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SUMMARY

Available performance data for production motors are usually of marginal value to the electric vehicle designer. To provide at least a partial remedy to this situation, tests of typical dc propulsion motors and controllers were conducted as part of the DOE Electric Vehicle Program.

The objectives of this program were to evaluate the differences in the performance of dc motors when operating with chopper-type controllers and when operating on direct current; and to gain an understanding of the interactions between the motor and the controller which cause these differences.

Toward this end, motor-controller tests performed by the NASA Lewis Research Center provided some of the first published data that quantified motor efficiency variations for both ripple-free (straight dc) and chopper modes of operation. Test and analysis work at the University of Pittsburgh explored motor-controller relationships in greater depth. And to provide additional data, 3E Vehicles tested two small motors, both on a dynamometer and in a vehicle, and the Eaton Corporation tested larger motors, using sophisticated instrumentation and digital processing techniques.

All the motors tested were direct-current types. Of the separately excited types, seven were series wound and two were shunt wound. One self-excited permanent magnet type was also tested. Four of the series wound motors used brush shifting to obtain good commutation. In almost all cases, controller limitations constrained the test envelope so that the full capability of the motors could not be explored.

E-1232

INTRODUCTION

This report summarizes motor-controller testing activities that were performed under the guidance of the NASA Lewis Research Center for the Electric and Hybrid Vehicle Program of the U.S. Department of Energy (DOE).

The goal of the Electric and Hybrid Vehicle Program is to promote and accelerate the development and public use of vehicles that use electricity as their principle source of propulsion energy. The Department of Energy has delegated project management responsibility for the propulsion system technology development part of the program to the NASA Lewis Research Center.

One of the early activities of the Lewis Research Center was the preparation of a state-of-the-art report. This report (ref. 1) and two design studies (refs. 2 and 3) pointed out that the size of the electric and hybrid vehicle industry is insufficient to justify extensive component development by private industry. Designers have adapted or modified equipment that was originally designed for other applications. Frequently, industrial electric truck motors or aircraft generators are modified for electric vehicles.

The available performance data for these motors is usually of marginal value to the electric vehicle designer. In addition to the nameplate data, typical data consists of a single speed-torque curve at rated voltage and a curve depicting the current-torque relationship. Usually a ripple-free (straight dc) power source such as a motor-generator set or battery is used to obtain the data for the speed-torque curve. The voltage is either held constant or allowed to droop in accordance with the natural voltage regulation of the source. The degree of relevance and the manner in which these data should be applied to chopper-controlled electric vehicles is not obvious. In chopper control, average motor voltage and current is controlled by varying the on-off times of a semiconductor switch between the battery and the motor.

Most of the electric vehicle builders are small concerns and lack the necessary equipment and resources needed to conduct performance tests. In addition, the economic incentives are insufficient to induce even the motor manufacturers to perform such tests on their own products. Also, the kinds of test data needed, the methods of performing the tests, and the manner of presentation of the results are not well defined.

To provide at least a partial remedy to this situation, tests of typical motors and controllers were conducted as part of the Electric Vehicle Propulsion Project managed by NASA for DOE. The individual test reports of this program are summarized here to help designers determine the relevance of existing data and to specify any additional tests that are required.

GENERAL DESCRIPTION OF THE TEST PROGRAM

The test program summarized here consisted of four major activities. These activities, which are described individually in later sections of this report, were intended to fulfill different needs. The tests conducted at the Lewis Research Center provided some of the first published data that quantified motor efficiency variations for both ripple-free (straight dc) and chopper modes of operation (refs. 4 and 5). Test and analysis work at the University of Pittsburgh explored the motor-controller relationships in greater depth (refs. 6 to 9). Tests conducted by both 3E Vehicles and Eaton Corporation obtained data on available motors that might be used on vehicles. 3E Vehicles tested two small motors on a dynamometer and in a vehicle (ref.10). Eaton Corporation tested larger motors and used sophisticated instrumentation and digital processing techniques (refs. 11 to 14).

The particular motors and controllers that were tested in the various programs were selected primarily because of availability and convenience. The motors and controllers are typical of those generally available to vehicle designers. No attempt was made to select the "best" piece of equipment. Consequently, the motors and controllers may not have been the most efficient, lightest weight, or lowest cost items available. The optimization of these factors was beyond the scope of these test programs.

All the motors tested were direct-current types. Of the separately excited types, seven were series wound and two were shunt wound. One self-excited permanent magnet type was also tested. Four of the series wound motors used brush shifting to obtain good commutation. In almost all cases, controller limitations constrained the test envelope so that the full capability the motors could not be exploited.

The investigators faced a variety of problems. These problems involved the selection of equipment and instrumentation, the specification of test procedures, the determination of the data processing methods, and the choice of data presentation formats and conclusions. Some of the problem solutions are similar while others differ and show different perspectives. The individual test reports contain detailed descriptions of these items. Only the more pertinent portions of the individual reports are summarized here.

LEWIS RESEARCH CENTER TEST PROGRAM

The primary objective of the Lewis motor-controller tests (as reported in refs. 4 and 5) was to compare motor performance for both ripple-free and chopped modes of operation. Secondary objectives included the development of test procedures and instrumentation techniques.

Two motors were chosen for this test series. One motor was a four-pole, series-wound, laminated-frame, direct-current machine rated at 14.9 kilowatts (20 hp). This motor was manufactured by Northwestern Electric Company and was used in a propulsion system test bed vehicle built for Lewis. The second motor was also a four-pole, series-wound, direct-current machine, but it had a nonlaminated frame and was rated at 22.4 kilowatts (30 hp). This motor was manufactured by Avon Manufacturing Inc. and was electrically indentical to the Baker motor used on the Otis P500 electric van. Both motors employed brush shifting to achieve good commutation.

Baseline ripple-free motor performance data were obtained by a series of load tests. A motor-generator set was used as a power source for these ripple-free tests. The motor-generator set allowed the voltage to be easily set at several different voltage levels and avoided the repeatability problems normally associated with batteries. For these tests the applied voltage was held constant as the load was varied.

Since the effective impedance of the power source appreciably affects wave shapes, a set of electric vehicle batteries was used as a power source for the chopped mode of operation. Fourteen lead-acid batteries provided a nominal 84-volt source. To increase the repeatability of this series of tests, the batteries were recharged whenever the open circuit voltage dropped below 80 volts.

EVC Inc. manufactured the chopper-type (pulse-width modulation) controller that was used for these tests. This constant frequency (400 Hz) controller used transistors as switches. Coaxial shunts and a wide-band wattmeter were used for the current and electrical power measurements.

The most interesting result is the relationship between motor efficiency and the mode of operation. At low levels of voltage and power (low duty cycle of the controller), the chopped mode motor efficiency was about 5 to 10 percentage points lower than the ripple-free mode motor efficiency. At higher voltage and power levels (controller duty cycle approaching 100 percent), the two values become nearly indentical. As expected, motor efficiency tends to increase as voltage and power increase. These results are shown in figure 1.

Some of the electrical power measuring problems are also illustrated in the reports. Although much effort was expended in procuring and calibrating a wide-band wattmeter, the results are somewhat less than ideal. All instruments must be chosen so that the peak values of the expected signals will not overload the instrument inputs. For this series of tests the peak values of voltage and current were expected to approach 100 volts and 300 amperes, respectively. These values correspond to peak power of 30 000 watts. Even if 1 percent of full-scale accuracy could be achieved, the error could range up to 300 watts. This error is more than 10 percent of the power reading at light loads as shown in figure 1. These light loads correspond to small duty cycles of the chopper and do not necessarily imply a reduction in the peak value of either voltage or current. Compounding this problem are factors such as instrumentation drift, common mode rejection, and transducer linearity. Data in the reports also indicate that errors greater than 50 percent may result from using the product of the average values of voltage and current as a substitute for true power.

The IEEE Standard Test Code for Direct-Current Machines (IEEE STD 113-1973) provided guidance for some of the tests. However, this code is intended primarily for use with shunt or compound wound machines and generally does not provide for brush-shifted series motors. For instance, to obtain a magnetic saturation curve such as in figure 2, the brushes must be located temporarily on the geometric neutral of the machine.

The magnitude of some of the individual losses are shown in figures 3 and 4. As expected, the largest loss category is the I^2R (copper) loss.

Of more than passing interest are the torque-current relationships illustrated in figure 5. With the brushes at the geometric neutral, there are virtually no differences between the ripple-free and the chopped data. However, with the brushes shifted, there are distinct and generally unexpected differences. These differences may help to explain why chopper-controlled, brush-shifted motors do not always perform in accordance with data from ripple-free tests.

UNIVERSITY OF PITTSBURGH TEST PROGRAM

To develop a better understanding of the chopper-motor interrelations, a more indepth investigation was undertaken at the University of Pittsburgh. Both experimental and analytical work were performed, and the results are detailed in references 6 to 9.

For the experimental portion of the investigation, the Lewis Research Center supplied two brush-shifted, series-wound motors and a controller. The motors were similar to those used in the Lewis Research Center test program. The chopper-type controller used thyristors as the switching elements and was manufactured by Cableform Ltd. To obtain independent control of both the chopper frequency and pulse width, the logic portion of the controller was disconnected. The thyristor firing circuit was driven by a variable-frequency square-wave laboratory supply.

Ideally, a motor should be tested as part of a motor-controller power source system. However, electric vehicle batteries change their characteristics as a result of age, temperature, state of charge, and prior use. Other undesirable features include the need to regularly check water levels, measure specific gravity, tighten terminal connections, and periodically recharge. Batteries also contain either sulfuric acid or caustic electrolytes, can generate hydrogen when overcharged, and comprise an electrical voltage source which cannot easily be turned off. These safety and maintenance problems, in conjunction with the need for repeatable results, were a strong incentive to use another type of power supply instead of batteries. Reference 6 details the rationale that led to using a motor-generator set and a bank of parallel capacitors as a battery simulator. The generator is a continuously variable voltage source. Its thermal time constant and overload capacity are similar to the motors being tested. The paralleling capacitors suppress voltage spikes, and external resistance can be added to obtain the same voltage regulation or effective resistance as the battery pack being simulated. The various wave shapes are similar. A similar power supply has been installed at the Lewis Research Center, and it has been used successfully for testing other propulsion systems.

To the extent that the test programs overlapped, the University of Pittsburgh tests confirmed the results obtained at the Lewis Research Center. The torque-current relationship anomalies that had been observed in the Lewis Research Center test program were analyzed in depth and are explained in reference 7. In the chopped mode of operation, the torque in a brush-shifted motor may be considered to consist of two components, the normal dc component and an ac component.

Since motor inductance strongly affects performance in the chopper control mode of operation, tests were performed to determine the values of inductance and resistance as functions of frequency and magnetic saturation. Typical results are depicted in figures 6 and 7. These figures are from reference 8 which has been incorporated into the IEEE Standard 113 as a reference.

An analytic model for a chopper-controlled series motor was also developed. This model accounts for the varying inductance and apparent resistance of the machine in predicting its performance. The finite-element technique is used in the time domain and accounts for eddy currents and saturation effects. The model is described in reference 9 from which figures 8 and 9 were taken.

3E VEHICLES TEST PROGRAM

A small cost-shared test and analysis program was conducted by 3E Vehicles. Reference 10 is a report of this activity. The primary objective of the government's portion of this test series was to obtain data on small motor-controller combinations for comparison with the data obtained from the other tests discussed in this report. The primary objective of 3E Vehicles' portion was to obtain data on systems that are applicable to small, lightweight (approximately 400-kg (900-lb.)) vehicles.

