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ABSTRACT

A motor development program to explore the feasibility of electronically commutated dc motors (also known as brushless) for electric cars is described. Two different design concepts and a number of design variations based on these concepts are discussed. One design concept is based on a permanent magnet, medium-speed, machine rated at 7000-9000 rpm and powered via a transistor-inverter power conditioner. The other concept is based on a permanent magnet, high-speed, machine rated at 22,000-26,000 rpm and powered via a thyristor-inverter power conditioner. Test results are presented for a medium-speed motor and for a high-speed motor each of which have been fabricated using samarium-cobalt permanent magnet material.

ELECTRIC CARS AS PRESENTLY MANUFACTURED use brush type, wound field dc traction motors for propulsion. The choice is a practical one based on the commercial availability of motors having the horsepower required and the capability of operating over a wide speed range. The application of power electronics makes possible the alternative of using a smaller, lighter, less costly ac machine. The system comprising a synchronous ac machine operated from a dc source by using electronic switching is commonly referred to as an electronically commutated dc motor or a brushless dc motor.

As part of the DOE Electric and Hybrid Vehicle Program, a motor development project is being carried out to explore in detail the feasibility of an electronically commutated dc motor attractive in performance and price to electric vehicle manufacturers. As part of this project, 1) the Garrett-AiResearch Company (under DOE/NASA Contract DEN3-64) and 2) Virginia Polytechnic Institute and State University in conjunction with Inland Motor Company (under DOE/NASA Contract DEN3-65) have each been developing electronically commutated motors for electric vehicle use. Each contractor has completed testing of a motor designed to use samarium-cobalt permanent magnet material. Based on these test results, each contractor is presently fabricating a refined version of its samarium-cobalt design suitable for installation in an electric vehicle. In addition, both VPI and Garrett have completed studies to identify magnetic materials which may be used in place of samarium-cobalt. As a result of these studies, ferrite materials have been identified as presently available magnetic materials suitable for application in these motors. A medium-speed version of a ferrite magnet motor is being fabricated and will be tested for performance. A preliminary design of a high-speed ferrite motor has been completed.

PROGRAM GUIDELINES

The following general guidelines were adopted for the motor designs: 1) the performance of a vehicle using the electronically commutated (e.c.) motor should match that of the best currently available electric vehicles, 2) the efficiency should exceed the efficiency of presently available dc motors and controllers, 3) the projected manufacturing cost in production quantities should make the e.c. motors competitive with dc systems, and 4) the motor, including electronics, must be compatible with present day electric vehicles and components.

Based on these guidelines, the motors were designed to supply the propulsion needed for a 1360 kg (3,000-pound) vehicle. This included the following requirements: 1) operation over the Schedule D driving cycle of the SAE J227a test standards (1),* 2) acceleration from zero to 72.5 km/h (45 mph) in 28 seconds, 3) continuous operation at 89 km/h (55 mph) for two hours, and 4) the ability to climb a 10% grade while maintaining 48 km/h (30 mph). In addition, two important assumptions were made: first, the input voltage would be 120 volts with 0.05 ohms internal resistance, approximating a lead-acid battery pack; and, second, that 100,000 units per year would constitute a viable production quantity to be used in cost projections. Achievement of the performance goals requires a motor rated at 11 kW (15 hp) continuous and 26 kW (35 hp) peak (2).

GENERAL DESCRIPTION OF MOTORS

The essential features of the electronically commutated motor are shown in figure 1.(3) An inverter is gated by a shaft position sensor

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* Numbers in parentheses designate References at end of paper.

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 converter (chopper) controls the voltage or current to the motor.

Two different design concepts have resulted, differing in the rated speed of the motor and in the approach to the design of the power conditioner electronics. A medium-speed machine rated in the range from 7,000 rpm to 9,000 rpm and powered via a transistor inverter is the system developed by Virginia Polytechnic Institute and State University in conjunction with Inland Motor Company. This machine is designed and rated for natural convective cooling in a moving vehicle. A high-speed machine rated for operation between 22,000 rpm and 26,000 rpm and using thyristors (also known as silicon-controlled-rectifiers, or SCR's) for the inverter switches is the design concept for the system designed by Garrett-AiResearch. This machine is designed for forced air cooling by an externally mounted fan.

The design variations to be discussed in this paper, as well as some important characteristics, are summarized in table 1. The medium speed and high-speed motors which have already been built and tested are designated as VPI/RECO-1 and AR/RECO, respectively. (The acronym "RECO" indicates rare-earth cobalt permanent magnets). VPI/RECO-2 is presently being built as a modified version of VPI/RECO-1 having lighter magnets and two additional poles. A modified version of the AR/RECO motor is also being built but incorporates only minor changes in the stator windings. VPI/FERRITE is a medium speed ferrite magnet motor now being fabricated. AR/FERRITE is a preliminary design of a high speed ferrite magnet motor. Power ratings shown are the minimum design ratings. AR/FERRITE has been designed to match the actually tested performance of the AR/RECO motor for purposes of comparison.

MACHINE DESCRIPTION

Each of the machines designed in this motor development program are of the permanent magnet synchronous type. The inherent simplicity of this type of construction is illustrated by figure 2 which shows the component parts (except for the conventional-appearing stator) of one of the e.c. machines discussed here. The major components which will be discussed in more detail are the permanent magnet rotor, the stator armature, and the rotor-position sensors. Costs are also addressed.

PERMANENT MAGNET ROTOR-Interest in permanent magnet motors increased with the development of high energy permanent magnet material, especially, samarium-cobalt, which became available in the late 1950's. The attractiveness of samarium-cobalt can be seen by comparing its magnetic properties with three of the best available magnetic materials, Ferrite, Alnico 5, and Alnico 8, as shown in figure 3.(4) The maximum value of the product of B and H, $(BH)_{max.}$ is commonly used as a figure of merit and represents the maximum energy per unit volume of the magnetic material. Also of importance is the shape of the curve with increasing demagnetizing force. A linear characteristic as exhibited by the samarium-cobalt indicates excellent resistance to demagnetization, both self-demagnetization (5) which can occur during the assembly or disassembly of the machine and demagnetization due to high currents flowing in a heavily loaded motor.

Both samarium-cobalt ($SmCo_5$ alloy) machines VPI/RECO-1 and AR/RECO, the first machines developed and tested in this motor development project, have four pole rotors. Samarium-cobalt magnets are bonded to a steel shaft, as shown in figure 4, and held in place by a nonmagnetic sleeve as shown in figure 5. The use of high energy permanent magnets leads to a rotor structure that is smaller and lighter than the conventional dc motor armature rotor. The result is lower rotor inertia and a smaller mechanical time constant. The smoother surface configuration possible results in lower windage loss.

