher power rating and/or efficiency for a given temperature rise and machine size.

As part of the Electric and Hybrid Vehicle Program, AiResearch Manufacturing Company and Virginia Polytechnic Institute were contracted to develop electronically commutated drum motors. Inland Motor was a subcontractor to VPI. Both contractors designed their motors to use samarium-cobalt ($Sm\,Co_5$) permanent magnets. To provide real hardware comparative data, VPI/Inland also designed, built, and tested a motor which used low cost, but low energy, ferrite magnets.

The two contractors used different approaches. The AiResearch approach is a small, forced air cooled, high-speed (26 000 rpm) motor, power transistors in the chopper and low-cost industrial thyristors in the inverter. The 26 000 rpm speed of the motor results in its very low, 16 kg 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. Figures 2 and 3 are photographs of the AiResearch motor and electronics, respectively. The electronics appear large in the present package configuration, but when packaged for use in a production vehicle, they would be about two thirds the size shown in Fig. 3 and weigh about 45 kg if air cooled.

VPI together with their subcontractor, Inland, used a medium speed (9000 rpm), larger size, convection cooled, design approach for both the samarium-cobalt and ferrite motors. These two motors are shown in Fig. 4. The smaller samarium-cobalt motor weighs approximately 27 kg while the larger ferrite motor weighs approximately 58 kg. VPI used high power transistors for both the chopper and inverter. At present, transistors are considerably more expensive than equivalently rated thyristors, but will result in lower electronic losses. The electronics for the VPI/Inland motors is shown in Fig. 5. It is packaged differently than the AiResearch version, but in its final configuration it would also be in the 40 to 50 kg weight range.

Both contractors, AiResearch and VPI, have tested their motors and have measured maximum combined motor/controller efficiencies of approximately 90 percent, comparable to the best conventional d.c. motor systems. The developments completed have demonstrated the technical feasibility and benefits of this type of motor. The continuing world-wide research in permanent magnets along with the declining cost of power electronics will enhance the commercial appeal of these motors.

Electronically commutated drum type motors for electric vehicles are described in greater detail in Refs. 1 to 3.

Disk Motors Unlike the drum motors, the two developmental disk motors are significantly different from each other. A cutaway model of the disk motor concept of the AiResearch Manufacturing Company is shown in Fig. 6. It is a homopolar design in which the rotor consists of a single, central, donut-shaped samarium-cobalt permanent magnet and two multi-fingered pole pieces. An ironless stationary armature is located between the tips of the pole pieces. The maximum design speed of this motor is 14 000 rpm and it 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 would be similar to that for the drum motors. The first model demonstrated mechanical integrity and electromagnetic feasibility, but windage and eddy current losses were excessive. In the revised model, interpolar space was filled and losses substantially reduced. The total losses were still somewhat higher and the efficiency lower than expected. The simplicity of this motor, however, promises very low cost.

The General Electric disk motor concept uses multiple permanent magnets in an aluminum rotor. Stationary armature windings are located axially on each side of the rotor. A new permanent magnet material, managanese-aluminum cobalt (Mn-Al-C), was intended to be used in this motor. However, this material was not available in sufficient quantity. Furthermore, in a study by the University of Dayton (4), it was found that Mn-Al-C magnets have degraded performance at temperatures above 100° to 150° C and therefore are undesirable for use in vehicle propulsion motors. The first full rated model, shown in Fig. 7, designed with samarium-cobalt magnets and a maximum speed of 15 000 rpm, was built and tested. Although the GE motor is more efficient than the AiResearch motor, it is more complex, having multiple magnets and two armature windings.

References 5 to 7 provide further details on these disk motor developments.

Induction Motors and Controllers

Similar to the permanent magnet motors, the a.c. squirrel cage induction motor is of simpler design and construction than the conventional dc motor. The rotor is solid, it has no brushes or commutator, and it can operate at much higher speeds. These features provide attractive weight, size, and cost advantages.

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

It should be noted that these smaller, lighter motors, both permanent magnet and induction types, do not have the mass to safely absorb thermal overloads to the degree that the larger, heavier dc motors do. Therefore, the controls for the lighter motors must incorporate means to restrict overloads to safe limits.

The technology of induction motors is well-established. Therefore, the technology development under the Electric and Hybrid Vehicle Program has been directed more toward the power and control electronics necessary to operate an induction motor in a battery powered vehicle. New induction motors as well as modified conventional motors have also been developed. A brief summary of the induction motors and controllers which have been brought to the full-rated test hardware stage is given in Table II.

The latest Gould induction motor controller inverter test hardware is shown in Fig. 8. This inverter uses thyristors as power switching elements and 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 current and voltage capability must be obtained with two or three paralleled transistors, each costing between $40 and $80. Single transistors with adequate rating cost $300 to $400, today. This controller exceeds the requirements of Fig. 1 in that it is intended to provide performance comparable to that of a small diesel automobile. Also, its circuitry serves the dual functions of motor control and on-board charger for the traction batteries.

