ACD 9854

FINAL REPORT
BRUSHLESS DC MOTOR
AND
CONTROLLER

March 1970

Contract No. NAS8-25085

Contractor: General Electric Company
Avionic Controls Department
P.O. Box 5000
Binghamton, New York

Contracting Officer: National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama

Prepared by: B. H. Hertzendorf
Dr. E. W. Manteuffel

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FOREWORD

This report was prepared by the General Electric Company, Avionic Controls Department, Binghamton, New York, on Contract NAS8-25085 administered under the direction of the National Aeronautics and Space Administration, Marshall Space Flight Center.

This is the final report (ACD 9854) covering the 6-month period of September 1969 to March 1970, summarizing the work performed in the design, development, fabrication, and testing of two 6.7 ft-lb brushless dc motors and one electronic controller.

This work was a group effort with the following principle contributors and their field of effort: B. H. Hertzendorf, Project Engineer, Dr. E. W. Manteuffel, Chief Consultant, M. F. O'Connor, Mechanical Design Engineer, and D. W. Pepin, Electrical Design Engineer.

Section 1
INTRODUCTION AND SUMMARY

INTRODUCTION

This report summarizes the work performed on contract NAS8-25085. This contract covered the design, fabrication and functional testing of two brushless dc motors. The motors have split windings which can be connected in either a series or parallel configuration. In a parallel configuration the motors are capable of operation at speeds of 1040 rpm and torque levels of 3.35 ft-lbs. In a series configuration the motors can operate at 520 rpm and 6.70 ft-lbs. One set of drive electronics was designed and fabricated to power the motors. The drive electronics have the unique capability of returning power to the supply when the motor is deaccelerated while operating at high speeds (i.e., regenerative braking).

SUMMARY

A summary of the brushless dc motor specifications, along with the actual test results are presented in Table 1. The test results shown are the average values for the two motors. Test data for each motor is given in Section 6. The motor meets all the contractual requirements as shown by the data in Table 1.

Figure 1 is a photograph showing the components of the motor and Figure 2 is a photograph of the motor mounted in the test fixture. All the performance tests were conducted with the motor mounted in the test fixture shown in Figure 2. Figure 3 shows the breadboard electronic controller which was developed to power the motor.

TABLE 1

SYSTEM SPECIFICATIONS

Rated torque	6.7 ft-lbs (series connection)
Power supply	30 to 36 volts at 25 amps
System gain	1.34 ft-lbs/volt (series connection)

BRUSHLESS DC MOTOR REQUIREMENTS AND TEST RESULTS

	Specified Requirement	Test Results
Torque gradient per section	$0.21 \frac{\text{ft-lbs}}{\text{amp}}$ ±10%	$0.218 \frac{\text{ft-lbs}}{\text{amp}}$
Winding resistance per section	0.25Ω ±15%	0.258Ω (with leads)
Demagnetization current	> 18 amps	~ 36 amps
Motor weight	< 12 amps	10.71 pounds
Maximum operating speed	1040 rpm	1040 rpm