The medium-speed samarium-cobalt machine has been redesigned with a six-pole rotor (VPI/RECO-2). The use of a greater number of poles allows the amount of magnet material to be reduced for the same power output. However, the frequency of switching required in the inverter is increased. Consequently, this design change is easier to effect in the lower speed machine.

Uncertainties about the future availability of samarium-cobalt and continually rising cobalt prices prompted an investigation into the possibilities of substituting another material for samarium-cobalt used in the rotors of these machines. The most promising readily available material appears to be strontium-ferrite 8. Designs based on this material were made for both a medium-speed and high-speed motor, VPI/FERRITE and AR/FERRITE shown on table 1. The resulting ferrite machines are 50-60% larger than their samarium-cobalt magnet counterparts. The VPI/FERRITE was selected for further evaluation. This machine is presently being fabricated and will undergo testing to establish the performance characteristic of this type of machine, and thereby, it is hoped, establish the feasibility of ferrite magnet material in these applications.

STATOR-ARMATURE-Compared to the conventional type dc machine in which the armature must rotate to effect commutation, the e.c. machine is an "inside-out" construction in which the armature is stationary and 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, lowering the Joule loss (I^2R) in the winding and 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. Noodleman (6) has estimated that this type of inside-out construction can dissipate twice the losses of the conventional machine construction. Basing his calculations on this factor, Nagarkatti (7) has further shown that this inside-out design can provide as high as 1.6 times the continuous torque of a conventional dc machine of the same volume. Figure 6 shows the armature lamination stack of one of the machines and figure 7 shows the laminations with the coils installed.

Two different techniques have been used to minimize variations in torque at low speeds caused by alignment of teeth and poles, i.e., cogging. In the first design of the medium-speed motor a fractional slot winding, that is, an odd number of coils, was used. Fifteen slots were used in a four-pole, three-phase design giving 1.25 slots per-pole-per-phase. In the final design of this machine (VPI/RECO-2), for purposes of manufacturing economy, an integral slot winding was adopted, i.e., 18 slots for a 6-pole field or 1 slot per pole per phase. In this latter design, the laminations were skewed to minimize cogging. In the high-speed motor designs, the skewed lamination technique was used. In the AR/RECO-1 machine 24 slots were used with a four-pole field. No cogging was apparent in any of the macines tested.

An additional feature of the medium-speed machine is the use of a tapped armature winding capable of being changed to 2, 3, or 4 turns per coil. The tap changing scheme was adopted, primarily, to avoid excessively high currents at low speeds. This was modified in the VPI/RECO-2 and VPI/Ferrite to a two-step change by allowing either parallel or series connections of sets of coils to be selected.

ROTOR POSITION SENSORS-In the high-speed machine in normal operation, the shaft position information is derived from the machine's back EMF. Hence, the position sensors are in effect the armature windings of the machine itself, activated by the rotating field poles. At low speeds when the back EMF is too low for reliable operation, an optical sensor coupled with a shutter assembly mounted on the shaft is used. This optical system is used whenever the motor is operating at less than 10% of the rated speed.

In the medium-speed machine, four small magnets, one for each pole, are attached to the shaft of the machine and three Hall effect devices, one for each phase, are attached to the housing. As the magnets move past the Hall effect devices, a pulse is generated which indicates the precise position of the rotor. This position information is processed by the electronics to achieve switching of the transistors in the proper sequence. This is shown schematically in figure 8. The position sensor assembly can be seen mounted in the machine in figure 9.

COSTS-The cost of cobalt has increased by a factor of 4 to 7 since 1977. The best quality magnets consist of five parts cobalt to one part rare earth. Consequently, their cost has increased proportionately to a present day cost of $50 to $80 per pound of 140 kj/$m^3$ $(BH)_{max}$ magnets in quantity. However, because of the simpler structure, the permanent magnet synchronous machine can be manufactured in quantity at less than half the cost of a comparable, conventional, dc machine, even with the present cost of rare-earth materials. The O.E.M. cost of the permanent magnet machine has been estimated at between $250 and $300 in quantities of 100,000 units per year. If the cost of samarium-cobalt were to stabilize at the present levels, the use of ferrite magnet material may not result in a significantly lower cost due to the cost of the addtional materials, particularly copper, required for the bulkier machine. This is especially true for the high speed machine. However, the ferrite material has the advantage of assured availability and a relatively stable cost.

POWER CONDITIONING ELECTRONICS

Two differently designed power conditioners to effect electronic control and motor commutation have been built. Functionally, these two conditioners are very similar, but they differ substantially in the implementation of these functions. High power transistors are used as switches in the inverter for the medium-speed motor, whereas SCR's are used in the inverter for the high-speed motor. Each of these two designs will be described separately. Costs are addressed also.

TRANSISTOR INVERTER POWER CONDITIONER-A block diagram of the complete system is shown in figure 10. The major power components are shown in figure 11. Transistors, Q_M and Q_B comprise a two-quadrant converter (chopper) and control power flow in either direction. During the motoring mode (positive energy flow), the current is regulated to provide the torque commanded by the vehicle operator. Average current is controlled by means of a closed loop system which compares the output of an in-line current shunt to a command signal and uses the output of a comparator to control the duty cycle of the chopper. The choke, L, is included to provide additional inductance to reduce current ripple. This type of regulation was selected rather than an open loop technique such as pulse width modulation (PWM) of the inverter transistors for the following advantages: inherent stability, controllable dc ripple, and simplification of the protection schemes. A description of this type of controller, as well as additional details of the transistor inverter power conditioner discussed here, can be found in reference (8). The regulated current is switched by the three-phase transistor inverter bridge providing the power to the machine armature windings in the proper sequence for motor operation. The broken line in figure 11 shows the current path for phase A-B in the motoring mode. In this case, transistors Q_1 and Q_6 are turned on. Transistor selection is controlled by the position sensors mounted on the machine shaft.

In the regenerative mode, diodes D1-D6 act as a three-phase, full wave, bridge rectifier allowing power to flow from the motor to the battery. The generated EMF of the motor is boosted by the action of the chopper transistor, Q_B, and the choke, L, to overcome the battery voltage. Inertial energy of the electric vehicle can, in this manner, be returned to the battery.

The weight of the completed breadboard version of the controller is about 41 kg (90 pounds). However, with the use of custom designed heat sinks and attention to packaging details, this weight could be reduced to about 27 kg (60 pounds).

SCR INVERTER POWER CONDITIONER-The power conditioner using SCR's as inverter switches is shown schematically in figure 12. SCR's have an advantage over power transistors in that SCR's are readily available in any current and voltage range of interest for electric vehicle applications, are very rugged, and are presently much less expensive. The major problem is that the SCR can be difficult to turn off. Turn-off, or commutation, requires that the current through the device be reduced to zero by removing the EMF (natural commutation) or reversing the EMF (forced commutation). The latter technique is used to decrease the time required to turn off the SCR.