A closeup view of the General Electric inverter for an induction motor controller is shown in Fig. 9. This 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 undoubtedly benefit from the increasing availability of these lower cost transistors.

The design and operating principles of current control demonstrated in the General Electric induction motor controller are being applied to the development of technology for a complete advanced integrated a.c. powertrain recently started by the Ford Motor Company and GE as part of the Electric and Hybrid Vehicle Program. This powertrain will include an oil-cooled motor integrally housed in a multi-ratio automatic transaxle, and an inverter which will use developmental power transistors which have the potential for low cost in volume production.

A third induction motor/controller development is that being pursued by the Eaton Corporation as part of a complete propulsion system. The Eaton system consists of an oil-cooled motor, an inverter which uses commercially available power transistors, microprocessor-based logic and control, and an automatically shifted two-speed transaxle. The most recent motor and transaxle, mounted in a test bed vehicle, is shown in Fig. 10. The inverter for this system is shown in Fig. 11. Results of laboratory tests on an earlier complete Eaton a.c. system indicate a maximum system efficiency of approximately 82 percent (battery terminals to axle shaft).

References 8 to 10 provide further details on the induction motor and controller developments.

Brush-Commutated Motor and Controller

Electric vehicles being built today, and those normally 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 Propulsion Development Project included two dc components and a dc system. These are a wound field, unconventional disk motor; a high efficiency, low noise controller; and a dc system complete with an automatic transaxle. These are summarized in Table III.

The engineering model of the brush-commutated dc motor concept investigated by Westinghouse is shown in Fig. 12. It is a version of the classic Gramme ring configuration which, though not new, presents the possibility for low cost manufacture. The rotating toroidal armature should be adaptable to automated machine winding. In the Electric and Hybrid Vehicle Program this motor is 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 eventually be possible to eliminate the separate commutator in this motor by spot hardening and face machining sections of the armature winding. Commutation could then be achieved by running the brushes directly on the winding. Tests of this full rated model indicated excessive losses which resulted in the low efficiency shown in Table III. Until the cause and cure for these losses are understood, further development is not warranted.

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. Both thyristors and transistors can be used as the switch. Controller switching frequency is limited by available semiconductors to usually around 500 Hz, but in some cases as high as 4000 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 controller for a shunt wound d.c. motor. An early model of this controller is shown in Fig. 13 with its cover removed. It uses 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, - about 5 amperes. An uprated version of this controller is nearing completion. In it, the chopping frequency has been raised to 20 kHz and battery charging capability is being added. Reference 11 provides further detail on this controller development.

The dc system, being developed by Eaton, uses a conventional shunt motor and a novel chopper control. The controller has one transistor-based 0 to 5000 Hz variable frequency chopper which controls armature voltage at low speeds and then is switched to control field voltage at higher speeds. This dual role for the chopper should result in lower cost when compared to the more conventional approach which uses two choppers.

Ratio Changing Transmissions

Although an electric propulsion system can be designed to furnish needed low speed torque and high speed power with a single, fixed speed ratio between the motor and vehicle wheels, a ratio changing transmission is sometimes advantageous. Two or more speed ratios will allow efficient use of a lightweight motor.

As mentioned previously, the ac induction motor propulsion system being developed by Eaton includes an automatically shifted two-speed transaxle. This transaxle, shown in Fig. 14, is a near-term development and could, in fact, be used with almost any motor. In addition to its function of transmitting mechanical power from the motor to the drive wheels, it also serves as a motor mounting (as indicated in fig. 10) and provides a source of cooling oil for the motor. The transaxle consists of a Hy-Vo chain drive reduction, a planetary gear and clutch assembly, final drive gearset and a differential assembly. The chain drive reduction was selected for high efficiency, low noise, high power-to-weight ratio and low cost. The gearset and clutch components were adapted from current automatic transmissions. Further details on this transmission are in Ref. 10. A three-speed version of this transaxle is presently under development as part of the Eaton dc propulsion system.

In addition to the automatically shifted transmissions which are part of the Eaton systems, development of an advanced continuously variable transmission (CVT) for the far-term has been pursued by Kumm Industries. This CVT work is aimed to provide the constantly changing gear ratio required to couple the varying speed of an energy storage flywheel to the changing speed requirements of the vehicle's driving wheels. The variable speed element of this transmission consists of two variable diameter pulleys coupled by a flat belt. Unlike the well-known V-belt variable pitch pulley, which changes effective diameter by changing the width of the pulley opening, the flat-belt pulley changes the diameter of the surface which supports the flat belt. This surface consists of a number of drive elements which are positioned radially by oppositely spiralled grooves in the two-ply side-plates as shown in Fig. 15. Thus, the speed ratio of the two pulleys connected by the flat belt may be changed by varying the radial position of the belt in one pulley with respect to the other. This belt drive, when used in combination with suitable gearing, will provide an output speed range of zero to 5000 rpm with a flywheel speed range of 14 000 to 28 000 rpm. It could also be used to match the speed of a motor at its most efficient points to the varying speed and power requirements of the vehicle. More details on this CVT concept are contained in Ref. 12.