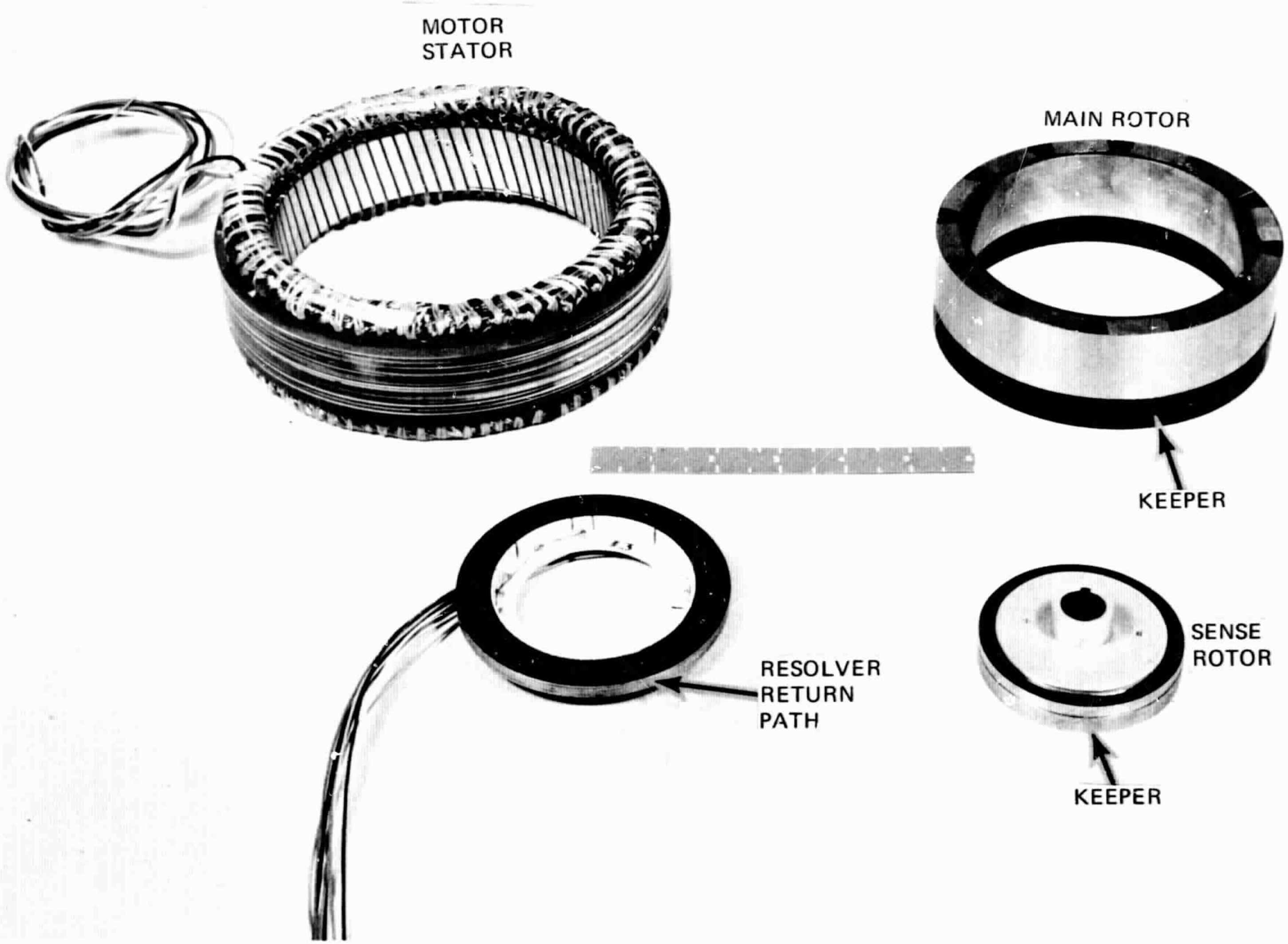


Figure 1. Brushless DC Motor Components

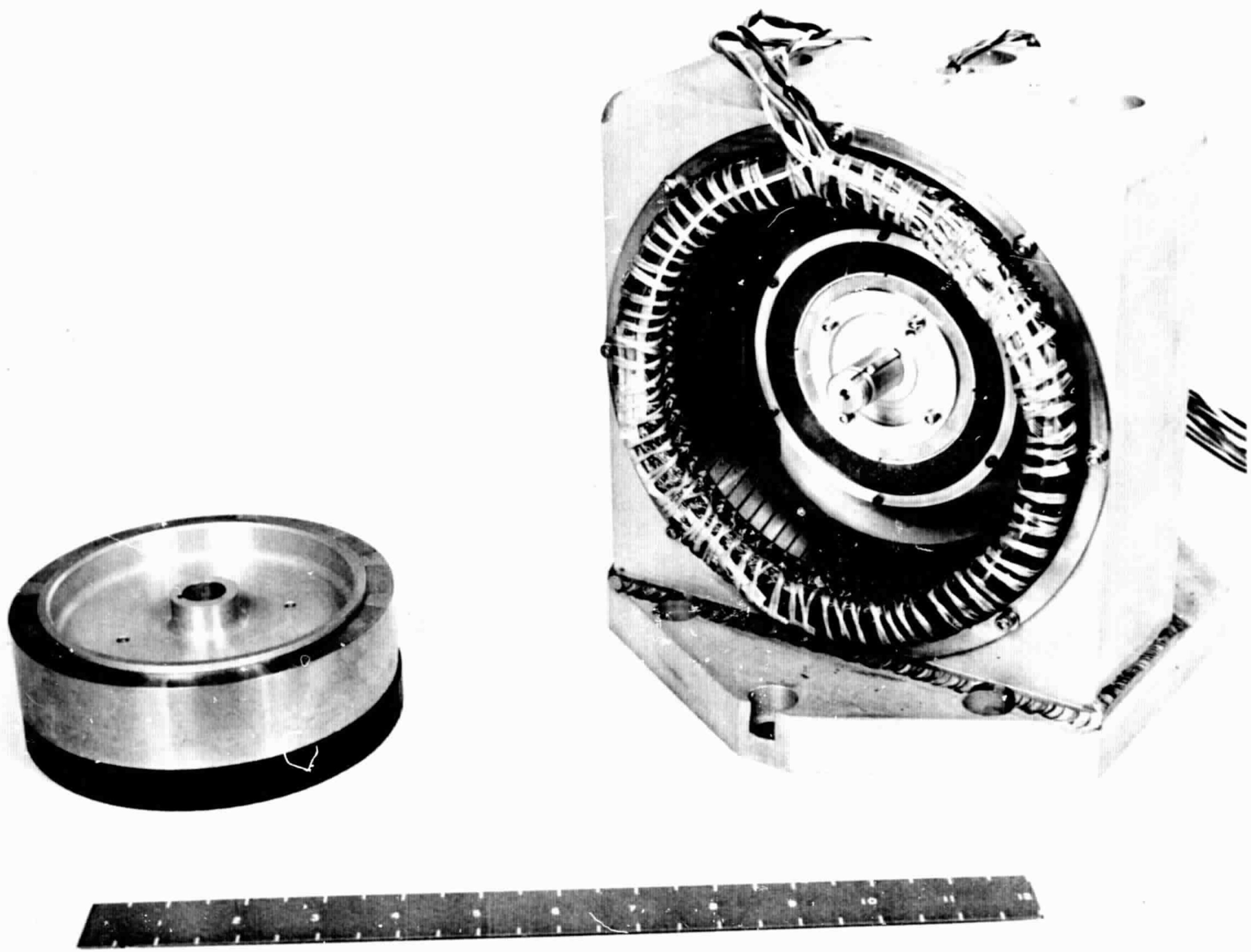


Figure 2. Brushless DC Motor in Test Fixture

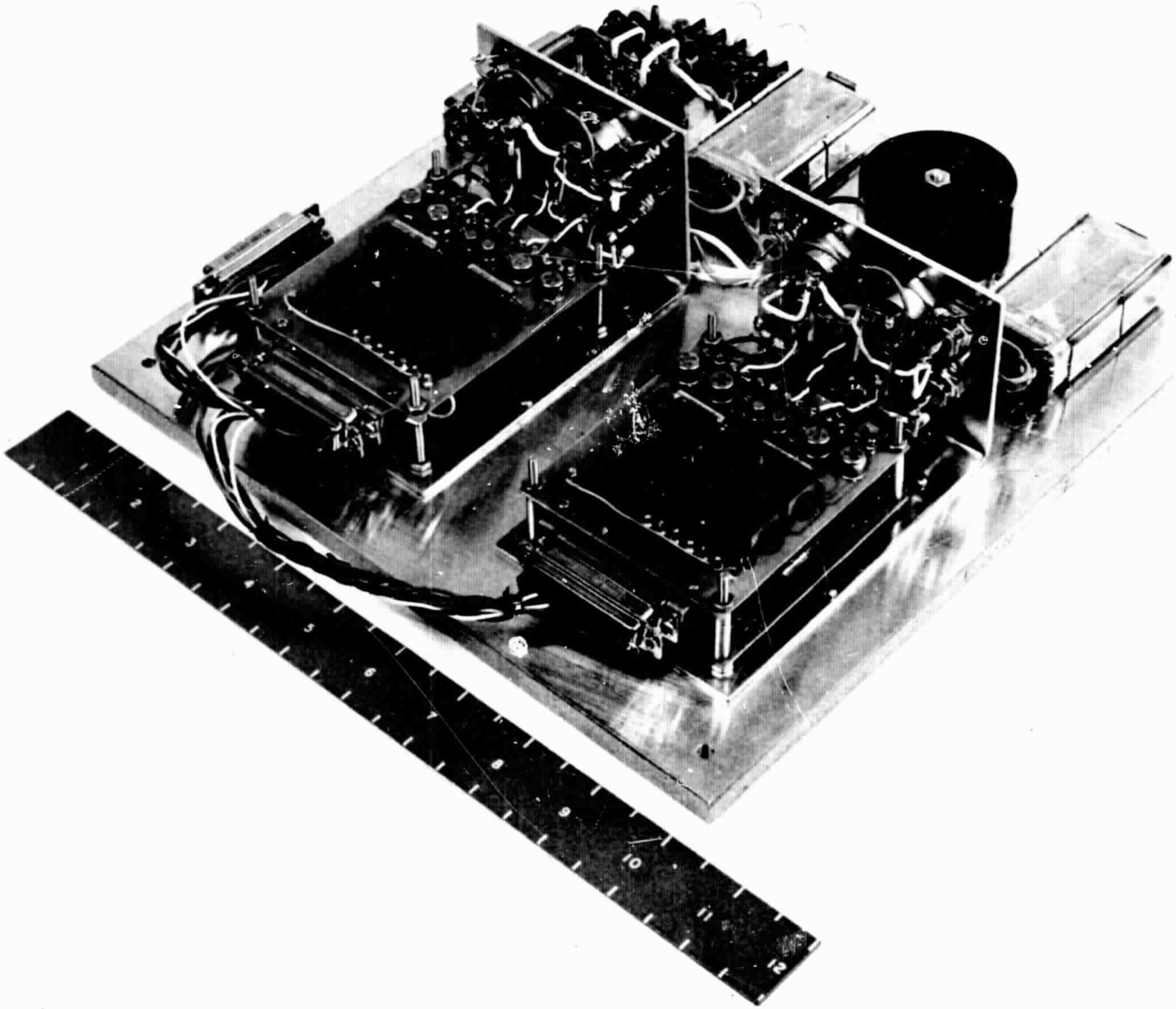


Figure 3. Breadboard Electronic Controller for Brushless DC Motor

Section 2

OPERATION OF THE BRUSHLESS DC MOTOR

TORQUE MOTOR

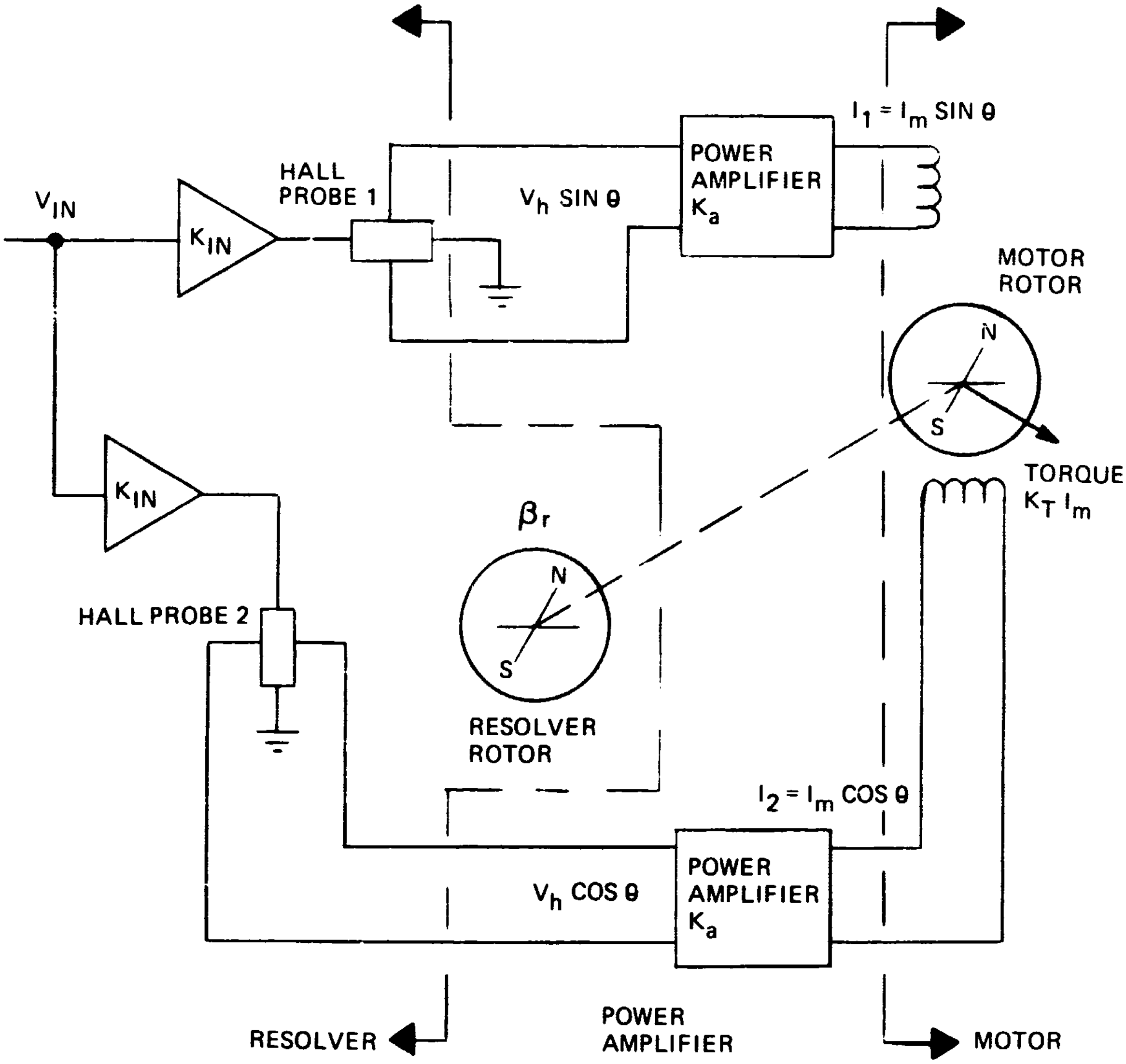
The General Electric brushless dc motor system consists of the three main parts:

1. A Hall effect-generator resolver with an output of two continuous voltages proportional to the sine and cosine of the position of the resolver rotor.
2. The motor electronics, consisting primarily of two dc power amplifiers, which receive the output from the resolvers and drive the motor windings.
3. The motor, which consists of a wound stator with two perpendicular windings and a permanent magnet rotor.