In the motoring mode, the SCR's are turned on in the proper sequence using rotor position information determined from the near-sinusoidally varying back EMF of the machine. The back EMF of the machine is also used to commutate the SCR's by a technique described in reference (9). This technique is based on the fact that a reverse EMF will appear across the SCR to be commutated if the next SCR in the sequence is turned on at an appropriately advanced angle. At low speeds, the back EMF is too low to properly turn off the SCR's. Therefore, the optical rotor position sensor is used in conjunction with logic circuitry to turn off the current control chopper, Q_H, for a period of time sufficient to allow the corresponding SCR to turn off by natural commutation. Transistor chopper Q_L may be included, as an option, to achieve forced commutation. It has been found that elimination of this transistor results in only a slight power loss at very low speeds. In motoring mode of operation switch SW1 is closed. Power is supplied via the choke L1 to the inverter bridge Q1-Q6. The current level is controlled by the switching action of Q_H. In the regenerative mode, switch SW1 is open, and the SCR's are operated as a three phase bridge rectifier. The voltage is boosted to an appropriately high level by Q_H, D1, and L1. The SCR inverter power conditioner in breadboard form is shown in figure 13. The weight of this power conditioner is 36 kg (80 pounds) in this form. In a production prototype, its weight should be about 27 kg (60 pounds).

COSTS-The electronics are, without question, the most expensive part of the electronically commutated motor. However, it must be kept in mind that the power conditioners as described in this paper contain virtually all the control functions that are likely to be required for operation in an electric vehicle. The O.E.M. cost of the power conditioner has been estimated at $1400 to $1650 for the SCR version. The transistor inverter cost is considerably higher now, but is potentially less expensive due to the less complex circuitry required. There is an increasing interest by transistor manufacturers in low cost high power transistors. If power transistors with good heat transfer characteristics were to become available at a price of $0.15 per ampere, a figure considered to be realistically achievable, transistor power conditioning as described here could be produced at an O.E.M. cost of about $600 per unit. The total cost of the electronically commutated motor would then be under $1000.

TEST RESULTS

Both the medium-speed and the high-speed electronically commutated motors, comprising the permanent magnet machine and power conditioning electronics, have been dynamometer tested for performance. The completed high-speed machine is shown in figure 15. Figure 16 shows the method of testing used for the high-speed machine. The medium-speed machine was tested independently in a similar set up.

Test results are shown in figures 17 through 20. Curves of efficiency as a function of torque for various speeds are shown. These curves are shown for both the motoring and the regeneration (brake) modes.

Figures 17 and 18 show the efficiency of the high-speed motor system including both the power conditioner and permanent magnet machine. The curves for the motor in the motoring mode of operation indicates a peak of about 90% at full speed, and fairly constant efficiency over most of the torque range. In the brake, or regenerative mode, the efficiencies fall off much more rapidly with speed. This is due to the higher losses incurred by the electronics in boosting the voltage output of the machine.

Figures 19 and 20 show the efficiency of the medium-speed machine but do not include the power conditioner losses. Losses higher than normal occurred in the power conditioner due to the unavoidable substitution of an underdesigned choke for the proper choke in order to complete testing on schedule. Resistive losses were also higher than necessary because of the breadboard nature of the power conditioner. The power conditioner efficiencies are, therefore, not included in these figures for the medium-speed machine because the test data is not believed to be representative of the potential performance of this power conditioner. This power conditioner has been upgraded for future testing of the VPI/RECO-2 version of the motor and the above problems have been eliminated. The machine efficiencies as shown on these curves are in excess of 93% over most of the torque range. The machine efficiencies are not strongly dependent on speed in either the motoring mode or the brake mode.

Based on the test data, efficiencies were calculated for operation over the SAE J227a, Schedule D, driving cycle and are shown in table 2. Efficiency over this cycle is defined as total output energy of the motor required to propel the vehicle over the cycle divided by the total energy input to the motor over the cycle. Energy due to regeneration is represented as negative and is, thus, subtracted from the input energy.

CONCLUDING REMARKS

Permanent magnet, electronically commutated motors have been shown to be capable of very high performance. The weights of the resulting machine-controller systems can be significantly lower than those of comparable dc motor-controller combinations. The most significant problem is that of cost. The motor development program is continuing at present with emphasis on reducing potential production costs. This involves exploring lower cost magnet material, investigating high power transistor technology further, and simplifying the present motor designs.

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Table 1-Electronically Commutated Motors Designed for DOE/NASA

	VPI/RECO-1	VPI/RECO-2	VPI/FERRITE	AR/RECO	AR/FERRITE
Magnet material	$SmCo_5$	$SmCo_5$	Strontium Ferrite 8	$SmCo_5$	Strontium Ferrite 8
Magnetic $(BH)_{max.}$, kj/m^3	140	140	26	175	26
Magnet weight, kg (lbs.)	2.4 (5.3)	1.5 (3.2)	4.4 (9.6)	1.4 (3.0)	5.9 (13.0)
No. of poles	4	6	6	4	6
Rated speed, rpm	7650	8600	9000	26,000	22,000
Peak power, kW (hp)	26 (35)	26 (35)	26 (35)	26 (35)	30 (40) (*)
Machine weight, kg (lbs.)	40 (88)	27 (60)	58 (127)	15 (33) (**)	34 (75) (**)
Machine efficiency, %					
estimated	93.4	95.9	95.8	93.0	93.0
tested	93.0	-	-	93.0	-
Inverter type	Transistor	Transistor	Transistor	SCR	SCR

(*) Note the higher rated design

(**) External cooling fan required for this motor at an additional weight of 2.7 kg (6.0 lbs.)

Table 2-Efficiencies Expected Over the SAE, Schedule D, Driving Cycle-J227a

Efficiency	VPI/RECO-1	AR/RECO
Machine	0.90	0.93
Power Conditioner	0.85*	0.94
System	0.77	0.88

*Includes Anomalous Losses in Power Conditioner

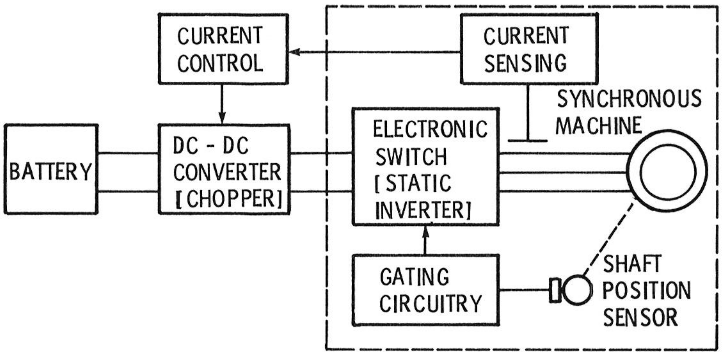

Figure 1. - Electronically commutated dc motor.