CONCLUDING REMARKS

Electric vehicle propulsion system component technology developments are aimed at reducing cost and improving performance. 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. 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.

Both near-term discrete ratio changing transmissions and a far-term continuously variable transmission are under development. These transmissions will allow increased flexibility in the design of electric vehicle propulsion systems.

Results of technology development on propulsion components to date have shown promise of significantly reduced weight, 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, but market forces other than the electric vehicle are working to reduce the cost of power electronics. The ultimate relative advantages of induction motor, permanent magnet motor, and brush-type motor propulsion systems remain to be determined.

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TABLE I. - DEVELOPMENTAL ELECTRONICALLY COMMUTATED MOTORS

Contractor	Construction and magnet	Maximum, rpm	Test hardware weight,[a] kg	Test hardware efficiency at 11 kW, percent[c]
AiResearch	PM Drum, SmCo[b]	26 000	16	[d]84 [e]87
VPI/Inland	PM Drum, SmCo	8 700	27	[d]87
VPI/Inland	PM, Drum, Ferrite	8 800	58	[d]84
AiResearch	PM Disk, SmCo	14 000	23	[e]80
GE	PM Disk, SmCo	11 000	59	[d]91 [e]95

[a]Without electronics.
[b]Requires external fan, approximately 2.7 kg additional.
[c]At best speed.
[d]Motor and electronics together.
[e]Motor only.

TABLE II. – DEVELOPMENTAL INDUCTION MOTORS AND CONTROLLERS

Contractor	Component	Motor maximum, rpm	Test hardware weight, kg	Test hardware efficiency at 11 kW, percent
Gould	3-ϕ inverter (thyristor)		47	90
	Motor (modified) (production)	8 000	Not applicable, test load only	Not applicable, test load only
Ge	3-ϕ inverter (transistor)[a]		59	92
	Motor (special)	15 000	46	[a]89
Eaton	3-ϕ inverter (transistor)[b]		[c]60 [d,e]43	[c]94 [d]96
	Motor (special)	[c]9 000 [a]12 500	[c]67 [d]55	[c]95 [d]92

[a]Motor includes integral reduction gearing to provide 5000 rpm output speed.
[b]Motor is oil cooled.
[c]Phase I design.
[d]Phase II design.
[e]With integral battery charger and higher power.

TABLE III. – DEVELOPMENTAL DC MOTORS AND CONTROLLERS

Contractor	Component	Test hardware weight, kg	Test hardware efficiency at 11 kW, percent
Westinghouse	Motor, disk Gramme ring 7200 rpm (max)	47	82
Chrysler	Controller, armature, and field choppers, transistor	36	98
Eaton	Controller, armature and field choppers	18	98
	Motor, dc shunt	82	93

TABLE IV. - RATIO CHANGING TRANSMISSIONS

Contractor	Type	Test hardware weight, kg	Test hardware efficiency at 11 kW, percent
Eaton	Automatic 2-speed transaxle	[b]48 [c]35	89 to 95
	Automatic 3-speed transaxle	36	96
Kumm	CVT, infinite ratio change[a]	---	[d]90 to 94

[a]Can provide zero output speed with finite input speed.
[b]Phase I.
[c]Phase II.
[d]Predicted.

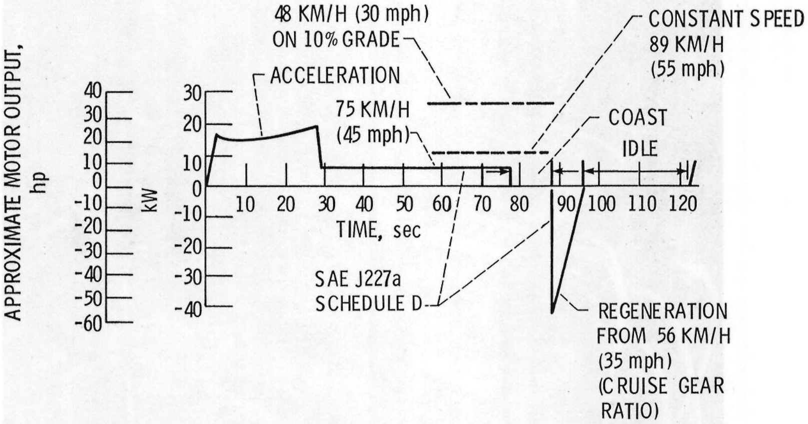

Figure 1. - Typical motor duty cycle for urban electric passenger vehicle.