The motor windings develop a magnetic field in the air gap as a function of the angular position of the resolver rotor. The resolver rotor is mechanically coupled to the permanent magnet motor rotor and aligned such that the resultant motor currents create a field which leads the permanent magnet field by 90°. This produces a motor torque tending to align the motor shaft with the stator magnetic field, but since this field follows the position of the resolver position, a motor torque is produced which is constant and independent of rotor position. Thus, the Hall effect resolver replaces the commutator in a conventional dc motor. The Hall effect resolver consists of a permanent magnet rotor and a return path for the magnetic field. The Hall probes are mounted in a holder in the air gap. In some cases the Hall effect resolver can be the motor rotor.

Figure 4 shows the basic motor design. The input command signal produces a current in the Hall probes given by:

$$I_{h1} = \frac{V_{IN} K_{IN}}{R_{h1}}$$



K_{IN} = HALL PROBE DRIVER GAIN (V/V)
I_h = HALL PROBE EXCITATION CURRENT (MA)
R_h = HALL PROBE INPUT RESISTANCE
β_r = MAGNETIC FIELD IN RESOLVER AIR GAP
K_h = HALL PROBE CONSTANT $\left(\frac{MV}{MA\ KILOGAUSS}\right)$
V_h = HALL PROBE OUTPUT VOLTAGE (V)
K_a = POWER AMPLIFIER GAIN (V/AMP)
I_m = MOTOR CURRENT
K_T = MOTOR TORQUE CONSTANT $\left(\frac{FT\ LB}{A}\right)$
θ = ANGLE BETWEEN HALL PROBE AND A POLE ON THE MAGNET

Figure 4. Brushless DC Motor

Since the field seen by Hall generator 1 is $B_r \sin\theta$

$$V_{h1} = I_{h1} K_{h1} B_r \sin\theta$$

$$I_{m1} = I_{h1} K_{h1} K_a B_r \sin\theta$$

Likewise, $I_{m2} = I_{h2} K_{h2} K_a B_r \cos\theta$.

Therefore, the motor current is proportional to the Hall drive current.

The torque constant of each phase is proportional to:

N	-	the number of turns on the stator
ℓ	-	the rotor axial length
d	-	the rotor diameter
B_m	-	the magnetic field in the air gap

Therefore:

$$K_T \sim N \ell d B_m.$$

Since the motor field changes sinusoidally,

$$K_{T1} \sim N \ell d B_m \sin\theta$$

and $$K_{T2} \sim N \ell d B_m \cos\theta$$

Therefore:

$$T_1 = K_T \sin\theta \, I_m \sin\theta$$

$$= K_T I_m \sin^2\theta.$$

Likewise:

$$T_2 = K_T I_m \cos^2\theta.$$

Now:

$$T_m = T_1 + T_2 = K_T I_m (\sin^2 \theta + \cos^2 \theta)$$
$$= K_T I_m$$

The results is a motor torque with a magnitude and direction proportional to Hall drive current (or the input command).

Section 3
MOTOR DESIGN

DESIGN APPROACH

The motor designed on this contract is a modification of a previous design. This results in a motor that is not optimized for the work statement requirements but is significantly less expensive and could be delivered in less time than a motor of a new design.

Because the design calculations of the original motor are presented in reference 1, this report will only give the results of the calculations.

MAIN ROTOR DESIGN

The main rotor for this motor is identical to the one designed previously. It consists of 12 Alnico-9 magnets separated by soft iron pole pieces. The iron pole pieces are silver brazed to a titanium support ring and the magnets are epoxied to the ring. The magnets are further restrained by a thin titanium shrink ring. Figure 5 shows the details of the rotor construction.

STATOR DESIGN

The stator has the same physical dimensions of a stator previously designed. The material selected for the punchings was a lightweight silicon steel, Armco Di-Max M-15.

Reference 1. Brushless DC Torque Motor Development by Dr. E. W. Manteuffel and B. H. Hertzendorf, ACD 9849, January 31, 1970

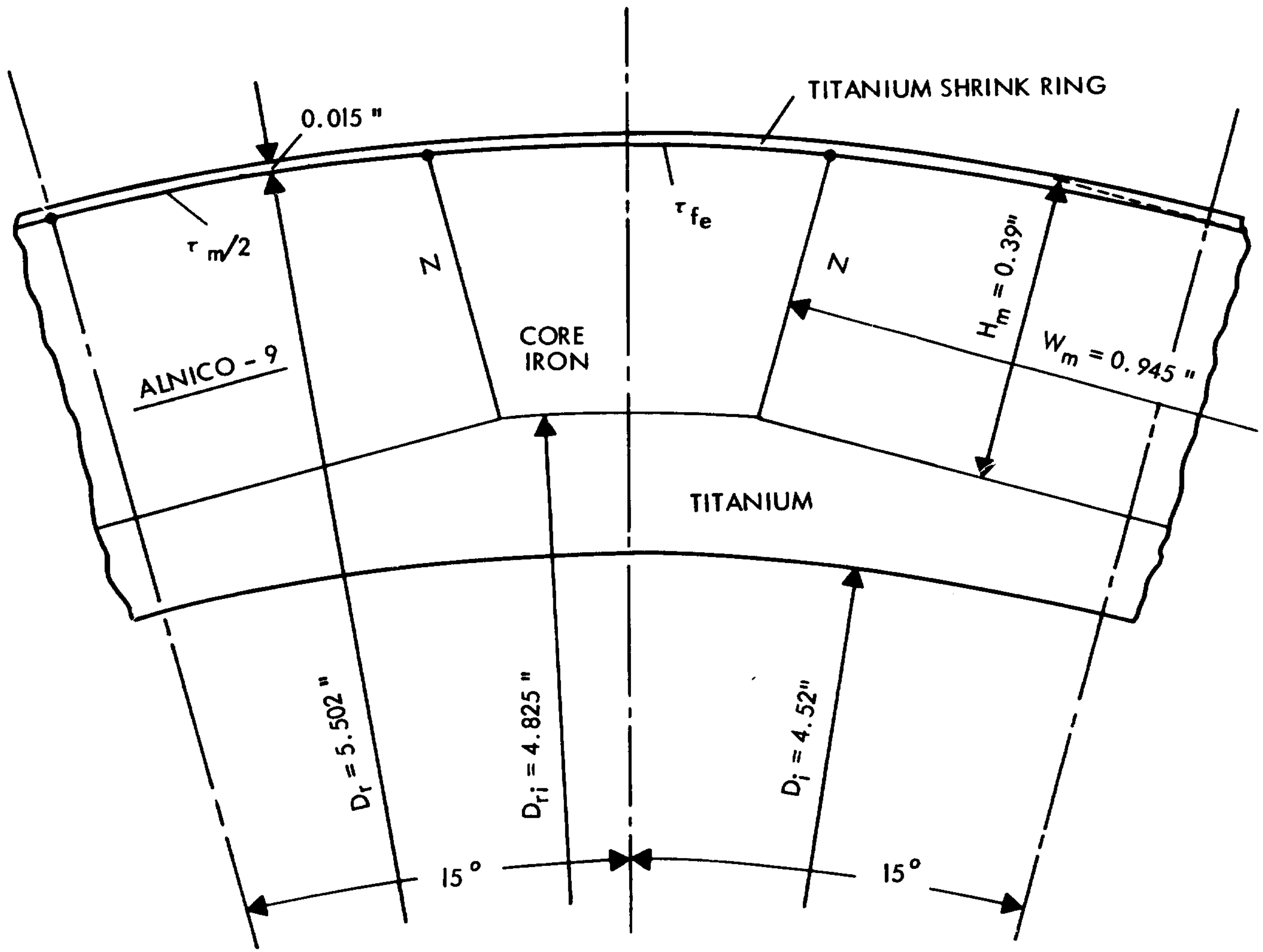


Figure 5. Rotor Construction and Dimensions

The winding scheme of the motor is defined by the work statement requirements of:

- A torque constant of $0.21 \frac{\text{ft-lbs}}{\text{amp}} \pm 10\%$ for each section
- A resistance of $0.25\Omega \pm 15\%$ for each section.

There are four sections to the winding. Each phase consists of two sections which may be connected either in series or in parallel. In the series connection the torque constant (and back emf constant) are doubled and the motor can supply 6.70 ft-lbs of torque at speeds up to 520 rpm. In the parallel connection the motor can supply up to 3.35 ft-lbs of torque at speeds up to 1040 rpm.