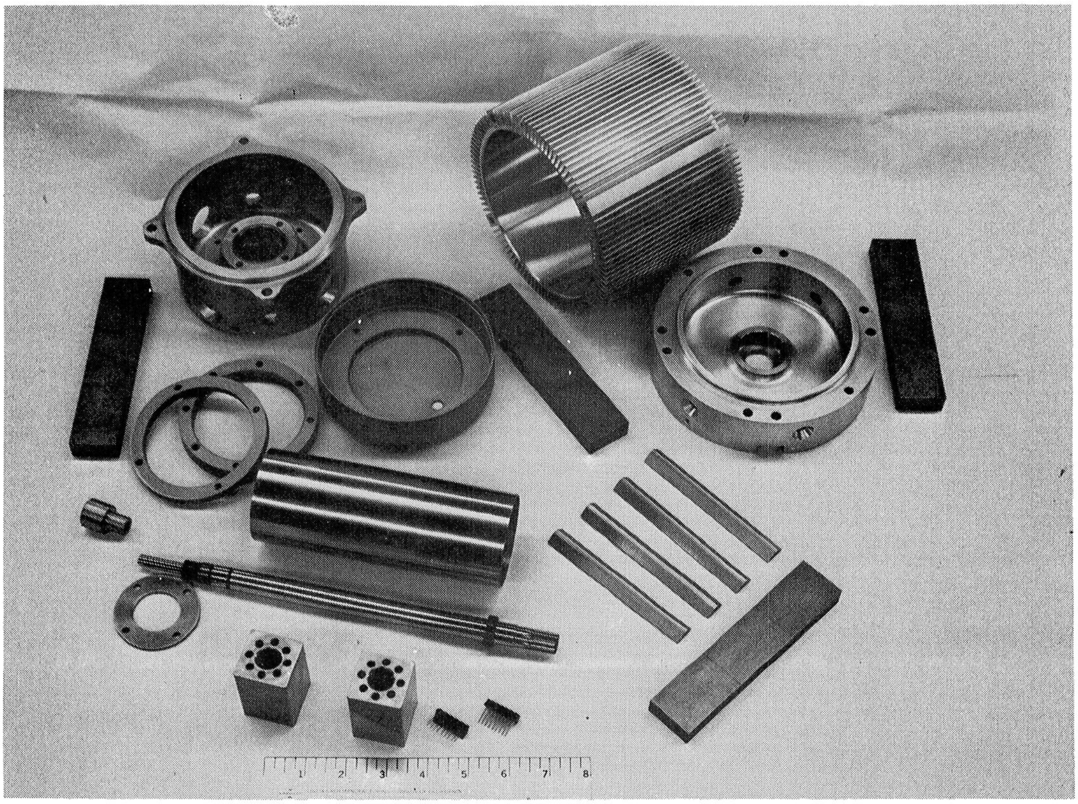

Figure 2. - Component parts of machine for electronically commutated dc motor.

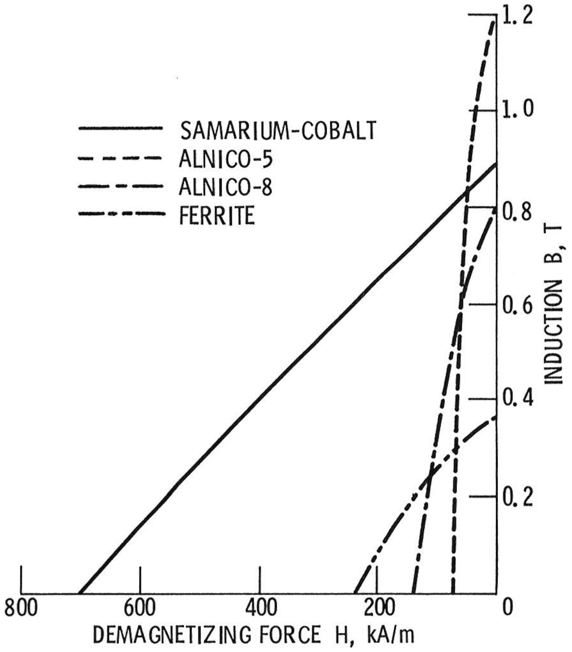

Figure 3. - Demagnetization curves of four selected magnetic materials.

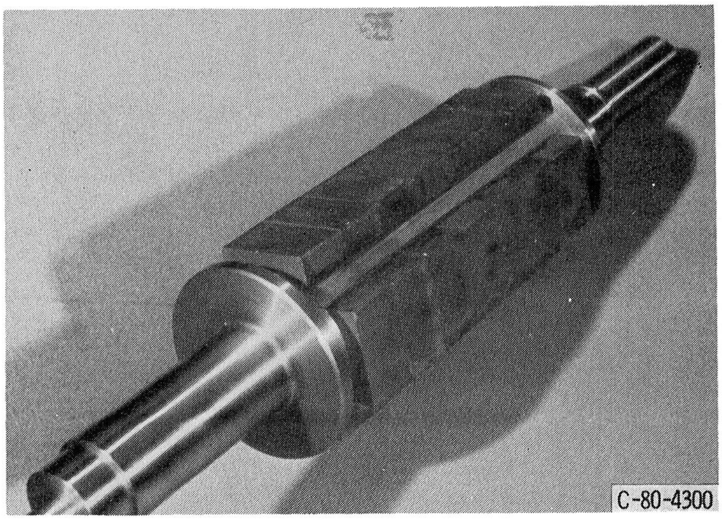

Figure 4. - Rotor with permanent magnets attached.

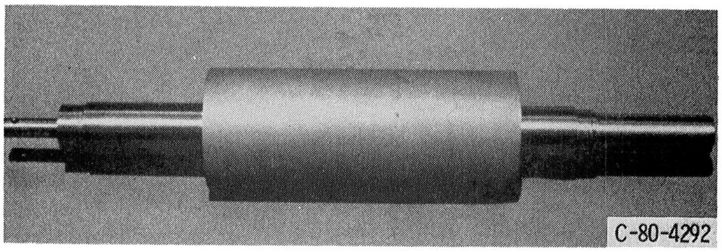

Figure 5. - Assembled rotor.