Dynamometer tests of the complete systems were followed by correlation road tests in an operating electric vehicle. A conventional series-wound motor and a permanent magnet motor of similar size and rating (2.5 hp and 36 V) were tested. Each motor was tested with two types of controllers: a four-step voltage switching type, and a 400-hertz transistorized chopper type. The series motor, manufactured by the General Electric Company, is normally used in golf cart applications. The permanent magnet motor, manufactured by Ohio Magnetics International, was designed for constant torque applications and was tested only to investigate its basic operating characteristics. The voltage-switching controller was built by 3E Vehicles and the chopper-type controller was supplied by EVC Inc. Four 12-volt batteries were used to supply power for all road and dynamometer tests.

As in the Lewis Research Center and the University of Pittsburgh test programs, 3E Vehicles used coaxial shunts and wide-band wattmeters to measure electrical power. The same kinds of problems were encountered. Two different wide-band wattmeters were used. One of them was supplied by Sine Engineering and the other instrument was supplied by Clarke-Hess Company. Despite the investigator's best efforts to calibrate these instruments, their readings typically varied by about 6 percentage points. For this test series, the investigator noted that on the battery side of the chopper, conventional dc shunts, voltmeters, and ammeters provided power and energy consumption accuracies that were within a few percent of the true values and would be suitable for normal vehicle use. On the motor side of the chopper, the discrepancies were much larger and would almost always be unacceptable. For laboratory tests, coaxial shunts and wideband wattmeters should always be used on both sides of the chopper.

The speed-torque curves and the efficiency-torque curves shown in figures 10 and 11 (from ref. 10) illustrate the differences between voltage-switching control and chopper control on the series motor performance. Since the chopper operated from a nominal 48-volt battery supply, the 25-percent duty cycle curves should be compared with the 12-volt nominal voltage switching curves. Similarly, the 50-, 75-, and 100-percent curves should be compared with the 24-, 36-, and 48-volt curves. The decrease in motor efficiency in the chopper control mode ranges up to 20 percentage points at light loads. Similar results were obtained for the permanent magnet motor and are shown in figures 12 and 13. The figures contain references to chokes, which are discussed in reference 10. Adding chokes (inductance) in series with the armature of each motor in the chopper-controlled mode reduced the amplitude of the fluctuations of motor circuit current and voltage and resulted in an increase in efficiency at light loads as expected. At heavy loads the cycle off-time is minimal, reducing the effect of the choke and, as a result, the efficiency either slightly decreased or remained constant. More details can be obtained from reference 10, which also discusses road testing and other component data.

EATON TEST PROGRAM

The objective of the Eaton test program was to provide the electric vehicle industry with performance data on motors being used in electric vehicles in combination with an existing controller. Two series-wound motors and two shunt-wound motors were tested. Some pertinent data for these motors are given in table I.

A General Electric Company model EV-1 controller was used with all four motors. This controller is a conventional SCR chopper type intended for use with the General Electric Company series-wound motor. Since this controller appears to be typical of available chopper-type controllers in the required power range, convenience and uniformity considerations led to its use with the other motors. For the shunt motors, a 1-millihenry choke was inserted in series with the armature. The addition of this choke improved controller stability at high duty cycles.

A large bank of industrial storage batteries supplied the power for these tests. The large ampere-hour capacity of these batteries reduced the variability and nonuniformity of typical battery supplies. However, this source still lacked the versatility of the motor-generator sets that were used for the Lewis Research Center and the University of Pittsburgh tests. In the ripple-free, or straight dc, mode of operation, a correction for battery voltage droop was required. For the chopped mode of operation a 0.059-ohm resistor was added in series with the generator to provide the necessary droop.

The instrumentation differed from that of the other tests in that optical isolators (Philips type PM 8940) were used to float the input signals and the data were processed by a Hewlett-Packard 5451B Signature Analysis System. The front ends of the isolators were battery powered, which completely eliminated all possibilities of ground loops. Analog to digital converters in the Signature Analysis System sampled data points at a 20-kilohertz rate and digitally calculated the average and RMS values of the various voltages and currents as well as the power.

Each motor was tested in both the straight dc and the chopped modes of operation for two temperature ranges (near room temperature and near maximum operating temperature) and for several values of input voltage. Each test run consisted of both increasing and decreasing the load to evaluate hysteresis effects. To reduce data scatter, each test run was repeated three times.

Typical data for a series motor are shown in tables II (a) and (b) (from ref. 11). Similar data for a shunt motor are shown in tables III (a) to (e) (from ref. 13). References 11 to 14 contain more complete results. The original data as obtained from the Signature Analysis System were fed into a digital computer and processed to produce these tables and the curves shown in figures 14 to 16.

The temperature tabulation in table II (a) illustrates one of the difficulties of specifying motor temperature. Not only does the temperature vary from one point to another in the machine, but the temperature difference also varies. Figures 14 and 15 show typical data in graphical form for the low temperature tests. The curves all have the expected shapes. Not shown here, but contained in the original reports, is data for a 130° to 150°C temperature range. The form of the data for this higher temperature is the same. The most discernable effect is a shifting to the left of the torque-speed curve (see ref. 11). The peak efficiencies are about the same and occur at moderate loads, reasonably high speeds, and near maximum voltage.

As in the other test programs, the peak value of motor efficiency in the chopped mode of operation is nearly the same as the peak value in the ripple-free mode. Since the peak value occurs at approximately 100-percent chopper duty cycle, this result is expected. The average and RMS values of the various voltages and currents are also shown in table II (b). These values were recorded primarily as an aid to future modeling work, but the usual comparisons of the power with the product of voltage and current may be made. As expected, the largest discrepancies occur at small duty cycles. Chopper efficiency can be calculated from the ratio of chopper output power to chopper intput power. However, the tolerances on the two power measurements result in considerable data scatter. Therefore, only the upper and lower limits of controller efficiency are shown in figure 16.

The data in tables III (a) to (e), for the shunt motor, are similar to the series motor data. Since the armature chopper is used only below base speed, and maximum field current is generally desired in this region, a 9-ampere field current was maintained for these tests. Above base speed, the armature voltage was held at its maximum value and tests were performed for several values of field current.

RECOMMENDATIONS AND COMPARISONS

Each investigator, because of the differing goals of his program, was required to develop his own specific test procedure. The IEEE Standard Test Code for Direct-Current Machines (IEEE Std. 113) provided guidance in some cases. However, this test code is intended for use with conventional industrial-type machines and does not cover many of the unique problems encountered in testing relatively low-voltage, series-wound, traction motors. Variations in test procedures result in nonuniformity in data acquisition, data reduction, and data presentation methods. A general set of test procedures for electric vehicle traction motor-controller testing (possibly patterned after IEEE Std. 113) is needed. These procedures should provide descriptions of the tests to be performed, the acceptable methods of performing the tests, and the pertinent features of the required equipment such as power supplies and instrumentation. Data reduction techniques and data presentation formats should also be discussed.

The type of power supply that is most appropriate for a particular test depends on the purposes and objectives of the test. The power supply characteristics affect the test procedures, the scope of the test envelope, the repeatability and uniformity of the tests, and the usefulness of the data. Both batteries and motor-generator sets were used to supply power for these test activities. In the case of the 3E Vehicles tests, where dynamometer and road test data were to be compared, it was essential to use the actual vehicle batteries for both the ripple-free and the chopped series of tests. For more general tests, a motor-generator set with parallel capacitors is much more versatile. Tests at the University of Pittsburgh and later at the Lewis Research Center demonstrate that this type of supply reasonably simulates electric vehicle batteries. For the Eaton tests, a large bank of industrial storage batteries also proved to be a realistic power source.

An essential point that the test conductor must recognize is that the effective internal impedance of the source and its repeatability can substantially affect the usefulness of the results. For systems testing in either the ripple-free or the chopped mode, the system should include the actual vehicle battery. The tests should be repeated enough times to determine the range of variability due to the battery. For component testing in the ripple-free mode, a motor-generator set appears to be the most versatile power source. The generator is a continuously variable voltage source and can simulate either a constant voltage bus or a source with any desired amount of voltage drop. If a bank of paralleling capacitors and an external resistor are added, the generator can effectively simulate the dynamic characteristics of a wide range of batteries when the controller is operating in the chopped mode. Ruggedness, overload capacity, and a high degree of repeatability are some of its main attributes.

All the investigators used coaxial shunts and wide-band wattmeters for the power measurements. The importance of using this type of equipment in the chopper-controlled mode of operation has been extensively investigated and reported by others. References 15 to 18 discuss various aspects of the measurement problem. Even though all the investigators who conducted these motor/controller test activities were aware of the problems and expended a considerable amount of effort on instrument calibration, the results are generally not as precise as desired. The lack of a generally recognized calibration standard that can check complete systems, the high peak-to-average ratio of the measured values at low duty cycles, and the difficulties of eliminating noise pickup are chiefly responsible for the lack of precision. Current and power measurement standards for nonsinusoidal signals and high-current shunts are being addressed by the National Bureau of Standards under an agreement with the Department of Energy. In the tests at Eaton Corporation, the input signals were floated by using battery-powered, optically isolated front ends in the instruments. This technique eliminated all possibilities of ground loops and reduced the common mode rejection problem. In addition, references 4, 5, and 10 to 13 contain data from which the size of the error that results from using the product of the average values of voltage and current instead of a wattmeter reading may be determined over a wide range of operating conditions. The 3E Vehicles report (ref. 10) notes that when using dc instrumentation the measurements taken on the battery side of the chopper are within a few percent of the actual value and are acceptable for typical in-vehicle monitoring. On the other hand, measurements taken with dc instrumentation on the motor side of the chopper have large errors and are probably not acceptable, even for in-vehicle monitoring.

Each investigator employed different methods for data acquisition, reduction, and presentation. In the 3E Vehicles tests, these tasks were all performed manually. In contrast, Eaton used a computer to do the same work. For the tests at the Lewis Research Center, a data logger recorded the data but the remaining tasks were performed manually. At the University of Pittsburgh, the data were manually recorded and selectively fed to a computer. Each method has its own merits and problems. Manual methods are relatively slow and prone to errors, but the equipment requirements are much simpler and the methods are very versatile. In general, where the quantities of data are relatively small and the investigator wishes to explore various alternatives, the manual methods seem to be most desirable. When the investigator must process large amounts of data in a repeatable manner and can predetermine what data are to be recorded and how they are to be presented, automatic systems become very practical. The Eaton system may be used as a model for future motor-controller testing.

An examination of the various figures and tables that were selected for inclusion in this report indicates substantial variation in the format of the data. Some of this variation is due to the selection criteria, which strove to provide a reasonable cross section of the available data but to avoid extensive duplication. Other variations are a direct result of the diverse purposes of the tests. For instance, the work done at the Lewis Research Center and the University of Pittsburgh was intended to explore some not-well-documented areas of motor-controller performance. The 3E Vehicles and Eaton work was intended to provide vehicle designers with information that would be useful to them. 3E Vehicles took a systems approach and plotted motor-controller-battery data in a manner that would be directly applicable to their vehicle tests. Since Eaton's data was intended to be more general, only their data include information for two different temperature ranges.

CONCLUDING REMARKS

This report summarizes the motor-controller test work that was performed as part of the Electric and Hybrid Vehicle Program of the Department of Energy under the technical direction of the Electric and Hybrid Vehicle Project Office of the Lewis Research Center. The work comprises a good initial step in developing test procedures and good instrumentation practice. Standardized test procedures would enable manufacturers and users to agree on conformance to specifications and would aid them in applying the data to specific applications. The importance of using suitable power supplies and instrumentation was discussed. Data reduction and data presentation are very closely related. Unfortunately, the kinds of data and the manner of presentation that would be most useful to the vehicle designer are not well defined. In addition, the anticipated effects of power supply variations, testing temperatures, manufacturing tolerances, and component substitutions need further consideration.