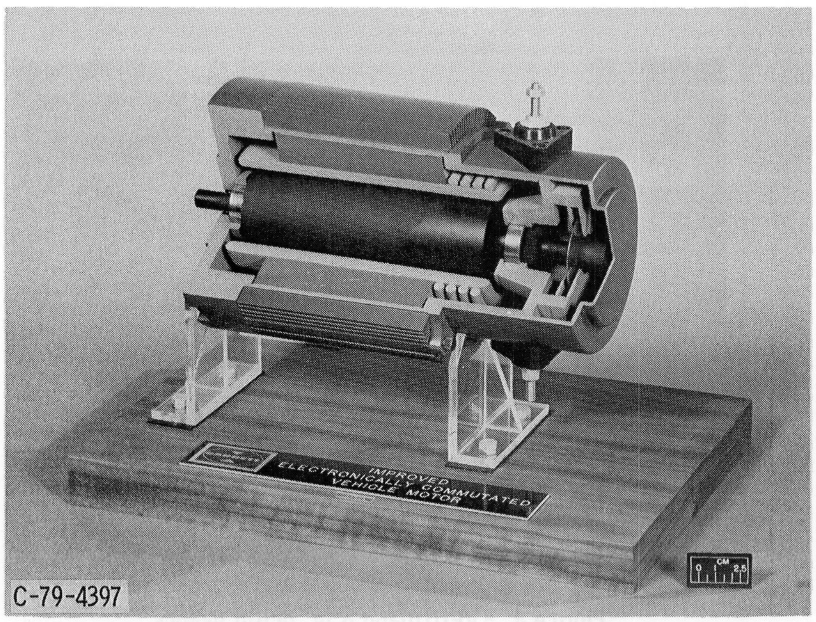

Figure 2. - Representative electronically commutated motor (without electronics).

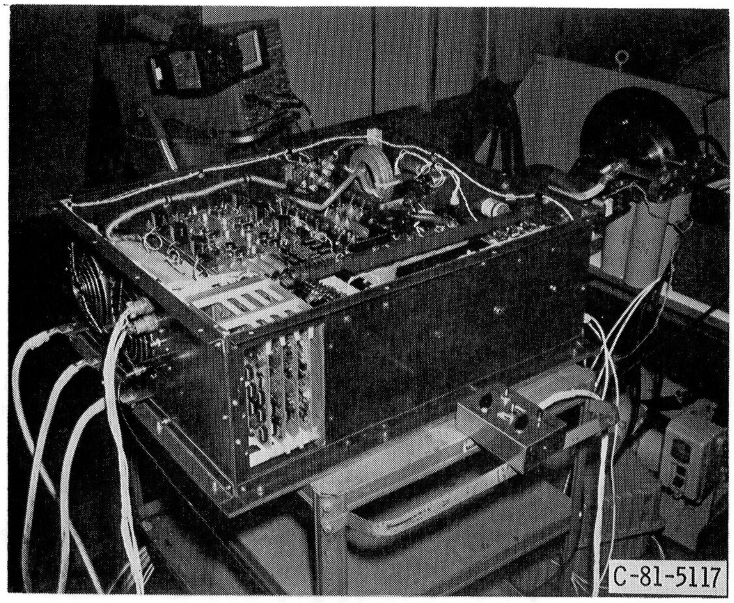

Figure 3. - Electronics for AiResearch electronically commutated motor.

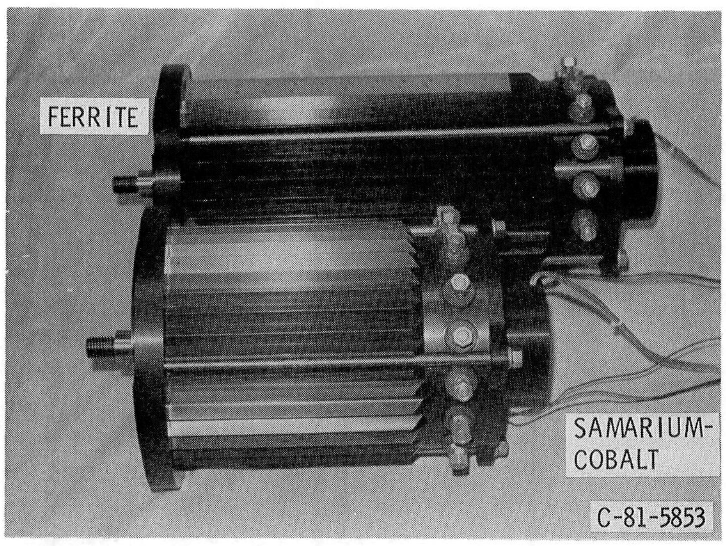

Figure 4. - VPI/Inland p.m. drum motors.