The winding selected is shown in Figure 6. The resistance of each section is:

$$R_w = \frac{N \ell_m}{A_{cu}} \cdot \rho$$

Where:

N = number of turns per section

ℓ_m = mean turn length of windings

A_{cu} = area of conducter

ρ = resistivity of copper

For:

N = 108 turns

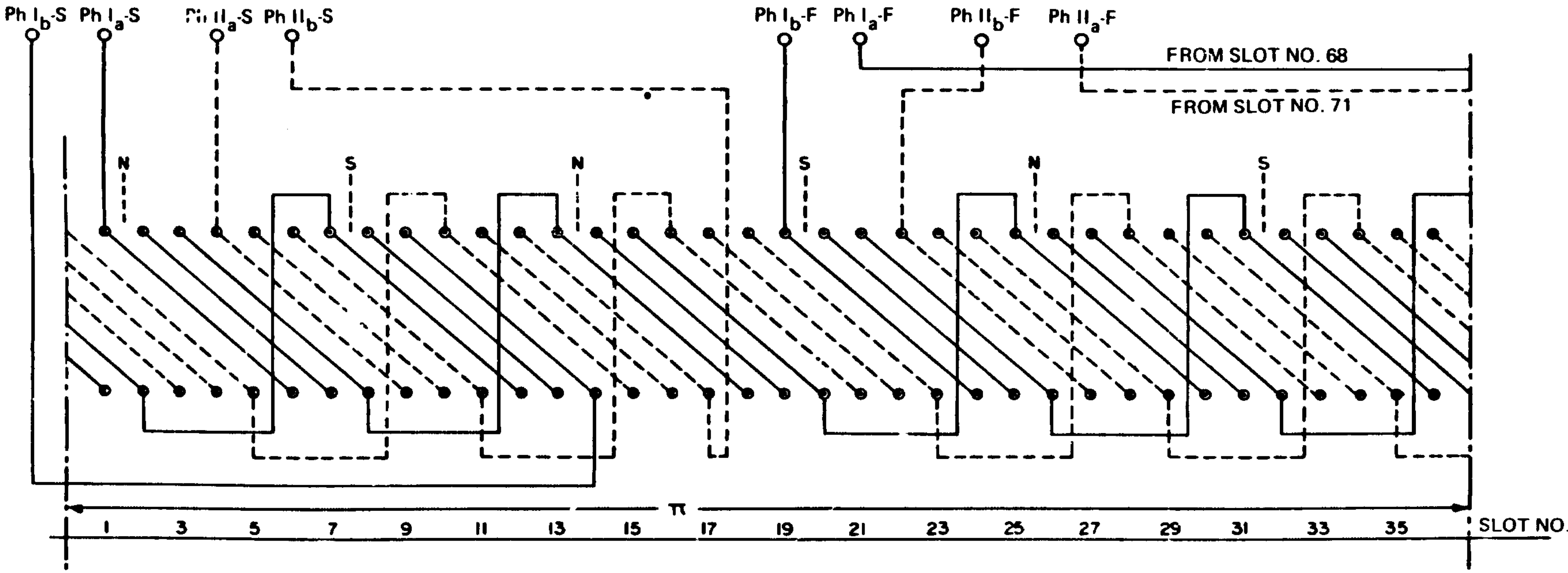
ℓ_m = 7.1 inches

A_{cu} = 2.517×10^{-4} in^2 (Number 25 wire)

ρ = 0.6787×10^{-6} Ω-inch

$$R_w = \frac{108 \times 7.1 \times 0.6787 \times 10^{-6}}{9 \times 2.517 \times 10^{-4}} = 0.230\Omega$$

The average measured value of the motor resistance (excluding leads) was 0.246Ω/section.



NOTES

1 $P = 6$, $q = 3$, $= 30^{\circ}$ ELECTRICAL, $N_S = 72$, $Zs = 12$ OR Y, $Nph = 216$ OR 108

2 WINDING OF EACH PHASE CONSISTS OF TWO SECTIONS OF 18 SKEINS OF 6 TURNS EACH

3 WIRE SIZE: 9 × Number 25 AWG. HML

4 MEAN TURN LENGTH: $l_m = 7.1$ INCHES

Figure 6. Two-Phase Dual Layer Short Pitch Winding for Brushless DC Motor

The torque constant is found from the general torque equation:

$$K_T = \frac{0.1\, fw_1\, D_A\, \ell_a\, B_{1\,max}\, N}{13.556 \times 10^{-6}} \quad \frac{\text{ft-lbs}}{\text{amp}}$$

Where:

fw_1 = winding distribution factor

D_A = armature diameter

ℓ_a = armature length

B_{max} = flux density in the air gap

For:

fw_1 = 0.870

D_A = 14.127 cm

ℓ_a = 3.389 cm

B_{max} = 6300 gauss

$$K_T = \frac{0.1 \times 0.870 \times 14.127 \times 3.389 \times 6300 \times 108}{13.556 \times 10^{-6}}$$

$$= 0.209 \ \frac{\text{ft-lb}}{\text{amp}}$$

The average measured torque constant was 0.218 $\frac{\text{ft-lb}}{\text{amp}}$.

RESOLVER DESIGN

The resolver provides sine and cosine signals to the electronics of the brushless dc motor. The calculations for the resolver magnet are presented in reference 1. This magnet is a 12-pole ring magnet of Alnico 6. The field in the air gap produced by this magnet is 3600 gauss. The two Hall generators are run in series with a selected resistor to set the Hall output voltage at 60 millivolts for a 5.0-volt input signal.

SUMMARY OF CALCULATED RESULTS

The calculated motor characteristics are summarized in Table 2.

TABLE 2

MOTOR CHARACTERISTICS

GENERAL

MOTOR SIZE

Outside Diameter	7.54 inches
Axial Length	2.125 inches
Weight (less hub)	10.43 pounds
Maximum Power Required (Including Electronics)	700W at + 33V

PERFORMANCE DATA

Torque Constant (per Bifilar Section)	$0.209 \frac{\text{ft-lb}}{\text{amps}}$
Torque Rating	6.70 ft-lbs
Current at Rated Torque	16.03 amps
Demagnetization Torque	14.0 ft-lbs
Winding Resistance (Bifilar Section)	0.230 ohm
Generator Constant (Bifilar Section)	0.283 volt/rad/sec
Copper Losses (at rated torque)	118 watts
Core Losses (at maximum speed of 1040 rpm)	5.20 watts

TABLE 2 (cont'd)

MOTOR DIMENSIONS

MOTOR STATOR	
Outside Diameter	7.540 inches
Inside Diameter	5.560 inches
Punchings - Material - Thickness	Armco DI-MAX M-15 0.014 inch
Stack Length	1.35 inches
Number of Slots	72
MOTOR WINDING	
Type	Two Phase - Dual Layer Short Pitch
Turns (Bifilar Section)	108 in parallel
Wire Size	9 x #25 in parallel
Winding Resistance (Bifilar Section)	0.230 ohm/section
MOTOR ROTOR	
Type	Permanent Magnet, 12-Pole
Outside Diameter	5.532 inches
Inside Diameter (less hub)	4.520 inches
Axial Length	1.280 inches
Magnet Material	Alnico 9
SENSE ROTOR RETURN PATH	
Outside Diameter	3.940 inches
Inside Diameter	2.930 inches
Stack Length	0.26 inch
Punchings - Material - Thickness	Armco DI-MAX M-15 0.14 inch

TABLE 2 (cont'd)

SENSE ROTOR

Type	Permanent Magnet 12-Pole
Outside Diameter	2.850 inches
Inside Diameter	2.250 inches
Axial Length	0.200 inch
Magnet Material	Alnico 6

HALL GENERATOR

Type	F. W. Bell Model FH-301-040
Sensitivity	1.0 V/A · Kg* minimum
Offset Voltage with B = 0	1.0 mv* maximum
Nominal Control Current	15 ma
Input Resistance	40-80 ohms
Output Resistance	~ 1.4 (input resistance)
Temperature Coefficient (-20°C to +80°C)	-0.1%/°C
Operating Temperature Range	-55°C to +100°C

*These specifications were requested by General Electric and are different from the standard FH-301 Hall generator.

Section 4

MECHANICAL DESIGN

MAIN ROTOR

DESIGN

The main rotor consists of 12 Alnico 9 magnets, separated by core iron segments. The magnets and core iron are mounted on a titanium support ring. A section of the main rotor is shown in Figure 7.

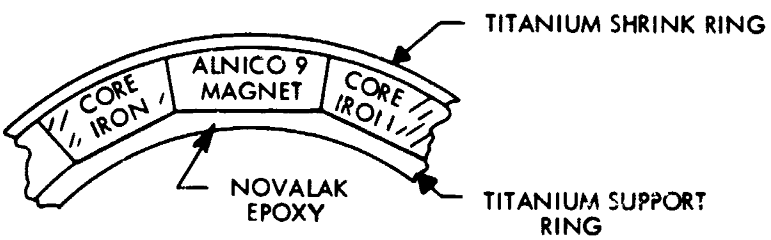


Figure 7. Main Rotor Section

The pole pieces are silver brazed to the support ring and the magnets are epoxied to it. The material selection was based on three items:

1. The required magnetic properties
2. The thermal properties
3. The strength properties

The pole pieces that were required to conduct a magnetic field, have a high magnetic saturation, have a high permeability and have good thermal expansion properties. The material selected was Carpenter Vacument core iron. Its properties are:

Thermal expansion	-	7.56 μ in/in
Magnetic saturation	-	21,500 gauss
Permeability	-	10,000
Tensile strength	-	50,000 psi
Resistivity	-	10.1 $\mu \Omega$ - cm

The Alnico 9 magnets were selected for their magnetic characteristics. The physical properties are:

Thermal expansion	-	6.1 μ in/in
Tensile strength	-	29,000 psi

Titanium was selected for the support ring and the shrink ring. The primary reasons for the selections were mechanical strength and its negligible effect on a magnetic field. The properties of the alloy selected, Ti-6AL-4V are:

Tensile strength	-	135,000 psi
Thermal expansion	-	5.7 μ in/in
Tensile modulus	-	16.5×10^6 psi

BRAZING AND EPOXY TESTS

Before assembling the pieces, several tests were conducted of the brazing and epoxy techniques.

To test the brazing, a soft iron rod, SAE 1020, 3/4 inch in diameter and 2 inches long was plated with silver to a 0.001 inch thickness. It was then brazed to a similar Ti-6AL-4V titanium test piece. In a vacuum after brazing, the test piece was cycled twice between room temperature and $-320^{\circ}F$ using liquid nitrogen. Then it was subjected to a pull test and the breaking strength was 33,000 psi. Further metalographic examination of a cross section of the braze showed no evidence of intermetallic compounds being formed that would lead to brittle structures. Therefore, the silver braze was selected.