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TABLE I. - MOTOR SPECIFICATIONS

Type	Series	Series	Shunt	Shunt
Manufacturer	General Electric	Prestolite	Reliance	General Electric
Horsepower	32	(a)	18	20
Voltage, V	165	96	96	96
Current, A	175	(a)	160	175
rpm	5925	(a)	[b]1800/4000	[b]2500/5000
Weight, kg	108	45.5	165.3	99.3

[a]Nameplate data not available.
[b]Base speed/maximum speed.

TABLE II. - GENERAL ELECTRIC MODEL 5BT 2366C10 dc SERIES MOTOR
GENERAL ELECTRIC EV-1 CONTROLLER

(a) General Electric straight dc tests. Temperature range, 25° to 45°C.

BATTERY TAP (VOLTS)	MOTOR FIELD TEMP (°C) #1	MOTOR FIELD TEMP (°C) #2	MOTOR ARMATURE TEMP (°C)	INPUT VOLTAGE (VOLTS)	INPUT CURRENT (AMPS)	OUTPUT TORQUE (Nm)	OUTPUT SPEED (RPM)	COMPENSATED OUTPUT SPEED (RPM)	COMPENSATED OUTPUT POWER (WATTS)	EFFICIENCY (%)
24	31	30	43	25.4	25.6	0.0	3600	3403.7	0.0	0.0
	31	30	36	25.2	30.3	0.7	3000	2853.2	209.2	28.8
	31	30	38	25.1	37.6	1.7	2400	2297.6	409.2	45.3
	30	30	39	25.0	49.0	4.3	1800	1726.3	777.7	66.1
	29	30	41	24.7	71.7	10.5	1200	1165.6	1282.2	74.5
	29	29	39	23.9	156.9	42.0	600	603.2	2654.1	70.5
	28	28	36	22.5	321.3	113.1	300	324.0	3839.0	49.8
48	36	36	52	50.8	33.6	0.4	5925	5599.6	234.7	14.6
	37	36	47	50.6	34.2	1.0	5400	5118.6	536.2	32.7
	38	38	49	50.5	40.1	1.9	4800	4560.2	907.7	47.2
	38	38	51	50.4	45.5	3.0	4200	4000.5	1257.3	57.6
	42	41	57	50.2	53.2	4.7	3600	3437.9	1692.8	66.3
	42	42	60	49.9	63.3	7.3	3000	2882.1	2204.2	72.5
	41	41	63	49.8	79.7	12.4	2400	2314.0	3006.1	78.6
	41	41	68	49.1	112.6	24.2	1800	1758.6	4458.6	82.5
	40	39	62	47.6	215.8	64.0	1200	1210.2	8114.3	78.3
	40	39	70	45.7	343.4	116.8	900	948.9	11611.1	70.4
72	36	36	61	76.1	51.5	3.7	5925	5605.7	2172.9	58.6
	39	39	64	75.6	56.3	5.2	5400	5139.5	2799.9	69.1
	41	41	66	75.4	63.2	6.9	4800	4579.4	3310.3	72.7
	42	42	70	75.3	72.3	9.7	4200	4016.5	4081.6	78.4
	42	42	75	74.9	85.3	13.8	3600	3458.0	4999.4	81.4
	43	42	78	74.5	105.5	21.2	3000	2899.6	6439.9	84.8
	43	43	81	73.5	147.9	36.9	2400	2349.8	9083.8	85.3
	43	43	78	71.2	257.2	79.5	1800	1820.7	15164.1	81.9
	43	42	85	69.3	363.3	123.5	1500	1561.5	20203.2	77.2

[a]From reference 13.

TABLE II. - Continued.

(a) Concluded.

BATTERY TAP (VOLTS)	MOTOR FIELD TEMP (°C) #1	MOTOR FIELD TEMP (°C) #2	MOTOR ARMATURE TEMP (°C)	INPUT VOLTAGE (VOLTS)	INPUT CURRENT (AMPS)	OUTPUT TORQUE (Nm)	OUTPUT SPEED (RPM)	COMPENSATED OUTPUT SPEED (RPM)	COMPENSATED OUTPUT POWER (WATTS)	EFFICIENCY (%)
96	38	38	67	100.9	69.9	8.2	5925	5633.0	4839.1	72.1
	41	41	67	100.5	76.1	10.3	5400	5156.9	5564.6	76.2
	43	42	72	100.2	87.1	13.8	4800	4598.3	6647.9	79.5
	44	44	75	99.8	101.8	19.2	4200	4039.5	8125.3	83.1
	44	44	78	99.1	125.8	28.2	3600	3487.5	10303.3	85.3
	44	44	75	97.6	176.0	46.7	3000	2948.7	14426.4	85.4
	44	44	83	94.9	283.5	88.9	2400	2429.7	22629.0	83.1
	45	45	91	92.5	376.9	126.0	2100	2184.3	28833.3	79.7
120	35	35	56	126.1	90.2	14.6	5925	5636.0	8620.6	79.6
	38	37	59	125.2	101.0	18.2	5400	5173.6	9864.5	81.4
	40	40	64	124.8	119.0	25.0	4800	4612.7	12081.1	84.6
	41	40	68	123.8	147.6	35.9	4200	4068.7	15302.5	86.4
	41	41	71	122.1	202.3	56.1	3600	3537.8	20792.5	85.7
	41	41	72	118.6	308.8	97.7	3000	3037.0	31085.0	83.9
	45	45	83	116.2	390.4	129.8	2700	2791.9	37965.2	81.0
144	38	37	59	150.2	114.5	23.3	5925	5678.2	13860.5	84.1
	43	42	65	149.5	132.0	29.7	5400	5201.0	16182.8	85.1
	44	44	76	148.1	163.7	41.5	4800	4664.3	20279.0	86.0
	41	41	77	146.2	216.6	61.8	4200	4135.7	26776.2	85.8
	40	40	75	142.1	322.4	101.3	3600	3650.3	38739.1	83.4
	45	45	90	139.1	401.2	130.3	3300	3419.5	46678.7	80.8

TABLE II. - Continued.

(b) General Electric chopped dc tests. Temperature range, 25-45°C; controller input tap, 144 volts.

MOTOR INPUT VOLTAGE NOMINAL	TEMPERATURE °C FIELD #1	FIELD #2	ARMATURE	CHOPPER INPUT VOLTAGE AVG.	RMS	CHOPPER INPUT CURRENT (AMPS) AVG.	RMS	CHOPPER INPUT POWER (WATTS)	CHOPPER OUTPUT VOLTAGE AVG.	RMS	CHOPPER OUTPUT CURRENT (AMPS) AVG.	RMS	CHOPPER OUTPUT POWER (WATTS)	MOTOR OUTPUT SPEED (RPM)	TORQUE (Nm)	POWER (WATTS)	EFFICIENCY (%)
24	42	41	46	147.2	149.2	15.4	43.3	2128.2	23.5	55.2	27.9	53.9	2048.2	3600	1.3	490.3	23.9
	42	42	46	146.8	148.8	16.9	46.1	2336.3	23.4	56.5	33.8	59.5	2214.1	3000	2.0	628.6	28.4
	43	43	47	146.4	148.6	18.2	48.4	2469.5	22.8	57.1	41.6	65.4	2327.8	2400	3.3	829.7	35.6
	43	43	48	146.4	148.4	21.1	54.0	2901.3	24.4	60.0	54.4	75.5	2758.6	1800	5.8	1093.7	39.6
	43	43	51	145.8	148.1	25.2	63.1	3455.6	24.2	59.9	77.3	94.7	3336.5	1200	12.4	1558.9	46.7
	43	43	55	143.9	146.8	46.7	108.4	5775.2	24.2	56.4	170.4	184.2	5508.7	600	48.1	3023.5	54.9
	45	45	56	138.9	144.3	94.5	195.0	10171.6	24.0	51.0	344.4	351.7	9586.5	300	122.0	3834.4	40.0
48	42	42	51	145.8	146.7	26.3	52.1	3707.7	46.8	76.8	34.4	56.9	3488.0	5925	1.8	1117.5	32.0
	44	44	53	145.3	146.5	28.3	54.8	3998.2	46.5	77.7	37.8	60.7	3754.7	5400	2.5	1414.3	37.7
	45	45	57	144.7	146.4	31.6	58.5	4386.5	47.1	79.7	43.0	65.3	4114.6	4800	3.4	1709.7	41.6
	45	45	58	144.6	145.8	34.5	62.6	4832.5	48.1	81.4	79.4	71.2	4542.1	4200	4.7	2068.0	45.5
	45	45	60	144.2	145.5	37.7	66.9	5175.3	47.6	82.2	57.1	77.5	4834.7	3600	6.5	2451.5	50.7
	45	45	65	143.4	145.1	41.8	73.4	5789.9	47.3	83.3	68.0	87.1	5435.1	3000	9.4	2954.3	54.4
	45	45	68	142.5	144.4	48.6	83.8	6551.6	47.0	82.2	85.5	102.2	6182.6	2400	14.9	3746.4	60.6
	45	45	72	141.6	144.3	64.8	108.8	8639.7	47.9	83.5	123.6	139.3	8154.8	1800	28.5	5374.4	65.9
	45	45	73	135.4	140.4	123.5	192.3	14508.3	47.3	76.7	249.4	261.0	13615.2	1200	79.1	9944.2	73.0
	45	45	75	124.1	133.7	239.6	332.1	23911.0	47.3	71.2	431.2	437.9	22559.6	900	156.3	14737.1	65.3
72	45	45	54	143.4	144.5	40.5	63.3	5734.4	69.9	97.5	50.4	68.7	5519.4	5925	4.8	2979.5	54.0
	45	45	57	143.3	144.3	43.9	67.1	6070.0	70.4	8.5	55.0	73.2	5844.4	5400	6.0	3394.3	58.1
	45	45	62	142.8	144.3	47.8	72.2	6630.9	70.6	99.6	62.2	79.7	6399.7	4800	7.8	3922.4	61.3
	45	45	64	142.2	143.9	52.9	78.5	7279.3	70.4	100.1	71.1	87.5	6999.1	4200	10.4	4576.1	65.4
	45	45	66	140.6	143.3	60.1	88.1	8166.9	70.4	100.4	84.2	99.2	7895.3	3600	14.4	5430.9	68.8
	45	45	66	[illegible]	141.7	72.0	103.6	9650.9	70.0	99.2	105.2	119.4	9303.1	3000	21.6	6788.7	73.0
	45	45	68	138.0	141.5	98.2	137.4	12937.3	71.1	99.8	148.5	162.1	12541.5	2400	37.8	9504.2	75.8
	[illegible]	42	[illegible]	129.7	135.0	179.8	255.0	21075.0	70.3	93.0	267.9	278.0	20232.1	1800	85.2	16066.6	79.4
	45	43	82	118.4	125.7	265.5	354.5	30516.7	70.4	87.7	403.5	414.0	29215.6	1500	142.3	22561.8	76.5

TABLE II. - Concluded.

(b) Concluded.