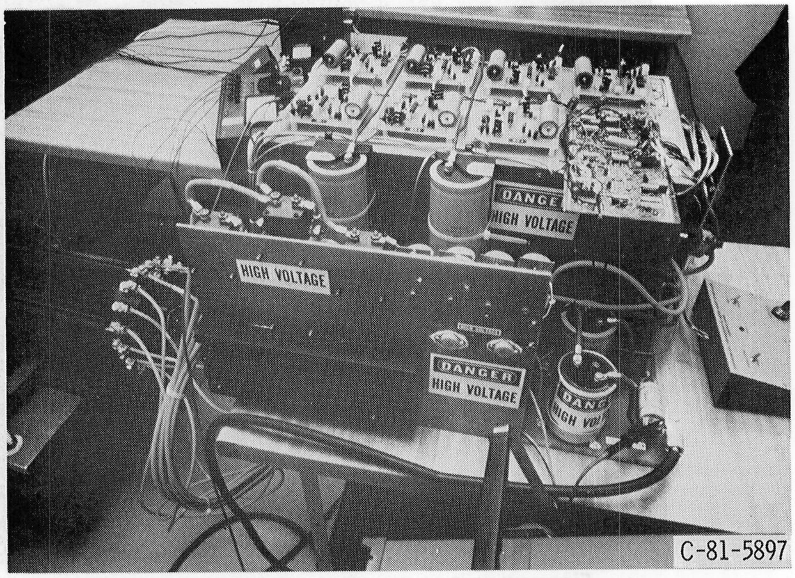

Figure 5. - Breadboard electronics for VPI/Inland electronically commutated motors.

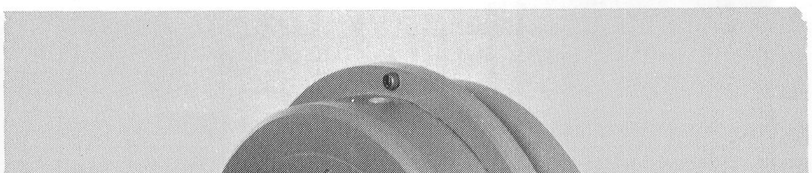

Figure 6. - AiResearch disk motor (without electronics).

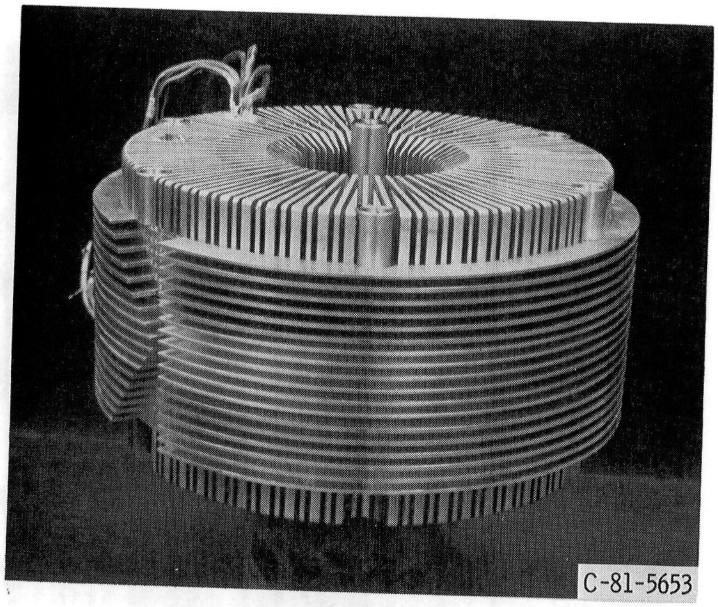

Figure 7. - Functional model GE p.m. disk motor.

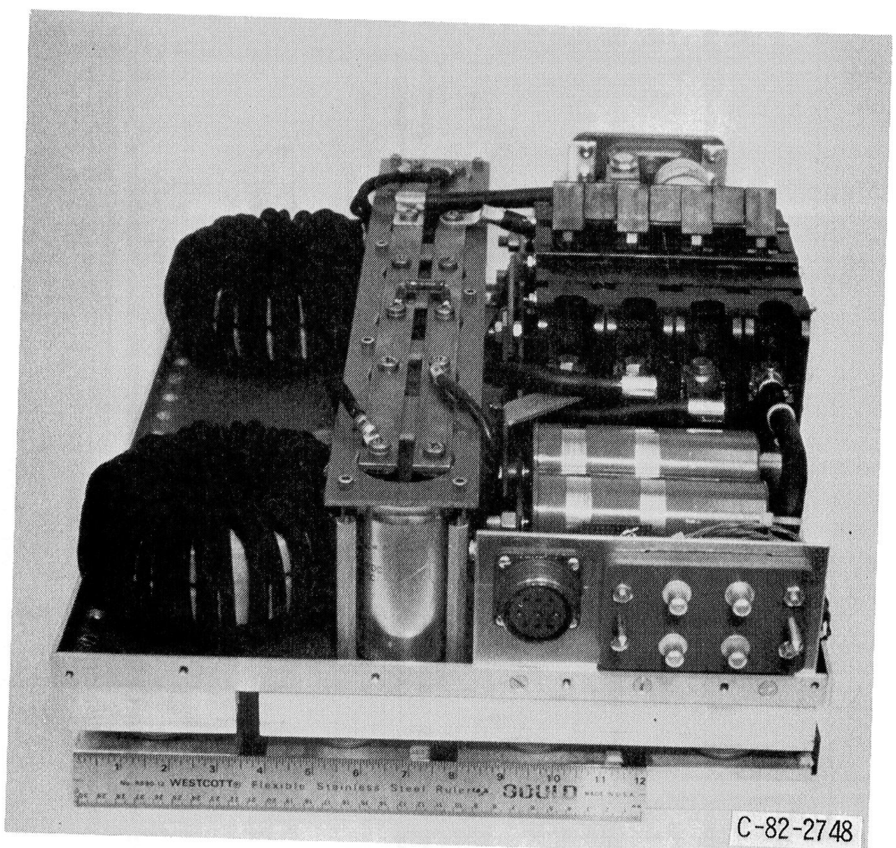

Figure 8. - Inverter for Gould uprated ac induction motor controller.