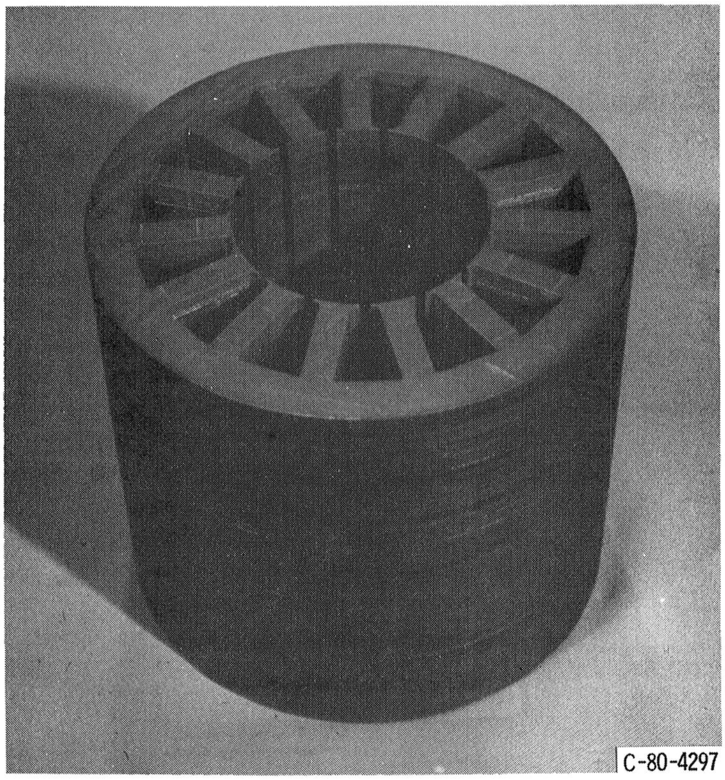

Figure 6. - Stator lamination stack.

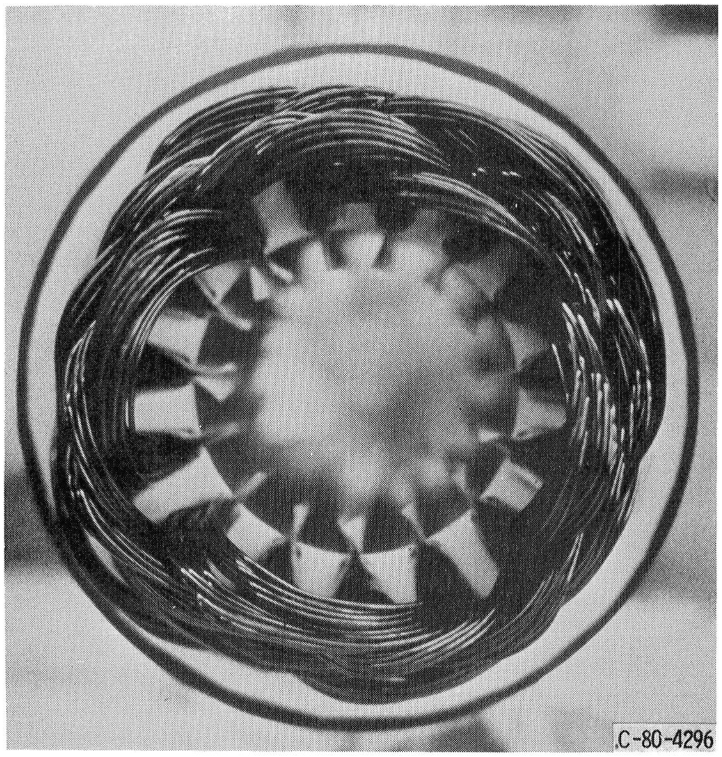

Figure 7. - Partially assembled stator showing armature coils.

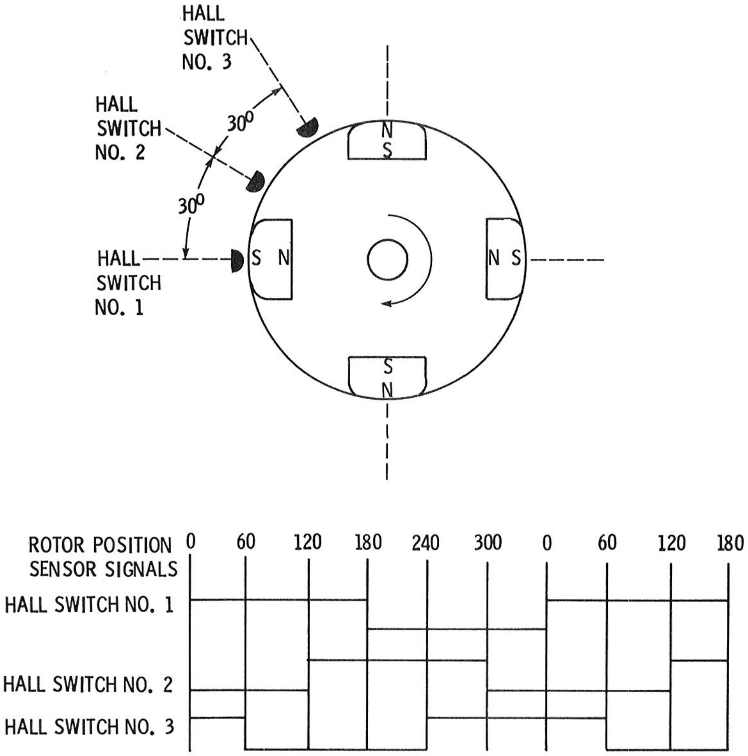

Figure 8. - Rotor position sensor.

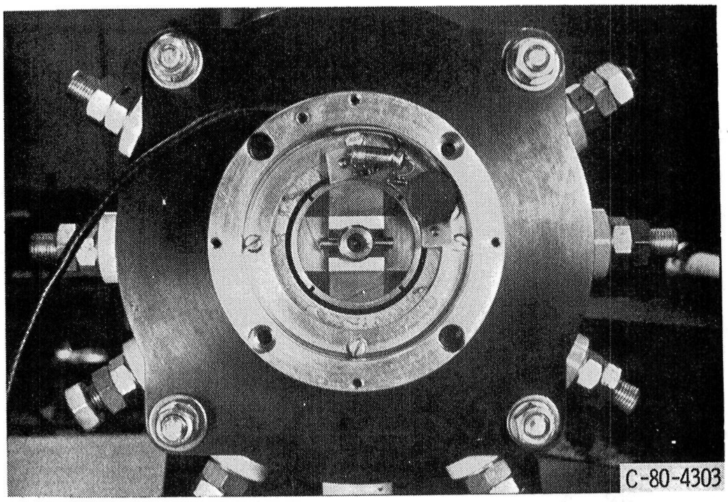

Figure 9. - End view of machine showing rotor position assembly.