MOTOR INPUT VOLTAGE NOMINAL	TEMPERATURE °C FIELD #1	FIELD #2	ARMATURE	CHOPPER INPUT VOLTAGE AVG.	RMS	CHOPPER INPUT CURRENT (AMPS) AVG.	RMS	CHOPPER INPUT POWER (WATTS)	CHOPPER OUTPUT VOLTAGE AVG.	RMS	CHOPPER OUTPUT CURRENT (AMPS) AVG.	RMS	CHOPPER OUTPUT POWER (WATTS)	MOTOR OUTPUT SPEED (RPM)	TORQUE (Nm)	POWER (WATTS)	EFFICIENCY (%)
96	45	45	55	141.6	142.4	58.5	65.3	8199.6	94.1	115.5	68.0	80.3	7843.6	5925	9.1	5648.6	72.0
	45	45	66	141.2	141.9	63.9	81.3	8894.9	94.7	115.9	75.4	87.7	8565.6	5400	11.3	6392.6	74.6
	45	45	69	139.9	141.7	72.1	90.4	9961.7	94.9	115.9	86.0	97.8	9623.7	4800	14.7	7392.1	76.8
	45	45	72	137.4	140.2	83.0	103.4	11446.6	93.9	115.1	101.4	112.2	10964.7	4200	20.0	8800.2	80.3
	45	45	74	135.9	139.0	101.4	124.6	13620.4	93.9	114.0	125.9	136.5	13045.1	3600	29.1	10975.1	84.1
	45	45	77	132.4	135.0	142.5	169.5	18393.6	94.3	111.7	177.1	186.6	17728.3	3000	47.9	15054.6	84.9
	45	45	80	130.8	124.7	259.8	290.2	30144.4	94.2	104.8	305.4	313.3	29096.6	2400	99.2	24942.2	85.7
	45	44	84	108.3	112.7	386.4	411.5	40858.5	93.7	100.7	422.4	430.1	38402.5	2100	146.9	32318.6	84.2
120	42	41	57	140.2	141.3	80.9	90.8	11387.9	116.6	129.5	86.7	93.7	10916.5	5925	12.1	7510.8	68.8
	43	42	62	139.7	140.5	87.2	97.7	12208.4	116.7	129.0	94.1	101.1	11624.0	5400	15.9	8995.0	77.3
	43	43	64	138.0	139.1	105.3	116.8	14522.4	116.7	128.1	114.7	121.3	14003.5	4800	21.9	11012.7	78.6
	44	44	70	134.0	137.0	133.0	144.9	18001.9	117.0	127.5	144.4	150.6	17422.1	4200	32.7	14388.3	82.6
	44	44	81	130.1	131.1	185.3	197.4	24069.8	117.1	123.9	197.9	103.9	23237.1	3600	53.0	19988.9	86.0
	44	44	86	118.6	119.4	303.6	310.5	36265.4	115.1	117.7	310.4	313.4	35174.6	3000	96.9	30454.8	86.6
	45	45	88	112.7	114.5	357.7	363.6	40978.7	109.5	112.3	362.4	363.6	39231.3	2700	117.2	33151.5	84.5
144	44	44	65	137.9	138.4	103.7	105.6	14805.5	136.4	139.4	106.9	108.3	14173.4	5925	18.7	11607.6	81.9
	45	45	67	137.2	137.5	116.8	119.2	16598.2	135.7	137.4	120.0	121.5	16046.8	5400	23.5	13294.5	82.8
	45	45	71	133.8	135.7	138.1	141.3	19161.5	133.6	134.7	142.2	142.6	18464.3	4800	31.5	15840.3	85.8
	45	45	78	130.4	131.6	172.3	175.0	22805.4	128.3	131.4	176.4	178.2	22041.1	4200	43.9	19316.4	87.6
	45	45	86	126.1	126.9	222.4	225.7	28375.2	124.3	125.3	228.0	229.7	27381.6	3600	64.0	24137.6	88.1
	45	45	92	118.9	120.1	302.8	307.9	36785.7	115.7	117.8	311.0	313.7	35341.0	3000	97.1	30517.7	86.4
	45	45	92	112.7	114.8	352.5	364.1	40767.0	109.2	111.3	358.3	361.6	39250.3	2700	116.2	32868.6	83.7

TABLE III. - RELIANCE MODEL EV250AT dc SHUNT MOTOR
GENERAL ELECTRIC EV-1 CONTROLLER[a]

(a) Reliance straight dc tests. Field loss, 9 amperes at 90 volts (810 W); temperature range, 25° to 45°C.

BATTERY TAP (VOLTS)	MOTOR FIELD TEMP (°C)		MOTOR ARMATURE TEMP (°C)	INPUT VOLTAGE (VOLTS)	INPUT CURRENT (AMPS)	OUTPUT TORQUE (Nm)	OUTPUT SPEED (RPM)	COMPENSATED OUTPUT SPEED (RPM)	COMPENSATED OUTPUT POWER (WATTS)	EFFICIENCY (%)
	#1	#2								
16	31	31	31	16.7	9.9	0.1	285	273.5	2.9	0.2
	31	31	31	16.6	20.6	6.5	265	255.5	174.0	15.3
	31	31	31	16.3	37.6	16.1	245	239.8	404.9	28.7
	32	31	31	16.2	66.9	30.5	225	222.8	711.9	37.9
	32	32	32	16.0	94.5	45.3	205	204.8	982.7	42.3
	32	32	32	15.8	123.2	64.4	185	188.1	1269.1	45.6
	33	33	33	15.6	151.7	78.3	165	169.8	1392.9	43.0
	34	33	33	15.4	188.0	97.7	145	152.6	1562.0	40.9
	33	33	34	15.0	221.2	116.9	125	136.3	1669.3	38.4
24	31	31	30	25.4	11.6	0.1	435	410.8	4.3	0.4
	33	33	31	25.0	26.7	7.4	415	398.9	309.3	21.3
	34	34	32	24.8	43.3	16.8	395	382.2	672.7	36.4
	34	34	33	24.4	65.0	28.8	375	367.5	1108.9	46.8
	35	34	33	24.2	94.6	45.4	355	352.4	1676.2	54.4
	35	35	33	23.9	114.6	55.9	335	337.0	1973.7	55.4
	34	34	31	23.6	140.3	71.9	315	320.6	2415.1	57.8
	35	35	31	23.4	167.4	88.1	295	303.5	2801.4	58.0
	36	36	32	23.2	194.9	103.4	275	285.5	3092.9	56.4
36	34	34	33	38.0	13.3	0.0	670	635.1	0.0	0.0
	34	33	33	37.6	22.8	5.4	650	622.1	352.0	21.7
	35	35	34	37.2	36.1	12.6	630	608.8	803.7	38.1
	36	36	35	36.8	54.4	21.3	610	596.7	1331.6	48.1
	37	36	36	36.7	73.4	32.2	590	578.9	1953.0	56.6
	37	36	36	36.3	97.3	45.0	570	565.1	2664.2	61.8
	37	37	36	36.0	115.6	55.0	550	549.7	3167.5	63.7
	37	37	37	35.8	143.2	71.0	530	534.0	3972.2	66.6
	38	38	37	35.6	166.4	85.3	510	516.7	4617.7	67.9
	38	37	37	35.2	198.2	101.8	490	502.0	5354.1	67.4
	38	38	37	35.1	223.2	117.3	470	483.9	5946.9	67.2

[a]From reference 13.

TABLE III. - CONTINUED.

(a) Concluded.

BATTERY TAP (VOLTS)	MOTOR FIELD TEMP (°C)		MOTOR ARMATURE TEMP (°C)	INPUT VOLTAGE (VOLTS)	INPUT CURRENT (AMPS)	OUTPUT TORQUE (Nm)	OUTPUT SPEED (RPM)	COMPENSATED OUTPUT SPEED (RPM)	COMPENSATED OUTPUT POWER (WATTS)	EFFICIENCY (%)
	#1	#2								
64	33	32	33	67.2	16.8	0.1	1215	1156.3	12.1	0.6
	34	34	36	66.6	36.9	11.4	1175	1129.3	1384.8	43.7
	35	35	38	65.6	64.2	26.1	1135	1107.2	3027.6	61.6
	36	35	40	64.6	94.1	42.2	1095	1084.9	4796.6	70.2
	34	34	40	64.0	121.7	60.1	1055	1054.4	6639.2	77.2
	34	34	40	63.5	156.0	78.8	1015	1023.0	8445.7	78.2
	35	34	42	62.8	196.5	102.1	975	994.0	10632.8	79.4
	35	35	42	62.3	237.1	122.3	935	961.6	12321.3	77.1
80	35	35	35	83.6	19.3	0.1	1530	1464.2	15.3	0.6
	36	36	37	82.8	45.0	12.7	1490	1440.1	1916.2	43.4
	35	35	36	82.3	65.1	24.2	1450	1409.0	3572.4	59.4
	36	36	36	81.4	87.6	36.4	1410	1385.3	5283.0	67.6
	37	36	40	80.7	110.2	49.5	1370	1358.1	7043.2	73.2
	38	38	42	80.0	139.4	67.6	1330	1329.7	9417.5	78.7
	41	40	44	79.6	176.1	84.7	1290	1296.9	11508.6	81.2
	41	41	47	78.8	198.5	100.7	1250	1269.5	13393.6	80.2
	41	41	49	78.3	227.9	118.7	1210	1237.5	15389.7	80.8
	41	41	50	77.7	154.9	135.0	1170	1207.1	17073.1	80.5
96	35	35	39	101.8	21.0	0.1	1880	1773.1	18.6	0.7
	35	35	41	101.5	47.0	13.2	1840	1740.1	2406.5	45.2
	35	36	41	99.8	60.7	20.5	1800	1730.8	3717.4	56.0
	36	36	44	98.8	76.1	31.0	1760	1709.8	5553.2	68.4
	38	37	45	98.0	98.8	41.0	1720	1685.2	7238.9	70.3
	38	38	45	97.5	117.8	52.5	1680	1653.9	9097.1	75.1
	39	38	46	97.1	141.4	67.8	1640	1621.3	11517.7	80.1
	39	40	48	96.5	165.5	81.3	1600	1591.5	13556.0	80.1
	39	39	46	95.9	189.5	96.4	1560	1561.1	15776.7	83.0
	40	40	47	95.5	213.3	111.7	1520	1528.8	17891.1	84.0
	39	39	47	94.7	250.6	130.9	1480	1501.2	20587.9	82.8

TABLE III. - CONTINUED.

(b) Reliance straight dc tests. Field loss, 6 amperes at 60 volts (360 W); temperature range, 25° to 45°C.

BATTERY TAP (VOLTS)	MOTOR FIELD TEMP (°C)		MOTOR ARMATURE TEMP (°C)	INPUT VOLTAGE (VOLTS)	INPUT CURRENT (AMPS)	OUTPUT TORQUE (Nm)	OUTPUT SPEED (RPM)	COMPENSATED OUTPUT SPEED (RPM)	COMPENSATED OUTPUT POWER (WATTS)	EFFICIENCY (%)
	#1	#2								
96	43	42	44	101.3	18.3	0.1	2150	2037.5	21.3	1.0
	43	43	45	100.7	30.7	6.8	2100	2002.2	1426.4	43.1
	43	43	46	100.0	49.5	15.3	2050	1967.0	3153.0	61.7
	44	43	47	99.5	65.5	22.3	2000	1929.2	4507.3	67.8
	44	44	47	98.7	82.8	32.1	1950	1895.6	6375.1	76.7
	44	44	50	98.3	104.4	44.6	1900	1855.1	8668.4	83.5
	44	44	47	97.5	125.9	53.8	1850	1820.9	10263.7	82.5
	44	44	52	96.6	149.7	67.0	1800	1787.9	12550.3	85.2
	44	44	51	96.4	171.8	79.3	1750	1742.5	14477.1	85.9
	45	44	51	95.5	200.6	92.0	1700	1709.5	16477.5	84.0
	45	44	52	94.5	222.5	103.8	1650	1677.8	18246.2	84.0
	45	44	53	94.2	156.9	122.4	1600	1632.6	20936.1	83.7

TABLE III. - CONTINUED.

(c) Reliance straight dc tests. Field loss, 3 amperes at 30 volts (90 W); temperature range, 25° to 45°C.