The epoxy used is Novalak, a GE compound. Test pieces consisting of Alnico 9 magnets and Ti-6AL-4V titanium were epoxied together and tested in shear. The results were:

Test #1	1725 psi
Test #2	1430 psi
Test #3	2000 psi
Test #4	1200 psi
Test #5*	1000 psi
Test #6*	650 psi

(*Epoxy batch was later found to be poorly mixed, probably due to impurities.)

In addition, one sample, #2, was subjected to a thermal cycle of room temperature to $-320^{\circ}F$. It was then given a shock of ~ 100 g's while still very cold. No damage to the joint was observed. Since the curing temperatures are $+482^{\circ}F$, the epoxy will have good high temperature properties. Therefore, it was selected as adequate for the design.

STRESS CALCULATIONS

Of special concern in the design is the stress levels in the shrink ring. The basic requirement of the shrink ring is that it maintains positive pressure on the core pieces and magnets at all times, and that its strength is sufficient to hold the magnets in place in event of epoxy failure.

The shrink ring characteristics are summarized as follows:

T (^{o}F)	Diameter Interference	Hoop Stress (psi)
-45^{o}F	0.0058 inch	17,300 psi
70^{o}F	0.0060 inch	17,700 psi
+160^{o}F	0.0061 inch	17,900 psi

If the magnets come loose, the shrink ring will restrain them. The peak load on the shrink ring is a combination of inertial forces on the magnet and inertial forces on the shrink ring.

Assuming an angular speed of 1800 rpm these forces are:

- Inertial forces of loose magnet — 27.4 pounds per magnet
- Outward pressure of magnets — 12.4 psi

If the forces due to the individual magnets are considered to be a radial pressure, and this pressure is uniformly distributed, the total inertial stresses are 2270 psi.

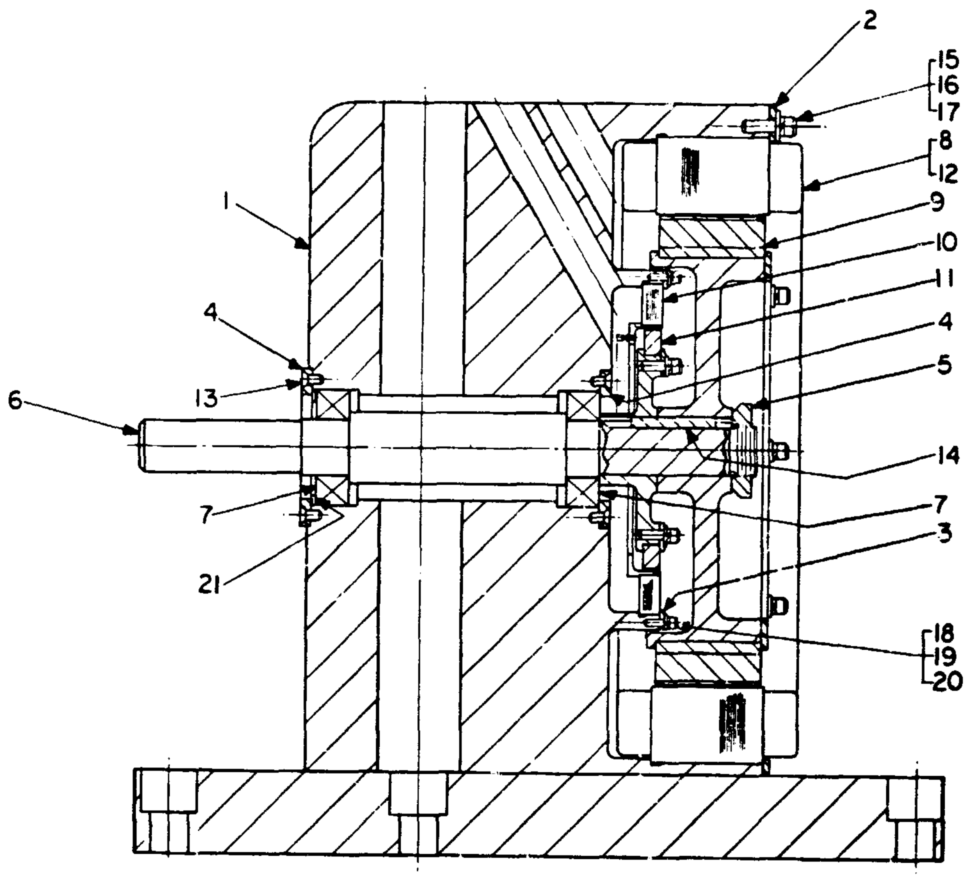
Therefore, in the event of an epoxy failure the magnets can be held by the shrink ring. It should be pointed out that radial magnetic forces between the magnets and stator were ignored, since the restraining force between the pole pieces and magnets will more than balance this.

HALL PROBE HOLDER

The Hall probes must be mounted in the air gap of the sense magnet. Noryl, a glass epoxy resin, was selected as the material for the Hall probe holder. The noryl ring is shown in Figure 1. The basic design consideration was to make a ring thin enough to hold the Hall probes in the air gap and strong enough to be rigid during the thermal excursions. Since the thermal coefficient of noryl is 15×10^{-6} in/in/^{o}F and that of the stator punchings is 4.7×10^{-6} in/in/^{o}F, expansion slots were cut in the noryl ring to prevent it from bowing at high temperatures.

TEST FIXTURE

The test fixture design includes the main body, the shaft and support hubs. An outline drawing of the fixture and motor is shown in Figure 8.



1	FIXTURE	9	MOTOR ROTOR MOUNTED ON HUB
2	RETAINING RING	10	SENSE STATOR ASSEMBLY
3	RETAINING RING	11	SENSE ROTOR
4	BEARING RETAINER	12	MOTOR STATOR
5	LOCK NUT	13	MOUNTING SCREW
6	SHAFT	14	KEY
7	BEARING	15-20	MOUNTING HARDWARE
8	MOTOR STATOR		

Figure 8. Brushless DC Motor in Fixture

Section 5

ELECTRONIC DESIGN

The electronic controller performs the following functions:

- Amplifies Hall generator output voltages, to drive the motor windings
- Develops internal dc power and reference waveforms
- Switches the motor windings from series to parallel configuration or visa versa.
- Provides capability of returning power back to the voltage source under certain deaccelerating modes

Figure 9 shows inter-relationships of functions, principal gains and operating levels. The single voltage supply to the system is +33 vdc. The dc-dc converter converts +33 vdc to the low power supply voltages required for the integrated circuits. It also produces a 5 KHz square wave which is integrated to provide the triangular waveform for the pulse width modulator.

The motor amplifiers amplify Hail Detector voltages V_{h1} and V_{h2} to drive two motor windings with currents I_{m1} and I_{m2}. The motor currents are proportional to the sine and cosine of motor shaft angle, causing a torque as described in Section 2.

Each motor amplifier consists of a power bridge circuit, a pulse width modulator, a summing amplifier and shunts. The pulse width modulator converts dc to 10 KHz pulse trains for the two Drivers. The Drivers are high voltage gates which contain a 40-volt rated output transistor. The drivers operate the transistor switches of the power bridge. Shunts in the bridge-circuit develop feedback voltage proportional to motor current.