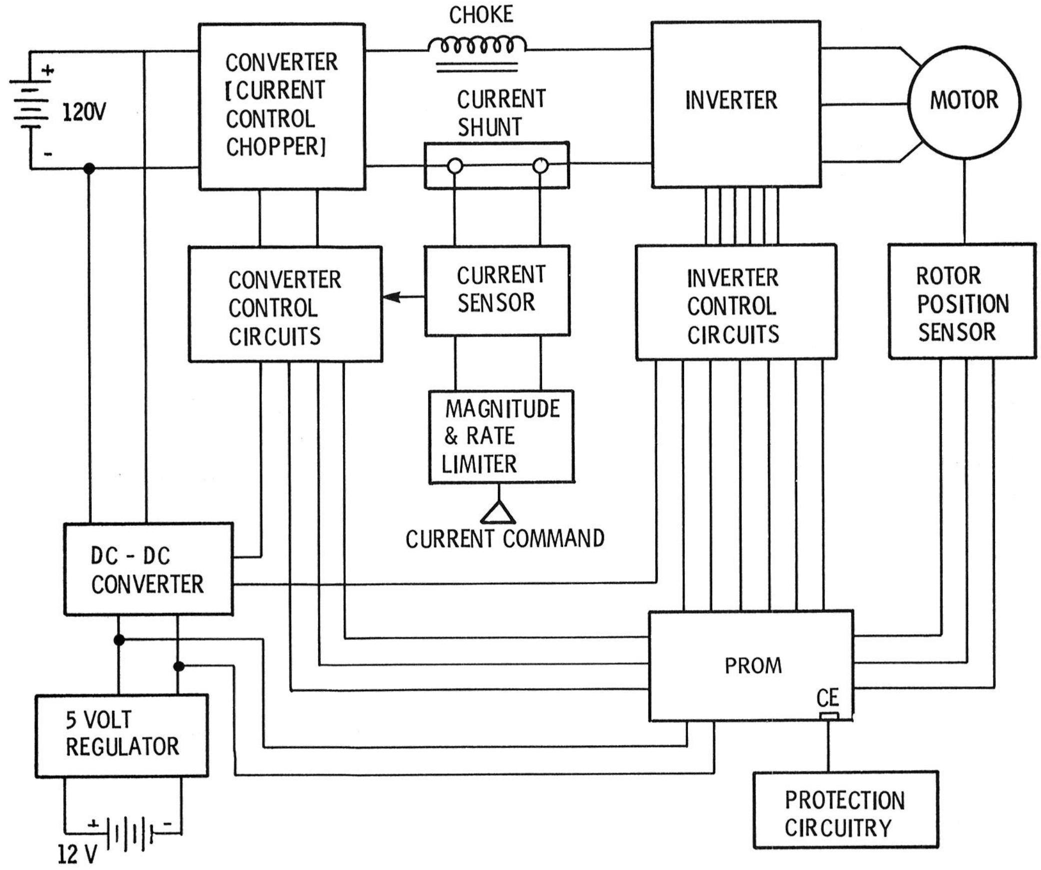

Figure 10. - Complete block diagram of transistor inverter power conditioner.

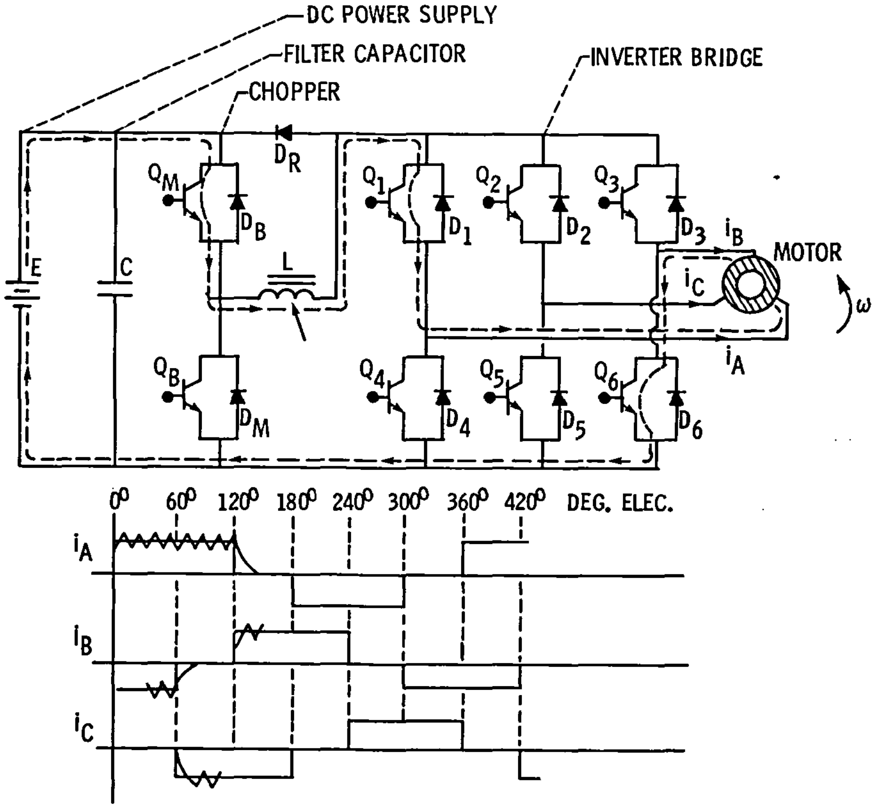

Figure 11. - Transistor inverter power conditioner schematic and idealized motor currents.

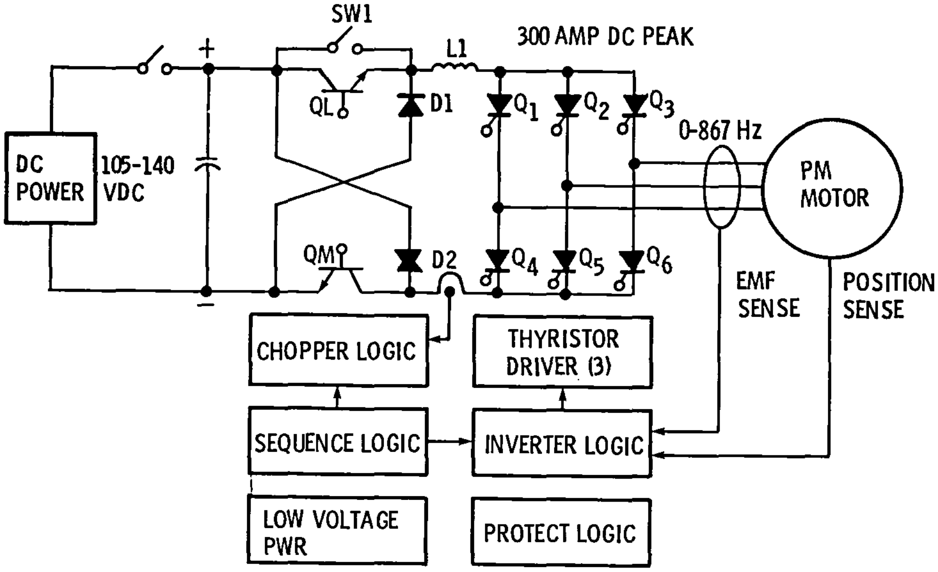

Figure 12. - SCR inverter power conditioner schematic.