BATTERY TAP (VOLTS)	MOTOR FIELD TEMP (°C)		MOTOR ARMATURE TEMP (°C)	INPUT VOLTAGE (VOLTS)	INPUT CURRENT (AMPS)	OUTPUT TORQUE (Nm)	OUTPUT SPEED (RPM)	COMPENSATED OUTPUT SPEED (RPM)	COMPENSATED OUTPUT POWER (WATTS)	EFFICIENCY (%)
	#1	#2								
96	34	35	39	101.2	15.4	0.1	3100	2941.8	30.8	2.0
	35	35	39	100.3	33.2	6.1	2950	2822.9	1804.1	55.1
	36	36	39	99.7	50.6	12.5	2800	2696.6	3531.5	71.4
	37	37	39	98.8	72.6	20.5	2650	2574.0	5528.4	78.3
	36	36	41	98.1	95.4	29.9	2500	2444.8	7831.5	84.7
	36	36	41	97.1	123.3	41.0	2350	2322.0	9974.3	83.6
	37	36	41	96.4	158.1	56.2	2200	2191.8	12905.4	84.5
	37	36	43	95.3	199.0	73.4	2050	2064.8	15878.5	82.7
	36	36	43	93.8	244.4	94.0	1900	1946.5	19169.8	81.4
	35	36	43	92.4	301.2	119.8	1750	1822.6	22876.1	78.9

TABLE III. - CONTINUED.

(d) Reliance straight dc tests. Field loss, 2.3 amperes at 23 volts (53 W); temperature range, 25° to 45°C.

BATTERY TAP (VOLTS)	MOTOR FIELD TEMP (°C)		MOTOR ARMATURE TEMP (°C)	INPUT VOLTAGE (VOLTS)	INPUT CURRENT (AMPS)	OUTPUT TORQUE (Nm)	OUTPUT SPEED (RPM)	COMPENSATED OUTPUT SPEED (RPM)	COMPENSATED OUTPUT POWER (WATTS)	EFFICIENCY (%)
	#1	#2								
96	39	39	39	100.7	15.3	0.1	3800	3621.6	37.9	2.4
	41	40	41	100.2	27.6	3.3	3600	3448.4	1192.2	44.1
	42	40	42	99.6	41.7	7.5	3400	3276.8	2574.8	63.5
	42	42	43	98.9	55.4	12.3	3200	3104.8	4001.0	74.5
	42	42	43	98.3	75.6	20.1	3000	2828.9	5957.3	81.5
	42	42	43	97.5	98.4	27.2	2800	2755.3	7851.9	82.7
	42	42	45	96.6	123.3	37.0	2600	2582.6	10011.4	84.2
	43	43	44	96.0	154.2	51.2	2400	2399.6	12871.9	86.6
	43	43	44	95.1	196.5	66.9	2200	2221.5	15570.7	82.3
	43	43	45	93.3	250.8	90.2	2000	2060.4	19471.2	80.7
	43	43	48	92.0	317.8	116.5	1800	1882.8	22980.8	75.2

TABLE III. - CONTINUED.

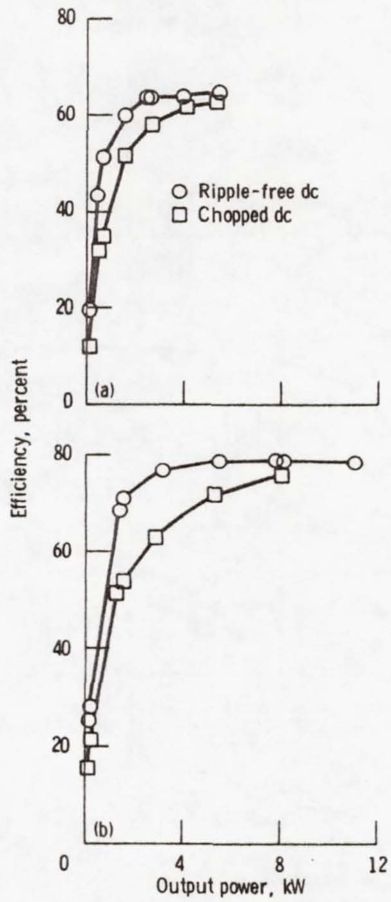
(e) Reliance chopped dc tests. Field loss 9 amperes at 90 volts (810 W); temperature range, 25° to 45°C; controller input tap, 96 volts.

MOTOR INPUT VOLTAGE NOMINAL	TEMPERATURE °C FIELD #1	TEMPERATURE °C FIELD #2	TEMPERATURE °C ARMATURE	CHOPPER INPUT VOLTAGE AVG.	CHOPPER INPUT VOLTAGE RMS	CHOPPER INPUT CURRENT (AMPS) AVG.	CHOPPER INPUT CURRENT (AMPS) RMS	CHOPPER INPUT POWER (WATTS)	CHOPPER OUTPUT VOLTAGE AVG.	CHOPPER OUTPUT VOLTAGE RMS	CHOPPER OUTPUT CURRENT (AMPS) AVG.	CHOPPER OUTPUT CURRENT (AMPS) RMS	CHOPPER OUTPUT POWER (WATTS)	MOTOR OUTPUT SPEED (RPM)	MOTOR OUTPUT TORQUE (Nm)	MOTOR OUTPUT POWER (WATTS)	MOTOR OUTPUT EFFICIENCY (%)
16	38	38	41	100.2	102.1	4.6	26.8	411.8	15.9	21.4	13.3	43.9	362.7	285	1.0	29.9	2.5
	38	37	41	100.2	101.0	12.1	42.8	1028.6	16.0	24.1	36.7	73.8	854.2	265	15.0	416.5	25.0
	38	37	42	99.9	101.0	18.8	55.7	1693.1	15.9	29.2	63.5	97.2	1420.9	245	27.6	708.5	31.8
	37	36	41	98.7	100.5	24.4	65.1	2122.1	15.8	31.5	87.4	116.9	1719.1	225	44.0	1037.2	41.0
	36	36	40	95.4	99.7	31.3	76.6	3859.5	15.8	33.7	115.9	142.7	2271.9	205	59.7	1282.2	41.6
	37	36	40	97.5	99.7	40.1	92.8	3575.9	15.9	35.6	150.7	168.5	3097.4	185	78.7	1525.4	39.0
	36	36	40	96.7	99.5	48.4	106.0	4137.5	15.8	35.6	185.0	202.7	3549.2	165	97.8	1590.7	38.8
	36	36	40	96.6	100.4	59.1	122.6	4860.6	16.1	36.4	218.7	233.8	4217.7	145	115.6	1656.1	34.9
	37	36	40	94.5	98.0	66.6	133.5	5399.9	15.8	34.6	240.3	253.1	4593.2	125	131.4	1720.8	31.8
24	36	36	36	101.2	102.5	4.7	23.5	380.3	23.7	26.7	11.4	36.5	297.7	435	0.2	9.1	0.8
	36	36	36	100.5	102.5	7.8	34.1	730.4	23.6	28.0	22.5	54.9	628.3	415	6.3	273.9	19.0
	36	36	36	99.8	101.5	15.6	46.8	1427.4	23.8	34.5	44.6	78.1	1281.3	395	17.7	732.5	35.0
	36	36	36	98.6	101.6	25.1	65.5	2300.6	23.8	36.4	70.5	102.5	2056.2	375	30.6	1202.2	41.9
	36	36	36	97.7	99.8	36.5	77.8	3301.3	23.8	38.6	102.5	131.1	2983.2	355	50.1	1863.4	49.1
	35	35	35	96.6	99.3	45.5	94.5	4318.9	23.9	43.5	129.0	153.6	3790.7	335	62.4	2190.1	47.6
	35	35	35	95.0	97.7	57.7	108.1	5038.3	23.8	44.0	164.7	184.7	4531.6	315	82.2	2712.8	50.8
	35	35	35	93.6	98.2	69.8	127.1	6084.4	23.9	44.4	197.1	213.0	5332.8	295	100.7	3112.3	50.7
	36	35	35	92.4	97.1	83.4	147.6	6864.7	23.6	41.4	226.8	237.2	5988.1	275	119.5	3443.0	50.6
36	32	32	33	101.3	102.4	4.6	23.6	574.8	36.0	38.7	11.0	30.6	470.7	670	2.0	140.4	11.0
	32	32	32	99.7	100.6	15.2	44.5	1608.2	36.0	43.6	30.8	62.2	1421.1	650	10.6	721.7	32.3
	31	31	32	97.6	99.5	30.5	65.9	2813.2	36.1	46.5	60.3	90.8	2542.4	630	25.4	1676.5	50.0
	31	30	31	97.4	99.4	39.5	76.3	3628.6	36.0	47.8	77.5	105.7	3248.6	610	35.6	2275.2	56.0
	31	31	32	96.0	97.6	53.6	92.4	4698.9	36.0	50.3	106.0	128.8	4389.7	590	41.0	3152.5	60.6
	31	31	30	94.2	97.5	65.9	110.3	5870.4	36.0	51.3	126.4	149.4	5343.9	570	62.4	3725.4	60.7
	29	29	30	93.5	96.6	82.0	129.8	7270.6	36.0	53.2	157.6	175.5	6629.7	550	79.9	4604.1	61.9
	29	29	31	91.4	95.5	95.4	144.4	8080.9	36.0	51.4	187.8	201.0	7494.2	530	94.3	5236.3	63.1
	33	33	36	90.4	93.9	112.3	166.5	9197.4	36.0	52.0	214.6	227.5	8384.9	510	112.1	5989.8	65.1
	33	33	37	88.6	93.6	134.1	192.4	10594.3	36.0	50.2	250.2	259.9	9597.5	490	131.5	6750.8	64.9
	36	36	39	87.1	93.0	154.3	210.6	11922.9	35.0	50.4	267.8	282.7	10544.7	470	144.7	7125.3	62.8

TABLE III. - CONCLUDED.

(e) Concluded.