The gain of the motor amplifiers is set by the input and feedback resistances

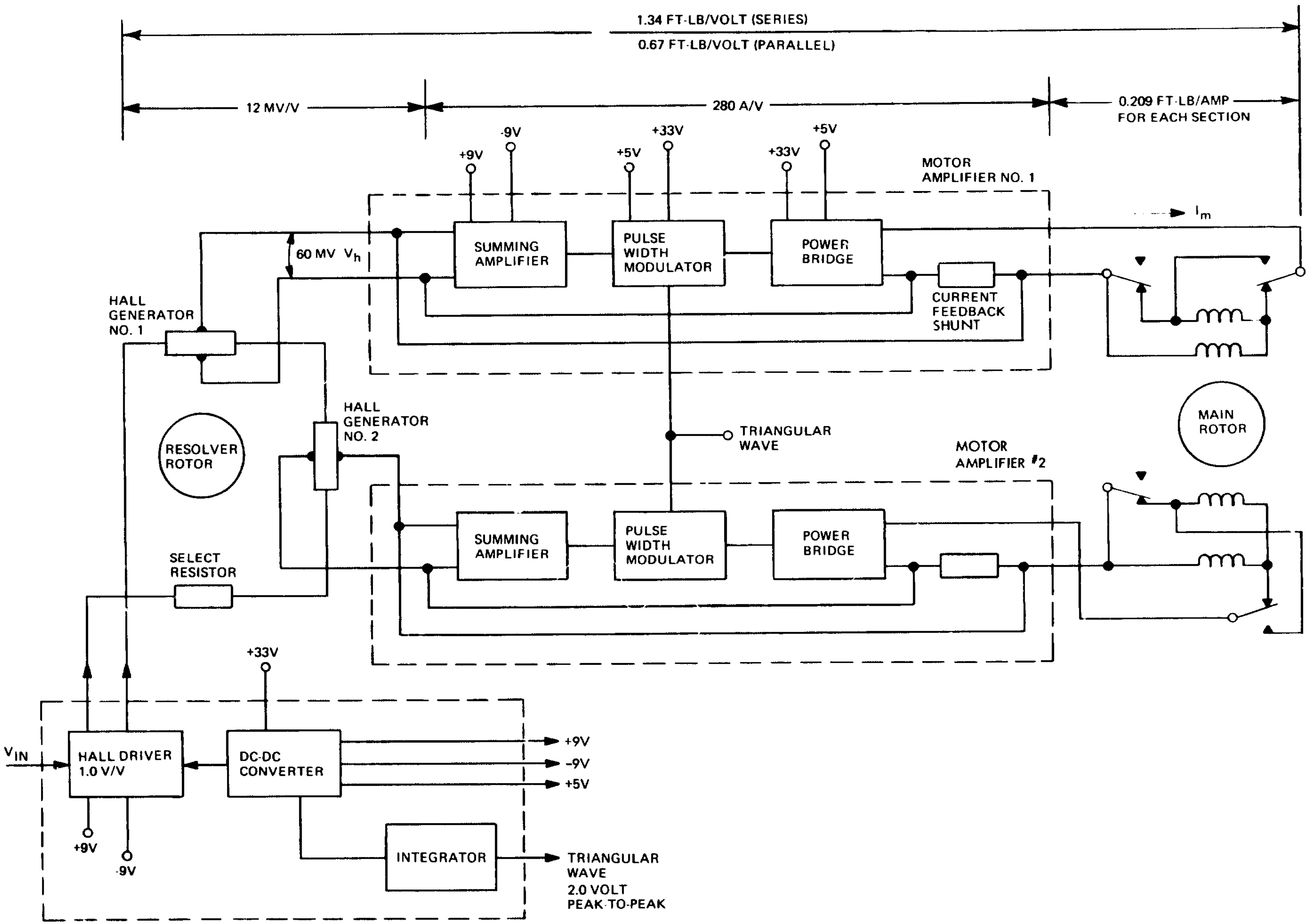


Figure 9. Block Diagram of Electronic Controller

The nominal gain of the amplifiers is 281 a/v, thus to obtain nominal output current of 16 amperes (peak), the signal from the Hall generators must be 60 millivolts (peak). The Hall generators transform the motor shaft angle into sine and cosine signals, proportional to Hall generator control current I_c. Hall generator current I_c is trimmed to the gains of the specific Hall generators installed. The control current required to obtain 60 millivolts is 13 milliamperes; current is adjusted by installing a selected motor current trim resistor during system tests. The two Hall generators were selected for equal gains to eliminate any matching of Hall generator gains. The Hall driver function is a straight forward 1 v/v dc gain.

POWER RETURN CAPABILITY

Although not a part of the actual contract the electronics was designed with the capability to return power to the dc voltage source.

If the energy stored in the motor windings is greater than the losses in the electronic controller and the motor windings the motor will act as a generator and return power to the voltage source when it is deaccelerated. The inductance of the motor windings allows power to be returned to a battery even though the back EMF of the motor is less than the battery output voltage. The amount of power returned to the source is a function of:

- motor speed
- motor current commanded
- battery voltage

Section 6 has test data which illustrates the power return capability of the electronic controller.

Section 6

FUNCTIONAL TESTING

MOTOR TESTS

The testing performed under this contract had two objectives.

1. To insure that the motors and drive electronics could meet design specifications.
2. To evaluate the performance of the motor and electronics as a system.

The contractual requirement and average measured value for the motor parameters are listed in Table 3.

TABLE 3

MOTOR PERFORMANCE DATA

	Motor Resistance	Motor Insulation Resistance	Torque Constant
Calculated Value	0.230Ω +0.012 Ω leads	>10 Megs	0.209 $\frac{\text{ft-lbs}}{\text{amp}}$
Motor No. 1			
(Black - White), ϕ_{1A}	0.254Ω	OK	0.209 $\frac{\text{ft-lbs}}{\text{amp}}$
(Blue - Red), ϕ_{1B}	0.254Ω		0.218 $\frac{\text{ft-lbs}}{\text{amp}}$
(Blue - Black), ϕ_{2A}	0.254Ω		0.208 $\frac{\text{ft-lbs}}{\text{amp}}$
(Red - White), ϕ_{2B}	0.254Ω		0.214 $\frac{\text{ft-lbs}}{\text{amp}}$
Motor No. 2			
(Black - White), ϕ_{1A}	0.261Ω	OK	0.217 $\frac{\text{ft-lbs}}{\text{amp}}$
(Blue - Red), ϕ_{1B}	0.261Ω		0.223 $\frac{\text{ft-lbs}}{\text{amp}}$
(Blue - Black), ϕ_{2A}	0.261Ω		0.222 $\frac{\text{ft-lbs}}{\text{amp}}$
(Red - White), ϕ_{2B}	0.261Ω		0.231 $\frac{\text{ft-lbs}}{\text{amp}}$

The functional testing of the motor consisted of measurements of:

- motor resistance
- insulation resistance
- torque constant

Table 3 is a tabulation of the results of the functional tests. The motor resistance was slightly higher than calculated because the length of each coil was increased to allow for easier fabrication of the windings.

The torque constant was determined by running the motor as a generator and measuring the back EMF constant. The torque constant is $0.737 \frac{\text{ft-lbs}}{\text{volt/amp/sec}}$ times the back EMF constant. The power input to the motor at rated torque can be calculated. A back EMF constant of $0.59 \frac{\text{volts peak}}{\text{rad/sec}}$ results in a torque constant of $0.435 \frac{\text{ft-lbs}}{\text{amp}}$. If 0.493Ω is taken as the average value of the motor windings resistance (without leads) then the power input at zero speed is:

$$P = \left(\frac{6.70 \text{ ft-lb}}{0.435 \frac{\text{ft-lb}}{\text{amp}}} \right)^2 \times (0.493\Omega) = 116 \text{ W}$$

in a series connection. This is slightly lower than the calculated value because of the higher torque constant. In the parallel connection the maximum torque and the torque constant are both halved so the current in the windings remains the same as for a series connection. However, the winding resistance is halved so the power to the motor is halved.

The back EMF constant also determines the maximum speed the torquer can achieve. In the series connection with a speed of 520 rpm and a back EMF constant of $0.59 \frac{\text{volts}}{\text{rad/sec}}$, 32 volts is required at the motor windings. In a parallel connection the speed is doubled since the back EMF constant is halved.

Measurements were made of the friction torque that the motor must overcome to rotate. This torque is a combination of hysteresis plus reluctance torque. The averaged value of this torque was 0.03 ft-lb with the reluctance torque contributing about 75 percent of the total friction torque.

Demagnetization tests were conducted with one rotor. The rotor was rigidly held in place and currents up to 38 amperes were put in the windings. There was no change in the back EMF.

The weight of the motor was well below the contract requirement of 12 pounds. The weight of the motor components are as follows:

	Pounds
Stator	7.54
Main Rotor	- 2.57
Resolver Rotor	- 0.13
Resolver Return Path	- 0.47
Total Weight	10.71

TESTING OF MOTOR AND ELECTRONICS

The electronic controller was connected to each motor and the system was run at constant speed with varying torque levels, and at a constant torque level while accelerating a load. In addition, the motor windings were switched from series to parallel while the motor was operating at low speeds.

Figure 10 is a plot of the command voltage versus the output torque. The motor was loaded by an ac motor and transmission which ran at about 30 rpm during these tests.

Figure 11 shows the power return capabilities of the electronic controller. The motor was in a series configuration and accelerating a 0.4 ft-lb-sec^2 inertia. The top graph, of Figure 11, shows the input command to the controller. The output torque of the motor is directly related to the input voltage of the controller. The bottom graph shows the line current, this data was recorded on a strip chart recorder and is redrawn slightly idealized. Since the inertia of the load is known the speed of the motor can be calculated. The results of this calculation is plotted in the center graph.