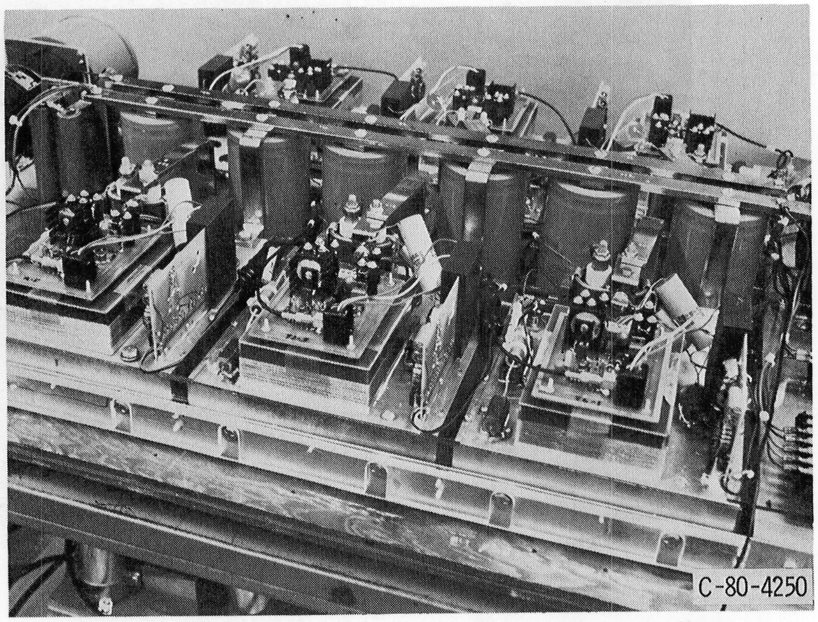

Figure 9. - GE inverter for induction motor controller.

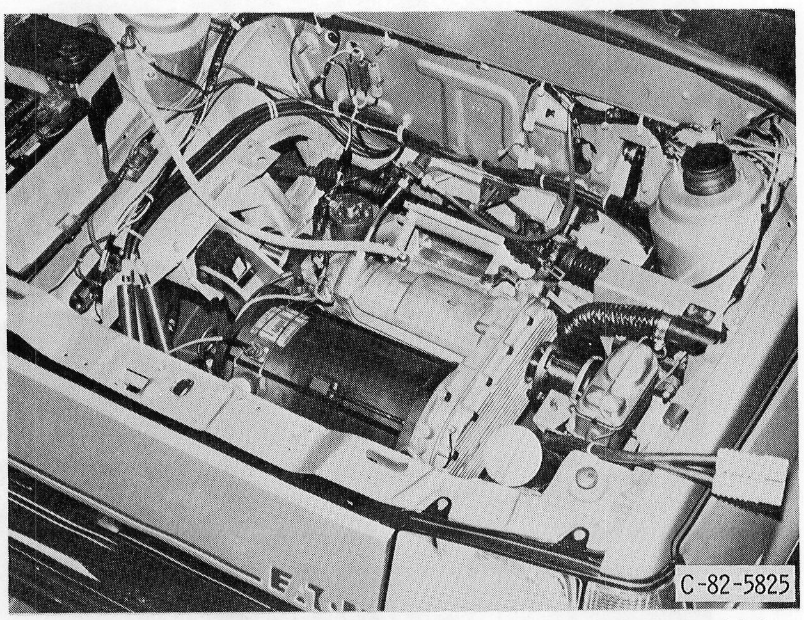

Figure 10. - Eaton ac propulsion motor and transaxle in test vehicle.