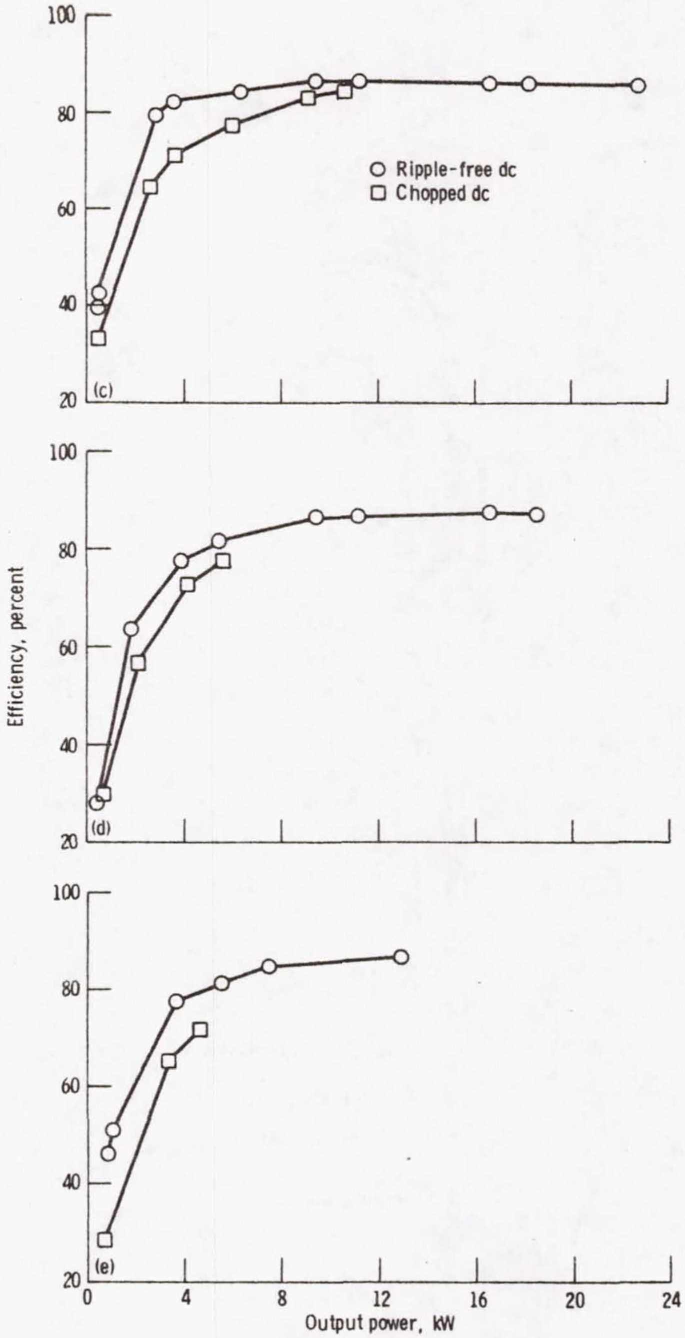
MOTOR INPUT VOLTAGE NOMINAL	TEMPERATURE °C FIELD #1	TEMPERATURE °C FIELD #2	TEMPERATURE °C ARMATURE	CHOPPER INPUT VOLTAGE AVG.	CHOPPER INPUT VOLTAGE RMS	CHOPPER INPUT CURRENT (AMPS) AVG.	CHOPPER INPUT CURRENT (AMPS) RMS	CHOPPER INPUT POWER (WATTS)	CHOPPER OUTPUT VOLTAGE AVG.	CHOPPER OUTPUT VOLTAGE RMS	CHOPPER OUTPUT CURRENT (AMPS) AVG.	CHOPPER OUTPUT CURRENT (AMPS) RMS	CHOPPER OUTPUT POWER (WATTS)	MOTOR OUTPUT SPEED (RPM)	MOTOR OUTPUT TORQUE (Nm)	MOTOR OUTPUT POWER (WATTS)	MOTOR OUTPUT EFFICIENCY (%)
64	31	31	31	101.3	102.7	4.5	17.0	475.9	63.5	65.6	6.1	18.3	410.6	1215	0.5	63.6	5.2
	32	32	32	97.6	99.6	28.6	50.7	2875.1	63.8	69.1	45.8	58.3	2541.2	1175	12.0	1477.2	44.1
	34	33	35	96.4	97.6	44.9	68.0	4295.8	64.0	71.5	56.6	77.9	4099.3	1135	23.2	2758.8	56.2
	33	34	34	92.6	94.2	77.7	101.8	6990.8	63.9	70.9	97.6	116.7	6688.5	1095	45.5	5220.0	69.6
	31	31	30	89.8	93.0	112.5	140.5	10042.9	63.8	73.2	140.9	157.9	9527.7	1055	70.5	7792.5	75.4
	32	32	31	86.5	89.2	156.3	182.0	13760.8	63.7	71.0	188.4	200.7	12579.1	1015	96.6	10262.5	76.7
	32	32	31	81.6	84.5	209.9	231.0	16732.1	63.8	68.9	242.5	250.5	15836.9	975	127.2	12993.5	78.1
	35	35	34	76.1	77.9	269.6	281.8	20093.4	63.5	66.6	293.9	300.6	19094.5	935	155.6	15242.5	76.6
80	35	34	37	98.8	99.8	10.5	14.6	1098.2	80.0	83.1	10.5	18.1	956.3	1530	0.7	112.2	6.4
	34	34	36	95.5	97.4	40.9	51.7	3913.1	80.1	83.4	45.7	56.1	3725.1	1490	14.2	2216.7	48.9
	34	33	37	93.4	95.4	70.9	85.3	6805.4	79.9	83.0	78.4	91.0	6625.0	1450	32.4	4922.1	66.2
	34	34	37	91.4	92.1	100.9	112.8	9301.0	79.9	82.7	108.4	119.6	9037.4	1410	49.6	7527.2	74.4
	34	34	36	87.4	88.7	142.1	148.1	12572.2	80.1	81.3	146.9	154.6	12256.5	1370	73.4	10535.4	80.6
	35	35	38	85.2	86.4	158.1	163.0	13749.0	78.7	80.7	166.6	170.0	13348.3	1330	81.4	11342.5	80.1
	35	34	38	84.5	85.5	171.1	176.4	14690.5	77.5	78.1	180.3	185.9	14367.9	1290	91.5	12366.5	81.5
	35	35	38	83.5	84.6	191.0	196.1	16072.7	76.3	77.6	201.2	204.7	15632.1	1250	100.0	13096.2	79.7
	34	35	37	82.5	83.5	201.4	207.3	16878.1	74.2	76.5	211.7	217.2	16247.0	1210	108.8	13792.7	80.9
	38	37	41	80.5	81.4	212.0	218.6	17300.1	72.9	74.5	223.0	228.2	16792.2	1170	117.0	14341.9	81.5



(a) 52 rad/sec (500 rpm).

(b) 105 rad/sec (1000 rpm).

Figure 1. - Motor efficiency at constant speed.



(c) 209 rad/sec (2000 rpm).

(d) 314 rad/sec (3000 rpm).

(e) 419 rad/sec (4000 rpm).

Figure 1. - Concluded.

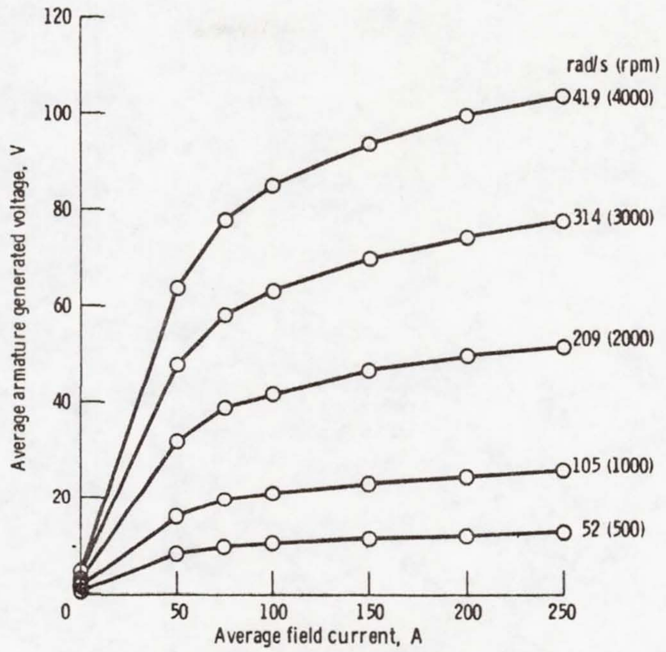


Figure 2. - Magnetic saturation curves at constant speed with brushes on neutral.

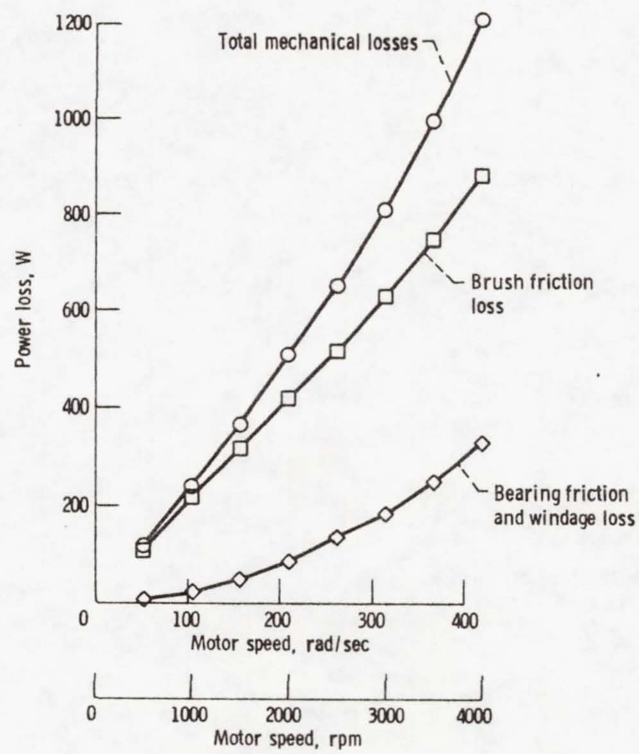


Figure 3. - Mechanical power losses.

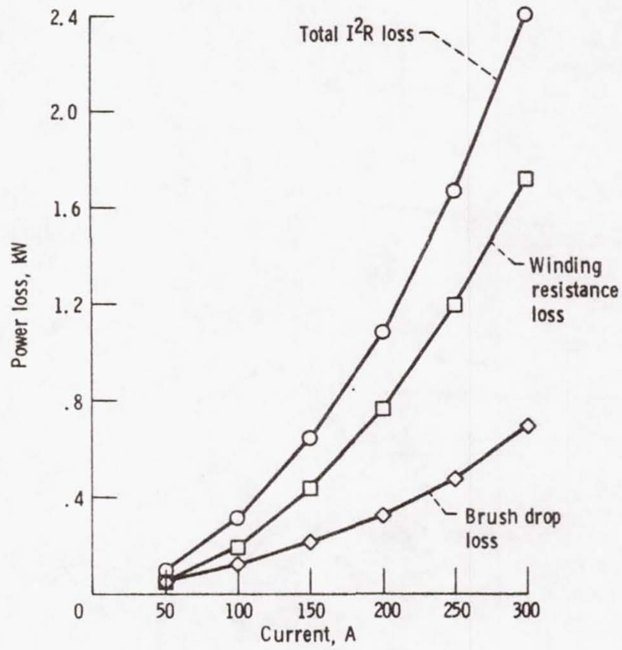


Figure 4. - I^2R power losses.

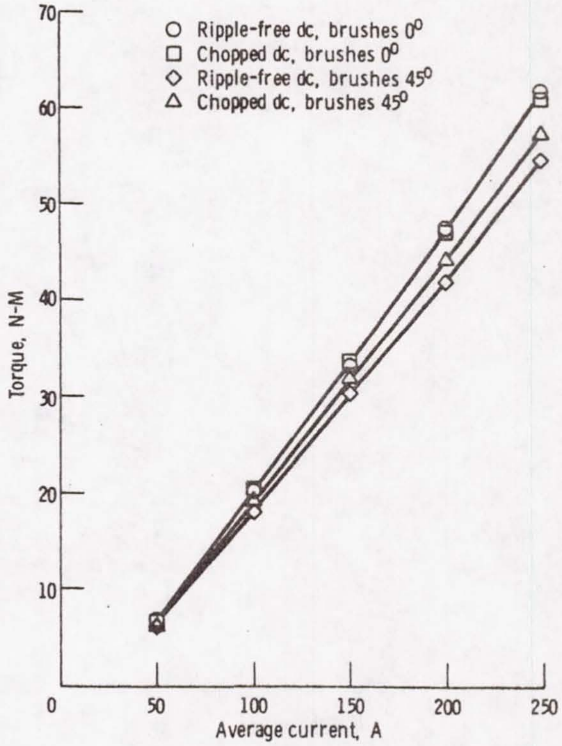


Figure 5. - Locked-rotor torque.

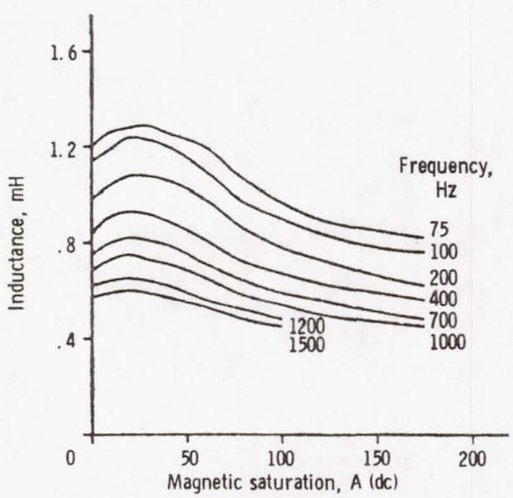


Figure 6. - Inductance as function of frequency and magnetic saturation (ref. 8). Copper blocks on 0^0; fields in series.