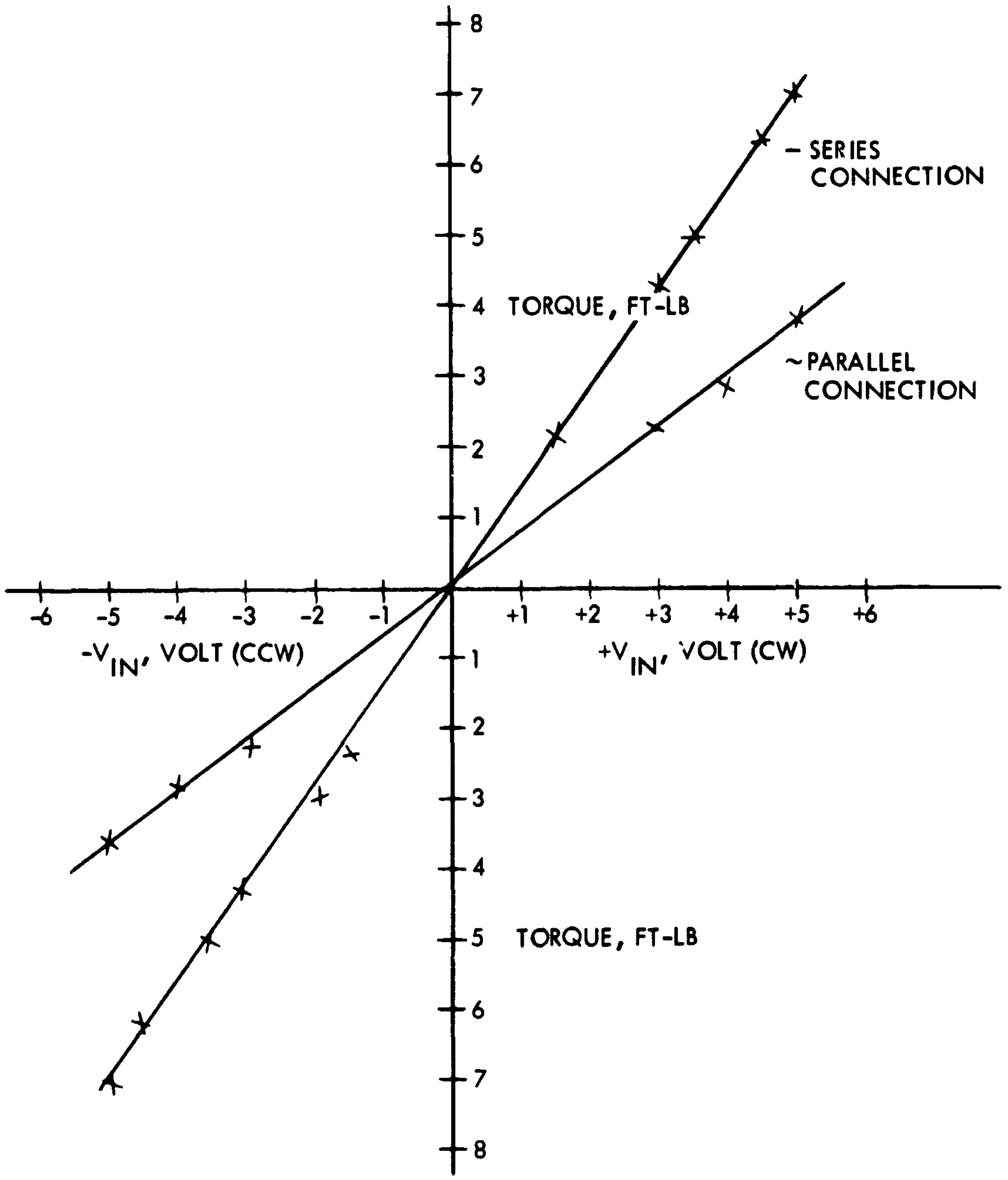


Figure 10. Input Command versus Output Torque

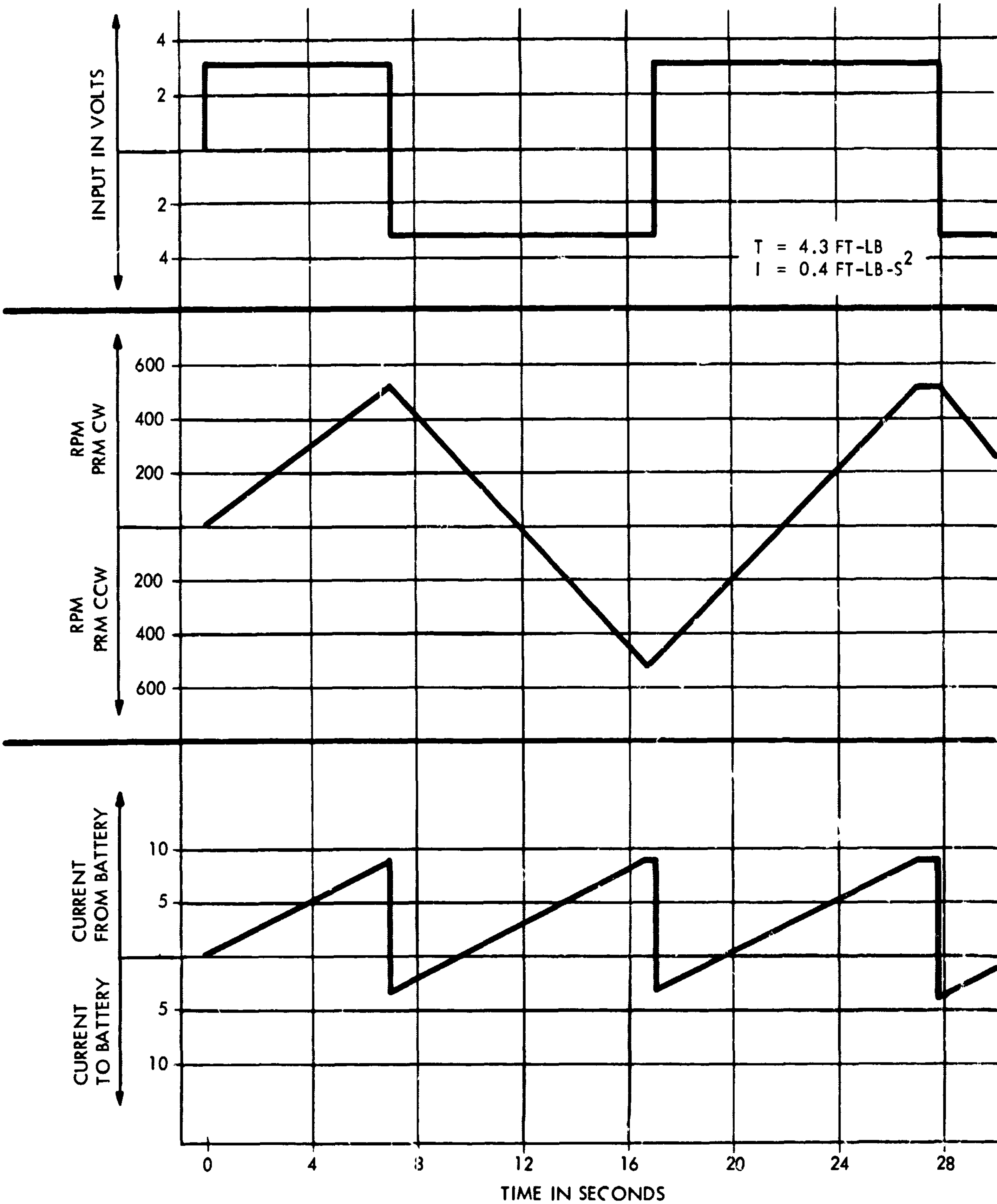


Figure 11. Graphs Showing Power Return Capabilities of Electronic Controller

Section 7

OPERATING INSTRUCTIONS

The following operations must be performed for the motor to operate correctly:

1. Mount the main rotor and sense rotor on their hubs.
2. Mount the resolver return path and the motor stator in the test fixture.
3. Place the rotors on the shaft of the test fixture and remove the keepers.
4. Align the motor.
5. Connect the electronics to the motor and the power supply.

Each of these operating steps are discussed in the following paragraphs.

MOUNTING OF ROTORS ON HUBS

The main rotor and resolver rotor are shipped with keepers. These keepers must not be removed until the rotors are inside their respective return paths. The resolver rotor can be arbitrarily mounted on its hub. The rotor will slip on the hub and is held in place by the retaining ring.

The main rotor must be lined up so the pin in the hub fits into the slot in the rotor. The hub must be pressed on the rotor.

MOUNTING OF STATOR AND RETURN PATH

The resolver return path should be mounted in the fixture so the wires come out at the top and towards the rear of the fixture. The lead wires are then threaded through the hole in the fixture.

The stator is mounted in the fixture with the lead wires coming out at the top and towards the front of the fixture.

MOUNTING OF ROTORS IN FIXTURE

The resolver rotor and hub is slid on the shaft. After the rotor is in the return path the keeper is removed with the jack screws. The rotor should be handled with the mounting screws which are inserted in the mounting holes in the hub.

The main rotor is held with the mounting screws and slid on the shaft. The keeper is removed with the packing screws and the locknut is screwed onto the shaft to hold the rotor in place.

ALIGNMENT OF ROTOR AND STATOR

For proper operation the current in the motor windings must be in-phase with the magnetic field in the air gap. The current in the windings is a function of the Hall generator output voltage, and the voltage induced in the windings is a function of the magnetic field in the air gap. Therefore, if the Hall generator output voltage is in-phase with the voltage induced in the winding that the Hall generator is going to drive, the motor will be properly aligned. The Hall generators should have about 5 volts on the input leads (refer to Figure 12) and their output connected to an oscilloscope or a recorder. The motor should be rotated externally with the output leads of one section connected to another channel of the indicating instrument. The main stator is then rotated until the two voltages are in-phase.

CAUTION

The Hall generator output leads must not be connected to the electronics and an oscilloscope probe at the same time. The Hall generators may be destroyed because of a difference in grounding between the oscilloscope and the electronics.