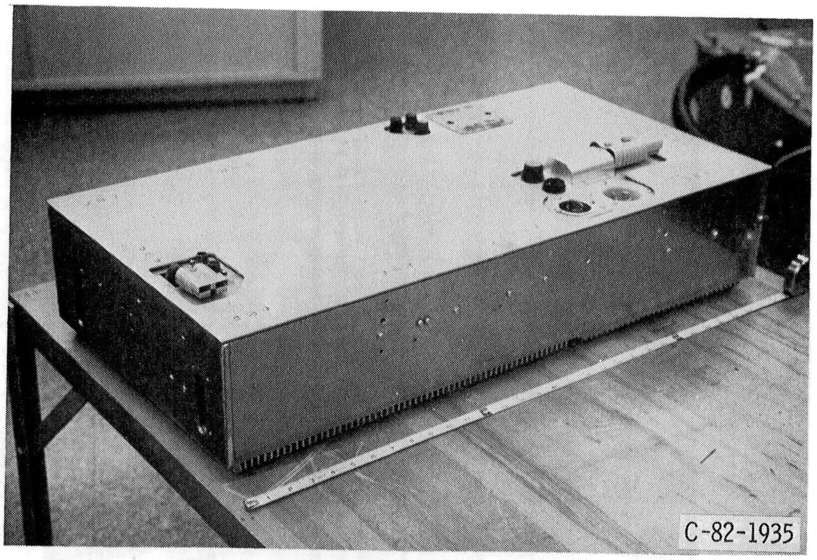

Figure 11. - Inverter for Eaton ac propulsion system.

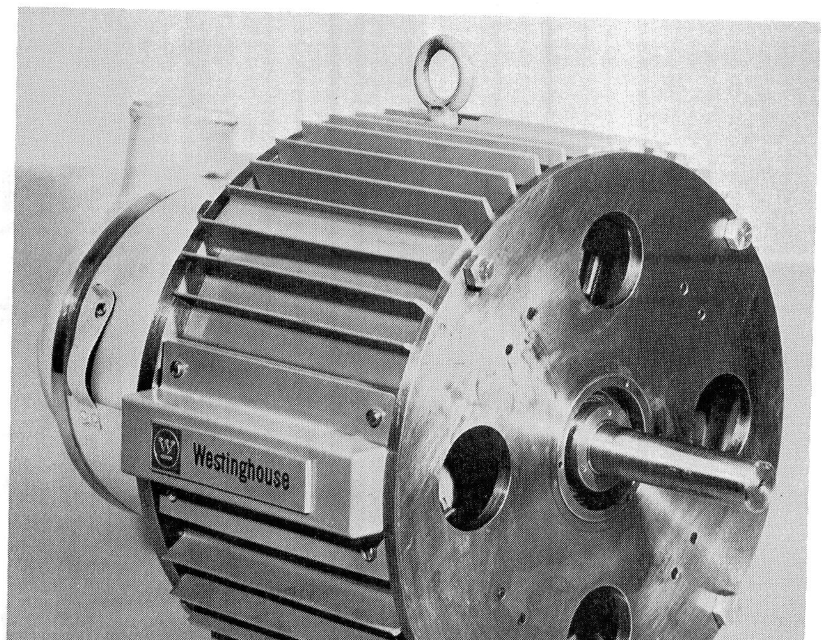

Figure 12. - Engineering model Westinghouse advanced brush-commutated dc disk motor.

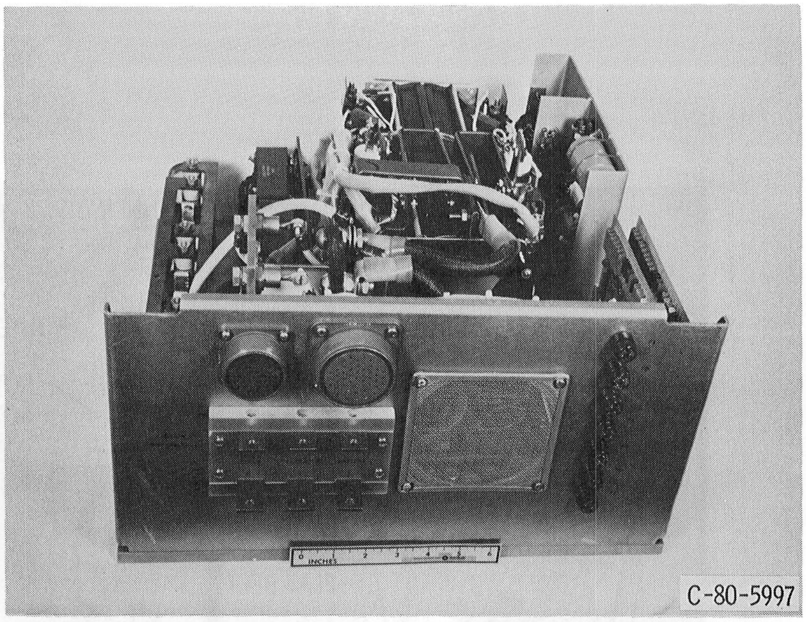

Figure 13. - Chrysler controller for dc brush - commutated motors.