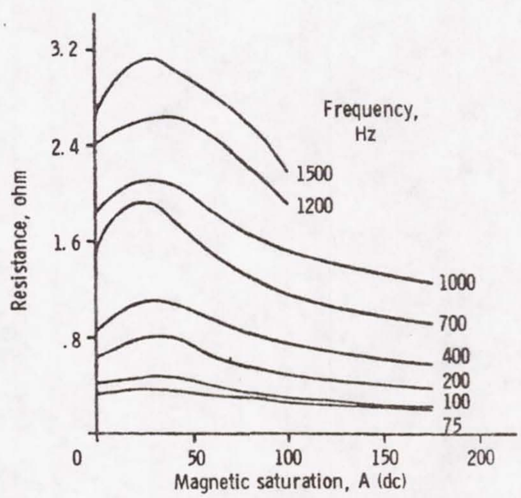


Figure 7. - Resistance as function of frequency and magnetic saturation (ref. 8). Copper blocks on 0^0; fields in series.

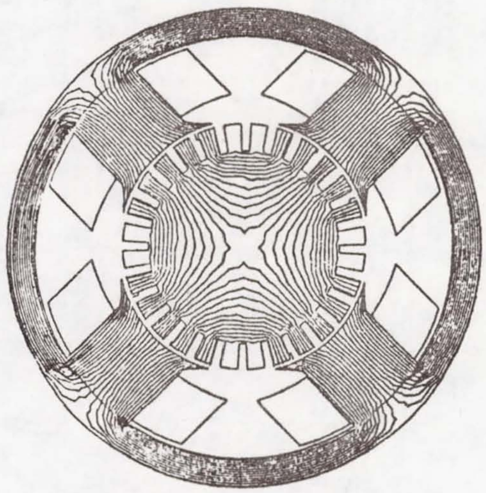


Figure 8. - Flux map, no eddy currents (ref. 9).

Figure 9. - Flux map with eddy currents in the frame (ref. 9).

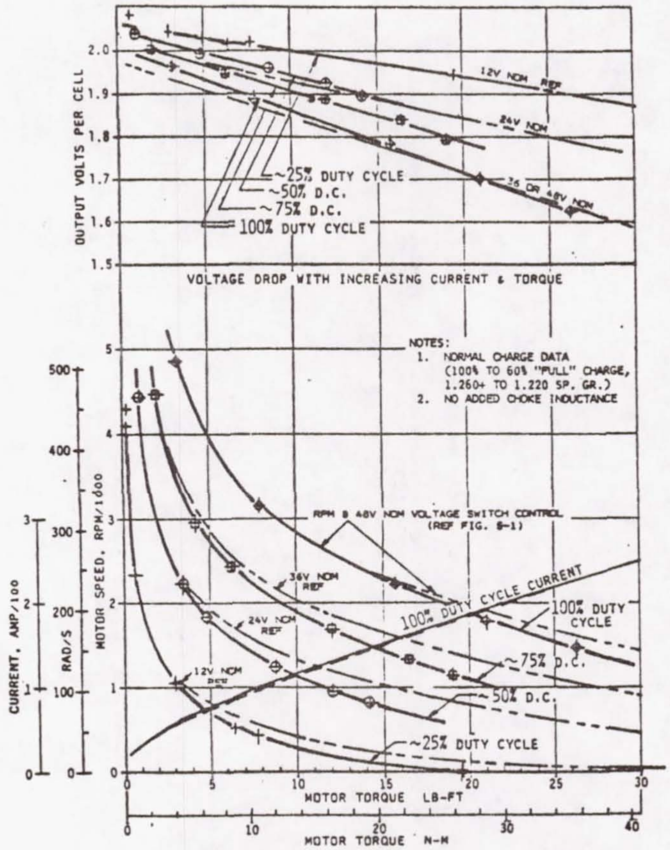


Figure 10. - Comparison of chopper-controlled and voltage-controlled series motor (ref. 10).

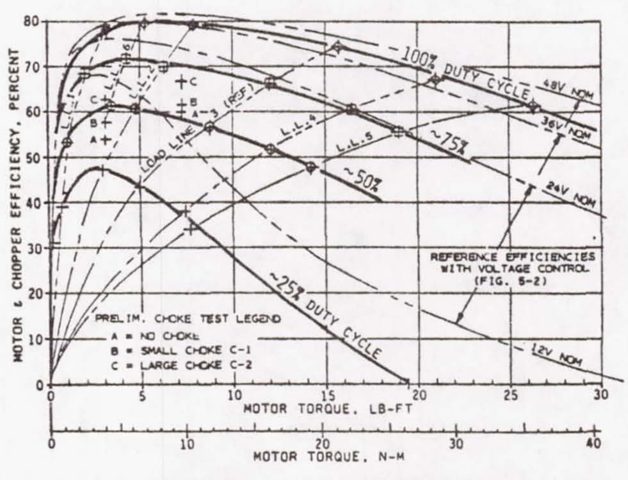


Figure 11. - Chopper-controlled series motor efficiency (without choke) and preliminary choke test results (ref. 10).

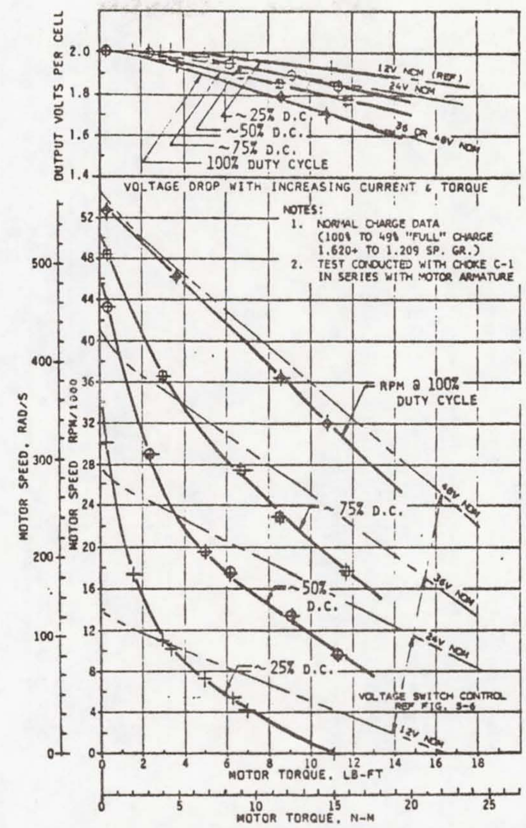


Figure 12. - Comparison of chopper-controlled and voltage-controlled permanent magnet motor (ref. 10).

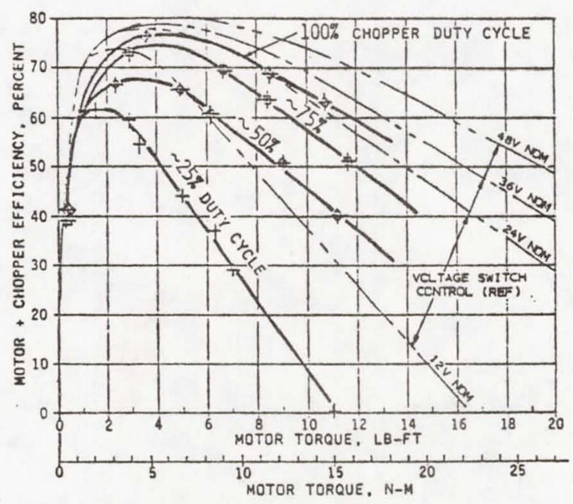
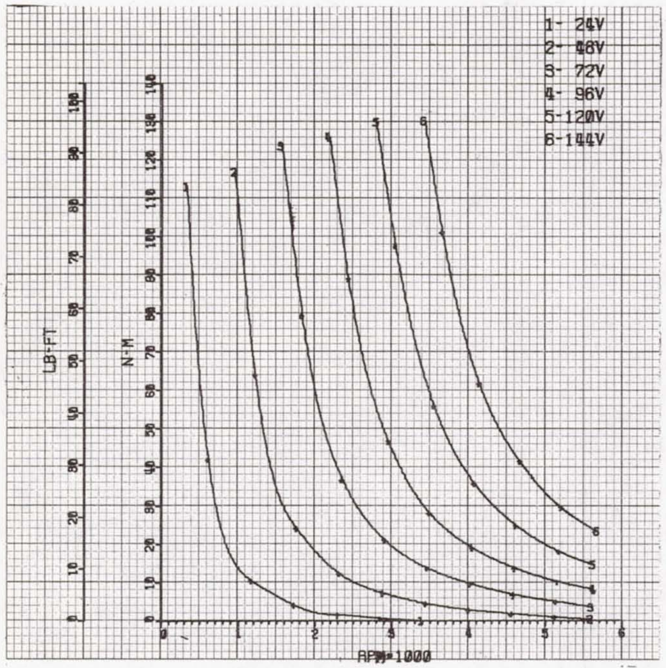
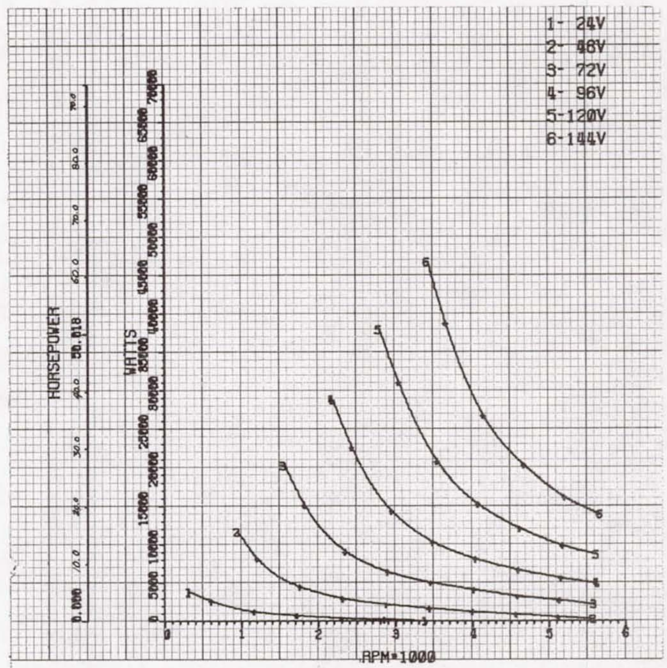


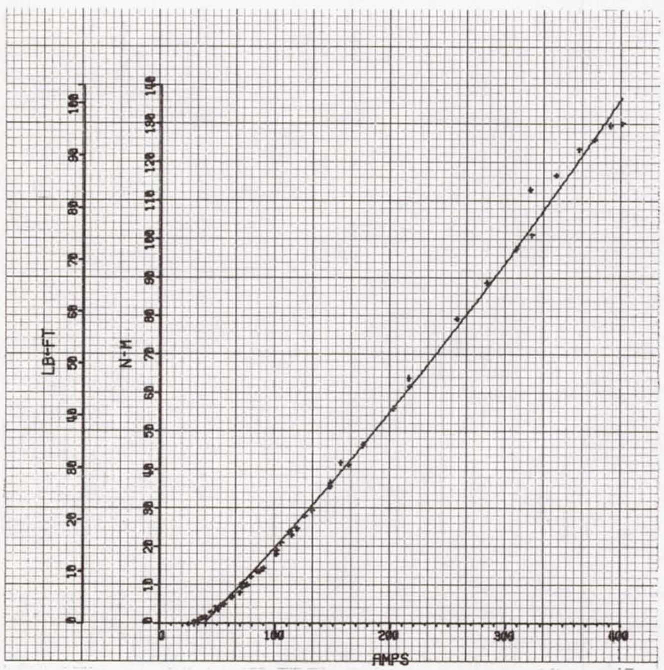
Figure 13. - Efficiency of chopper-controlled permanent magnet motor with choke C-1 (ref. 10).