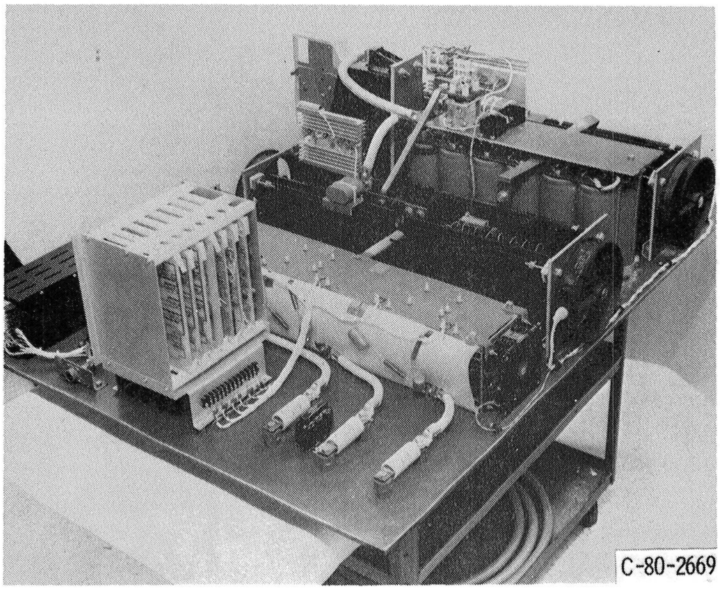

Figure 13. - Breadboard version of SCR inverter power conditioner.

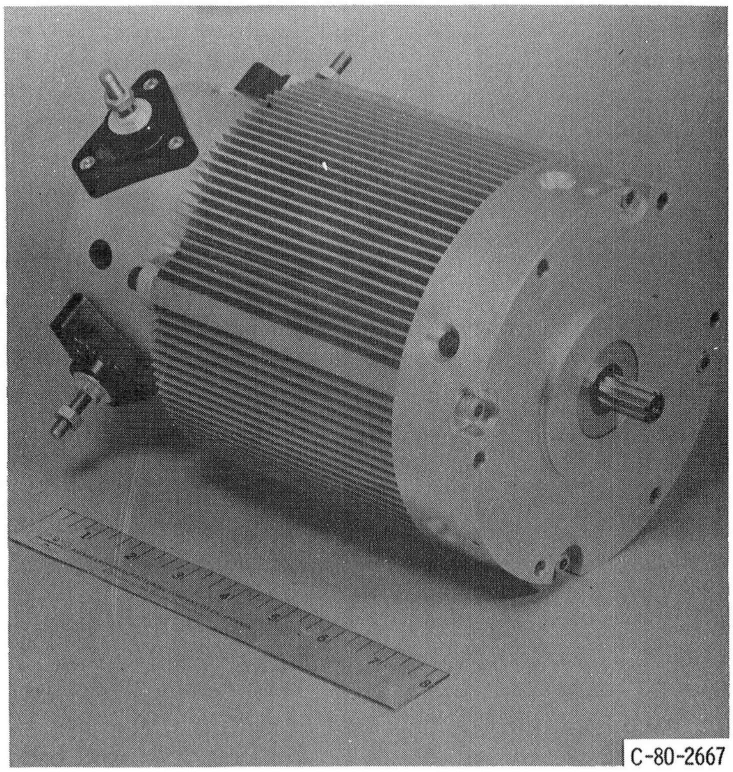

Figure 14. - The completed high-speed machine.

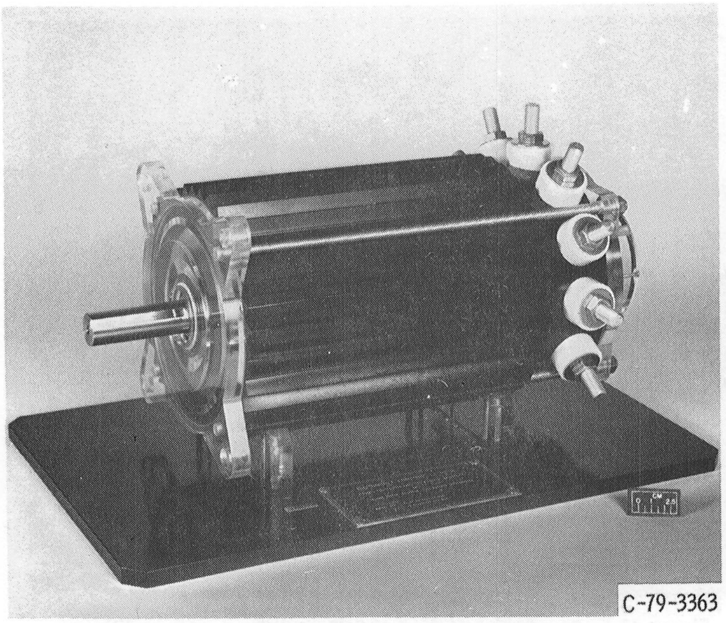

Figure 15. - The completed medium-speed machine.

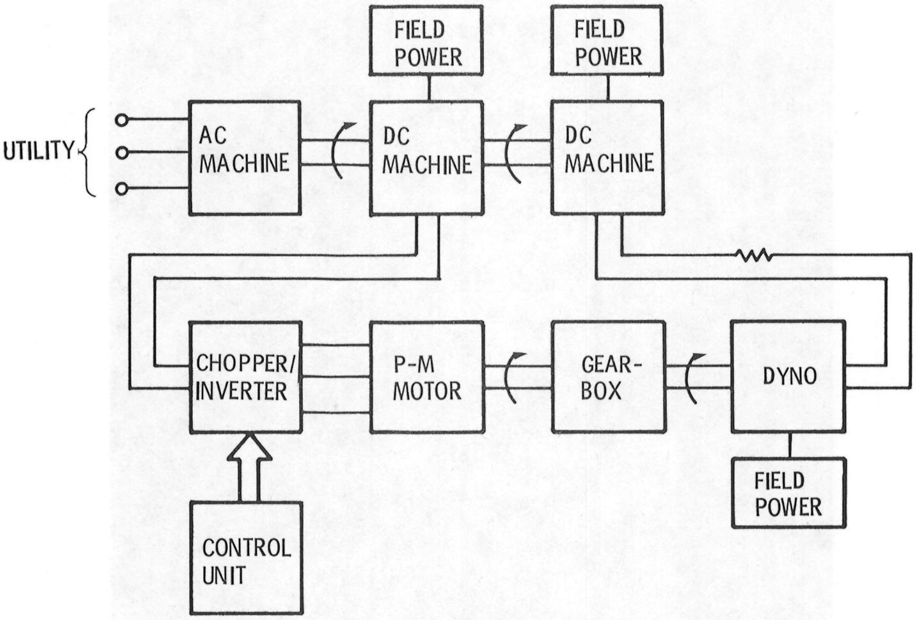

Figure 16. - Block diagram of laboratory test system.