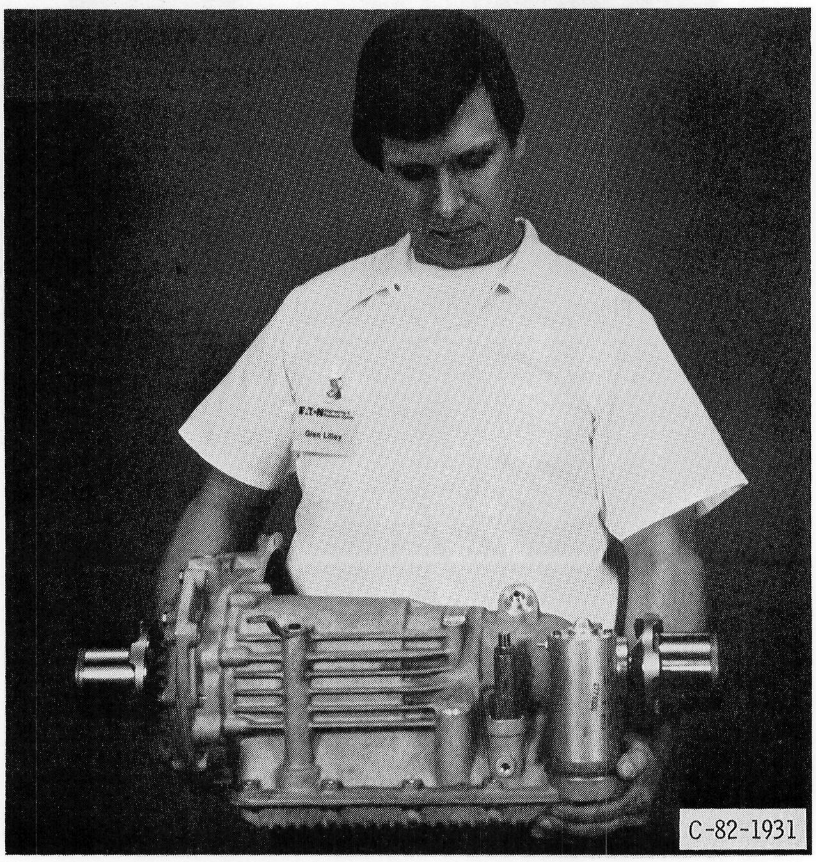

Figure 14. - Eaton phase II automatic transaxle.

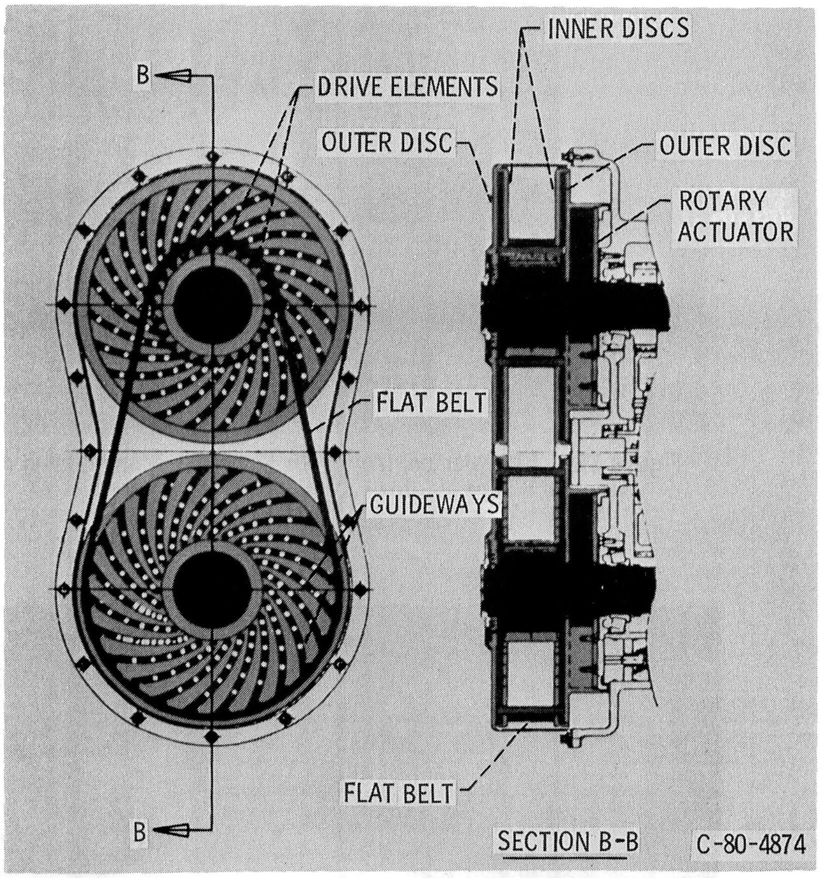

Figure 15. - Variable ratio pulleys for Kumm flat belt CVT.

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15. Supplementary Notes

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16. Abstract

The goal of DOE's Electric and Hybrid Vehicle Program is to advance technologies for electric and hybrid vehicles in order to enhance their potential as transportation options of national significance. 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. This paper describes improved and advanced component technology developed under the NASA-managed propulsion portion of the DOE program. This includes electronically comutated permanent magnet motors of both drum and disk configurations, an unconventional brush-commutated motor, ac induction motors, various controllers, transmissions and complete systems. One or more of these new approaches to electric vehicle propulsion may eventually displace presently used controllers and brush commutated dc motors.

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