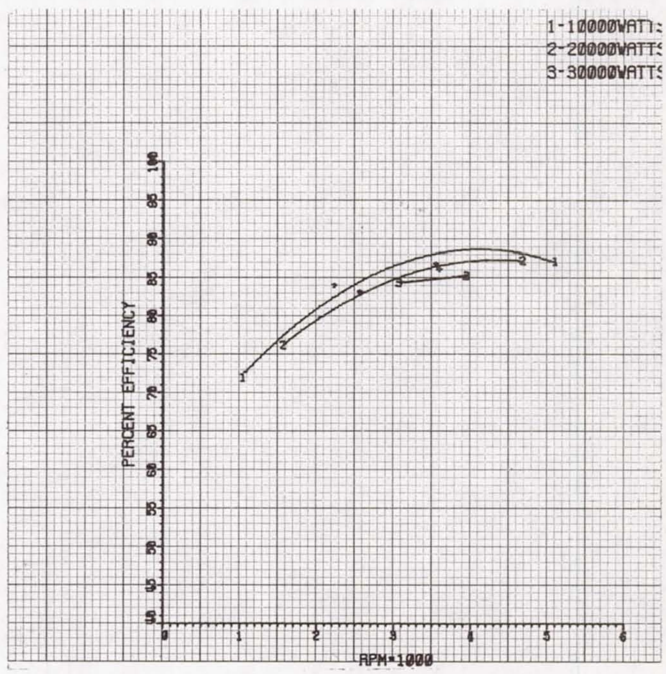
SPEED - TORQUE CHARACTERISTICS



OUTPUT POWER - SPEED CHARACTERISTICS

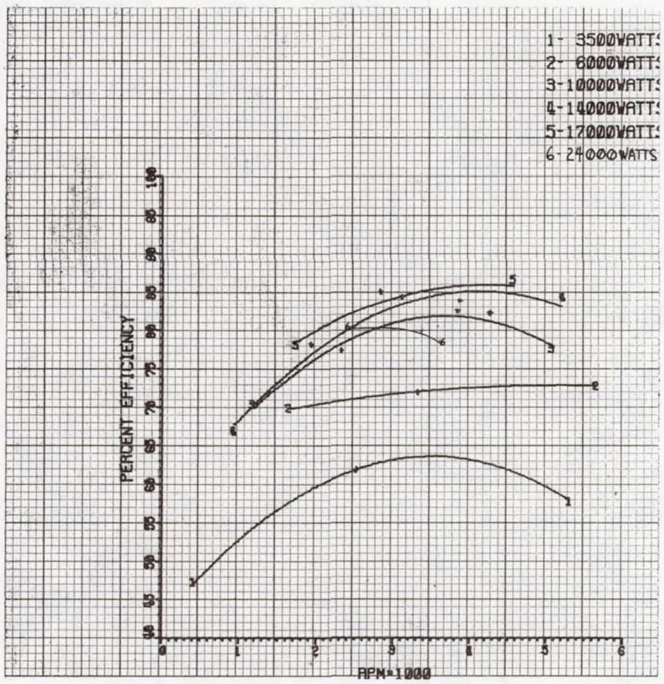


TORQUE - CURRENT CHARACTERISTICS



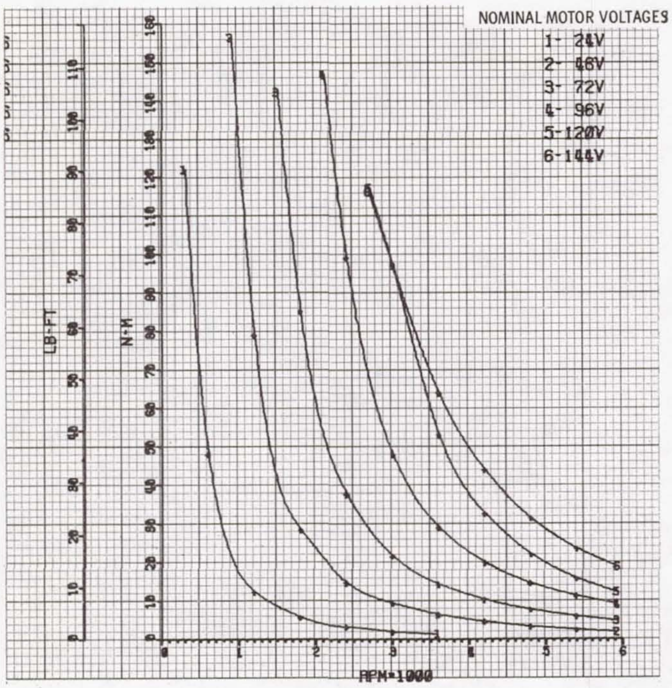
MOTOR EFFICIENCY - SPEED - POWER RELATIONSHIPS

Figure 14. - Low temperature, straight dc characteristics for series motor.

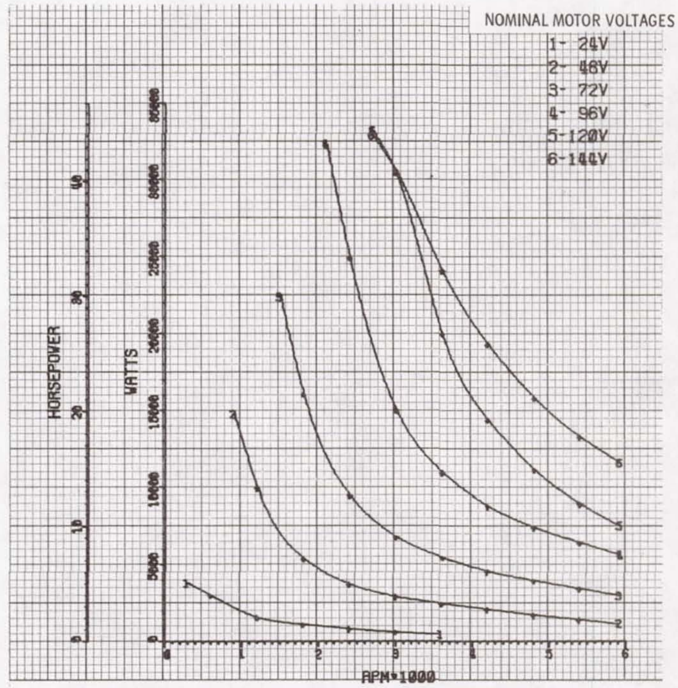


MOTOR EFFICIENCY - SPEED - POWER RELATIONSHIPS

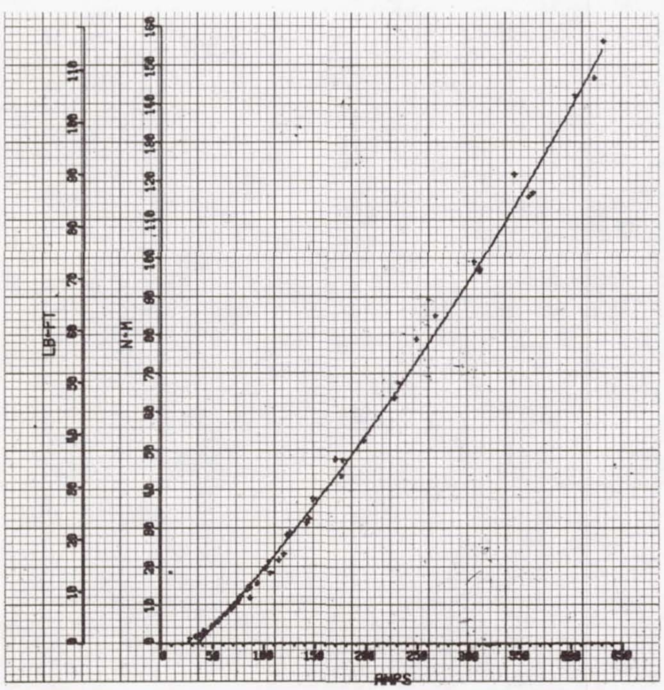
Figure 15. - Low temperature, chopped dc, and 144-volt input characteristics for series motor.



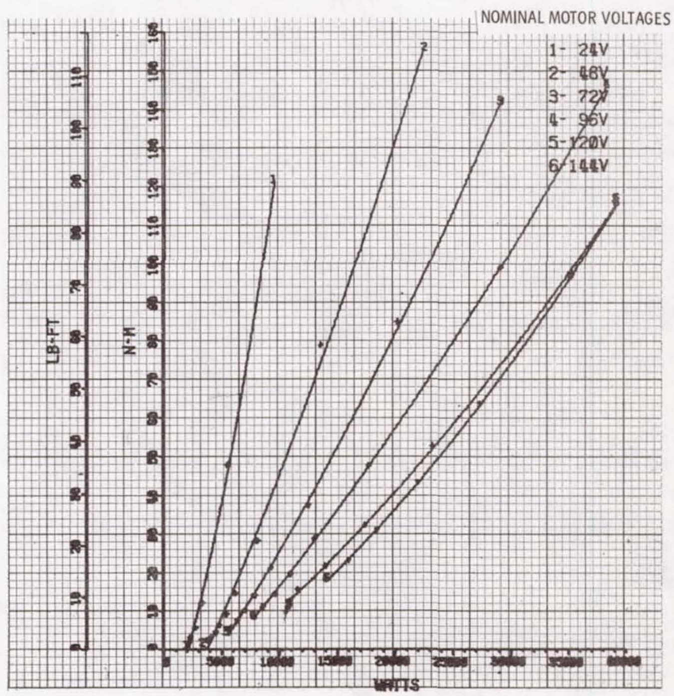
SPEED - TORQUE CHARACTERISTICS



OUTPUT POWER - SPEED CHARACTERISTICS

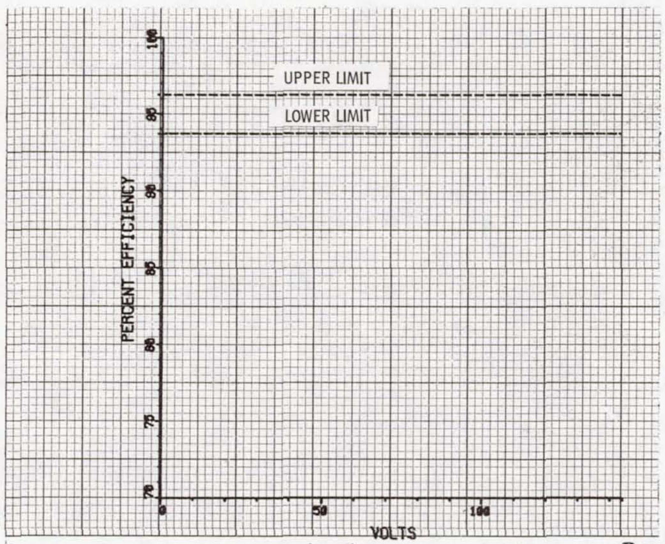


TORQUE - CURRENT CHARACTERISTICS



TORQUE - POWER - VOLTAGE RELATIONSHIPS

Figure 15. - Concluded.



CONTROLLER EFFICIENCY

Figure 16. - Low temperature, chopped dc 144-volt input.

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12. Sponsoring Agency Name and Address U.S. Department of Energy Office of Vehicle and Engine R&D Washington, D. C. 20545		14. Sponsoring Agency ~~Code~~ Report No. DOE/NASA/51044-24

15. Supplementary Notes

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16. Abstract

Available performance data for production motors are usually of marginal value to the electric vehicle designer. To provide at least a partial remedy to this situation, tests of typical dc propulsion motors and controllers were conducted as part of the DOE Electric Vehicle Program. This report summarizes the motor-controller test work performed by the NASA Lewis Research Center, the University of Pittsburgh, 3E Vehicles, and the Eaton Corporation as a part of that program.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
AC motors; DC motors; Chopper controller	Unclassified - unlimited STAR Category 33 DOE Category - UC-96

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