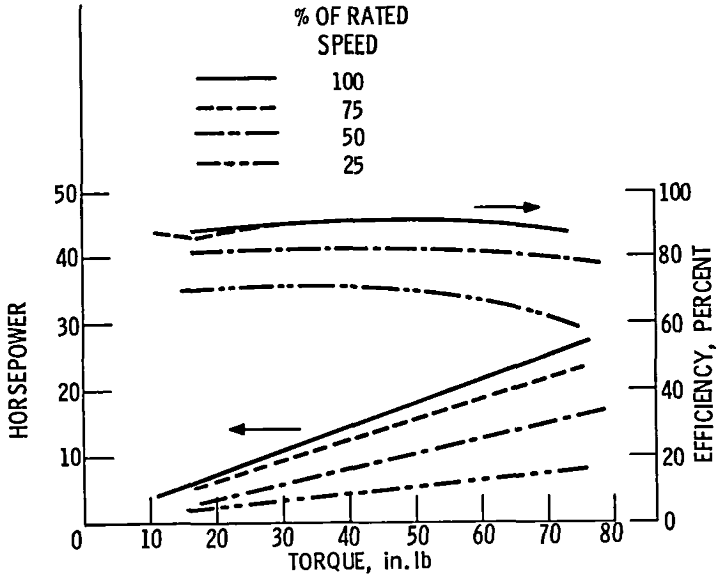

Figure 17. - Performance of high-speed motor during drive mode.

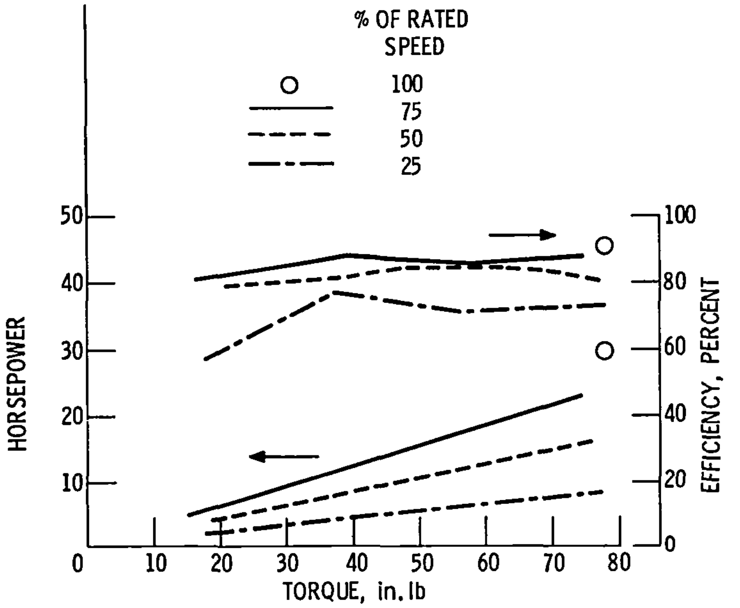

Figure 18. - Performance of high-speed motor during brake (regeneration) mode.

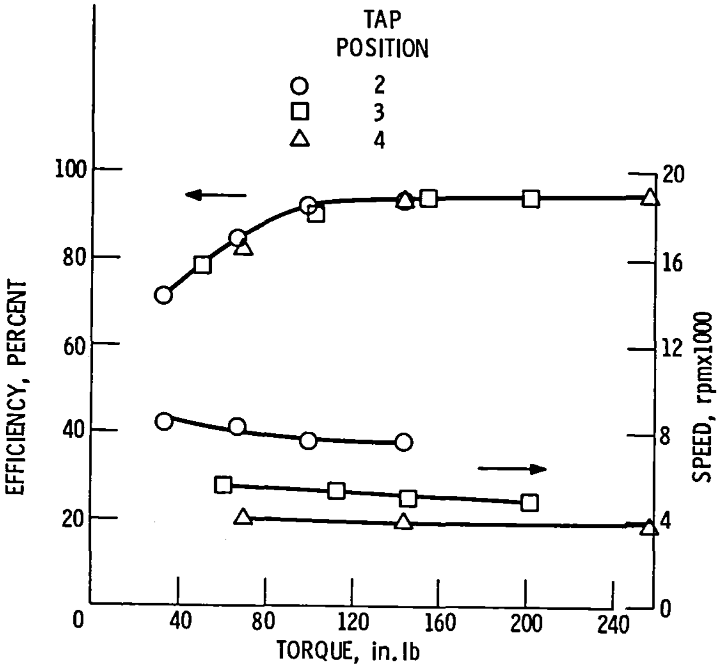

Figure 19. - Performance of medium-speed machine during drive mode.

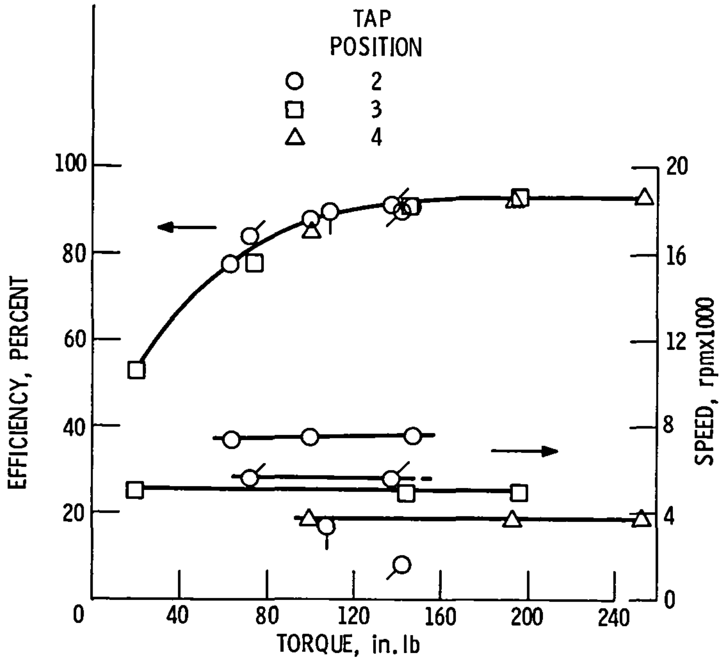

Figure 20. - Performance of medium speed machine during brake (regeneration) mode.

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16. Abstract

A motor development program to explore the feasibility of electronically commutated dc motors (also known as brushless) for electric cars is described. Two different design concepts and a number of design variations based on these concepts are discussed. One design concept is based on a permanent magnet, medium-speed, machine rated at 7000-9000 rpm and powered via a transistor-inverter power conditioner. The other concept is based on a permanent magnet, high-speed, machine rated at 22,000-26,000 rpm and powered via a thyristor-inverter power conditioner. Test results are presented for a medium-speed motor and for a high-speed motor each of which have been fabricated using samarium-cobalt permanent magnet material.

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