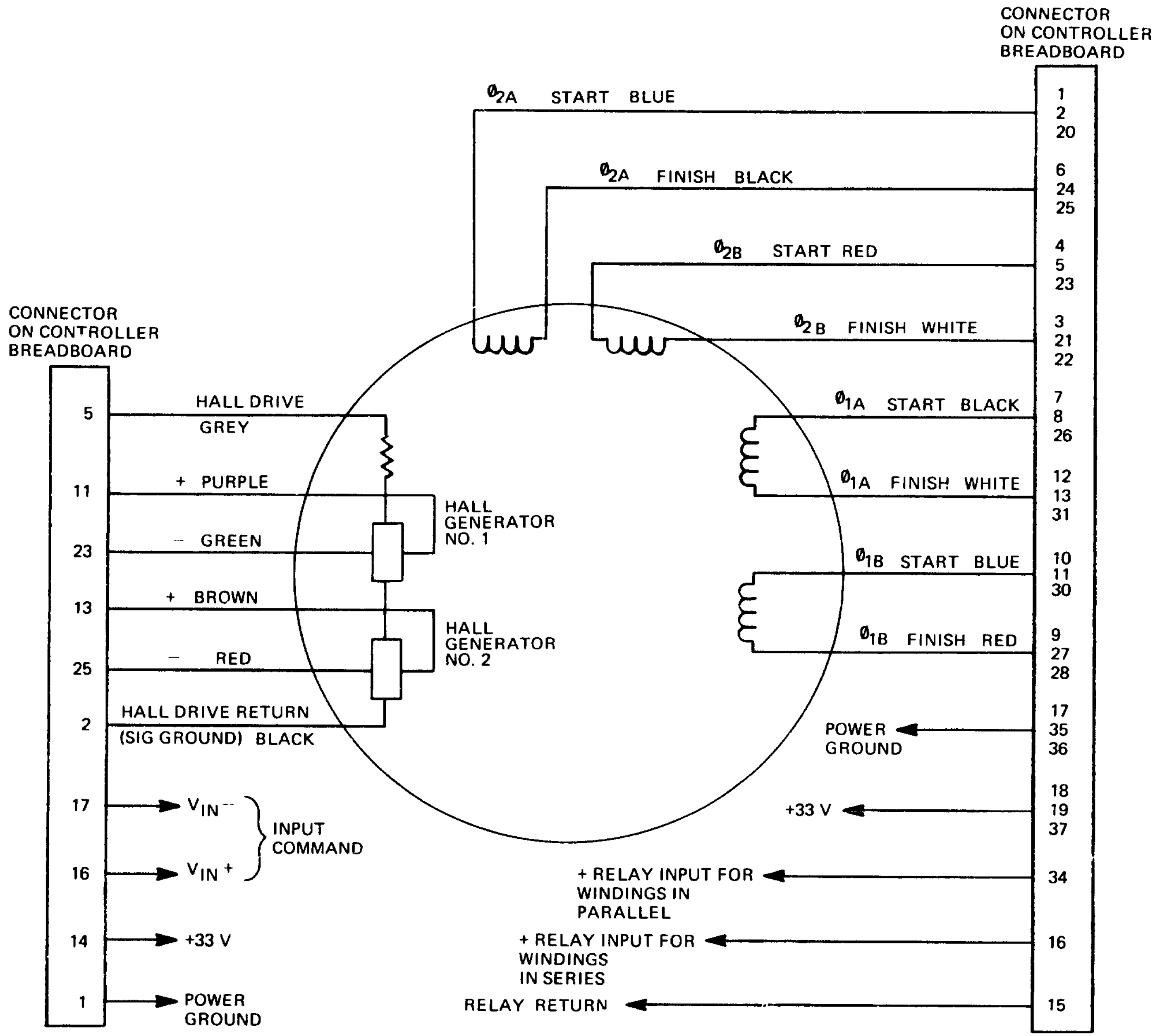


Figure 12. Electronic Interconnection Diagram 022270

ELECTRONIC INTERCONNECTIONS

The interconnections between the motor and electronics are shown in Figure 12. Hall generator 1 is associated with motor phase 1 and Hall generator number 2 goes with phase 2. A 5.0-volt input command gives the maximum torque level. A positive command turns the motor in a clockwise direction (clockwise direction viewed looking into the fixture).

The relays are magnetically latched and operate with a 28-pulse between either the series or parallel input and return.

Section 8
CONCLUSIONS AND RECOMMENDATIONS

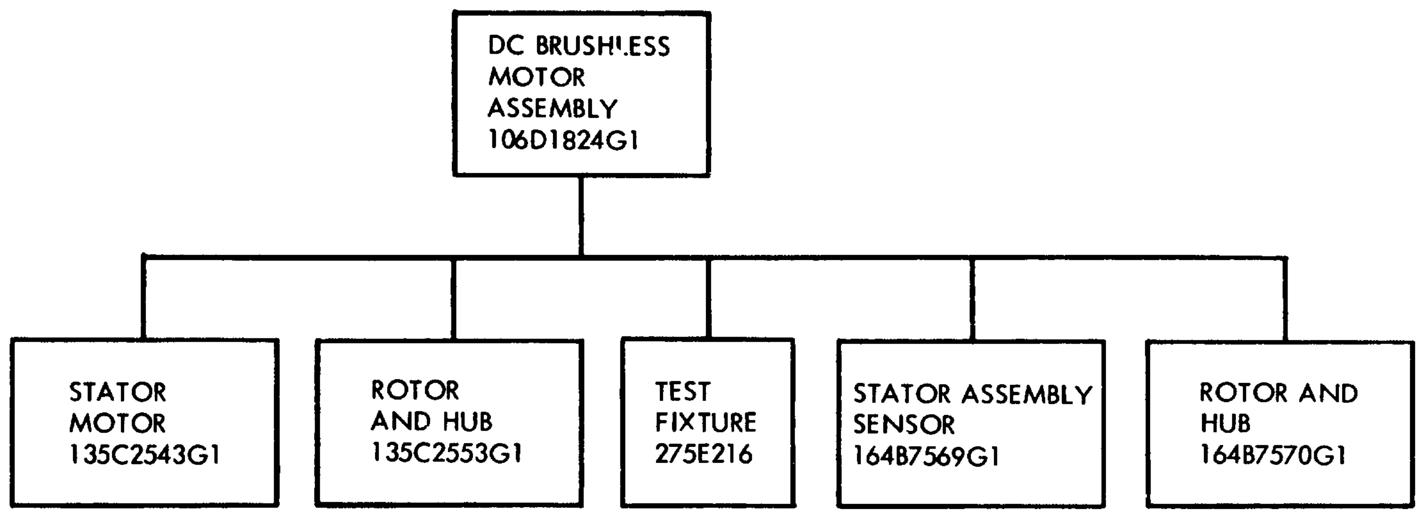
The brushless dc motors developed under this contract met all the contract requirements. In addition, since a similar motor was evaluated in environmental tests (reference 1) the brushless motor will perform satisfactorily in a space environment.

Because of the wide temperature range specified in this contract certain changes must be made in the motors supplied before they are subjected to temperature extremes. These changes which consist of replacing the aluminum hub on the test fixture with a titanium hub, selection of a high temperature Hall generator and selection of a different material for the Hall generator holder can be accomplished without changing the motor design.

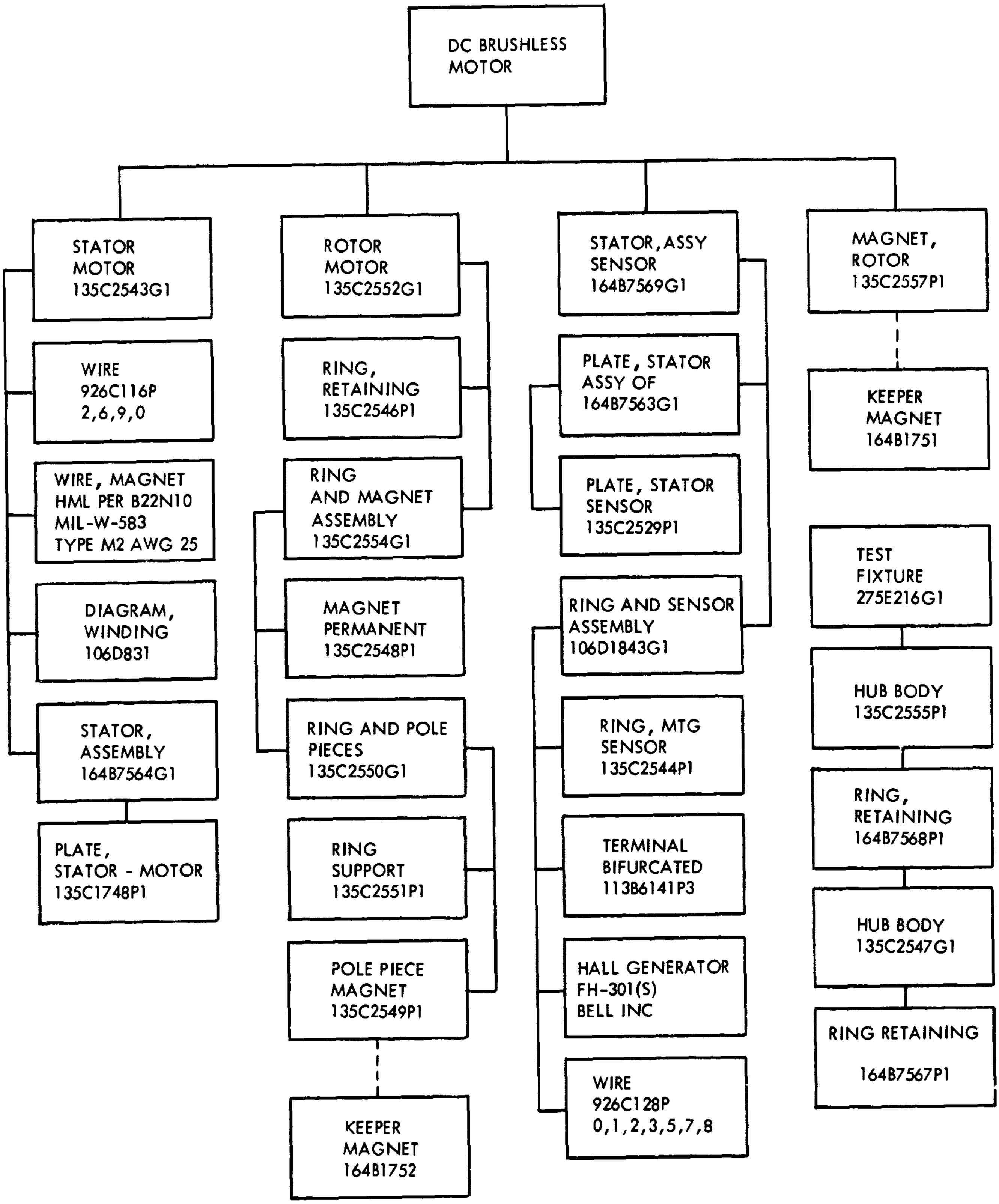
The motor design was not optimized because the basic motor design was adapted from another contract. The General Electric Company has a preliminary design for a 16-pole, 6 ft-lb motor. This design is for a second-generation brushless dc motor and employs a ring magnet of a new design. This proposed motor has many features that would make it ideal for a long life space mission.

The electronic controller could be fabricated from high reliability components and packaged to meet the stresses of a space environment. Similar controllers have been evaluated in environmental tests under other contracts.

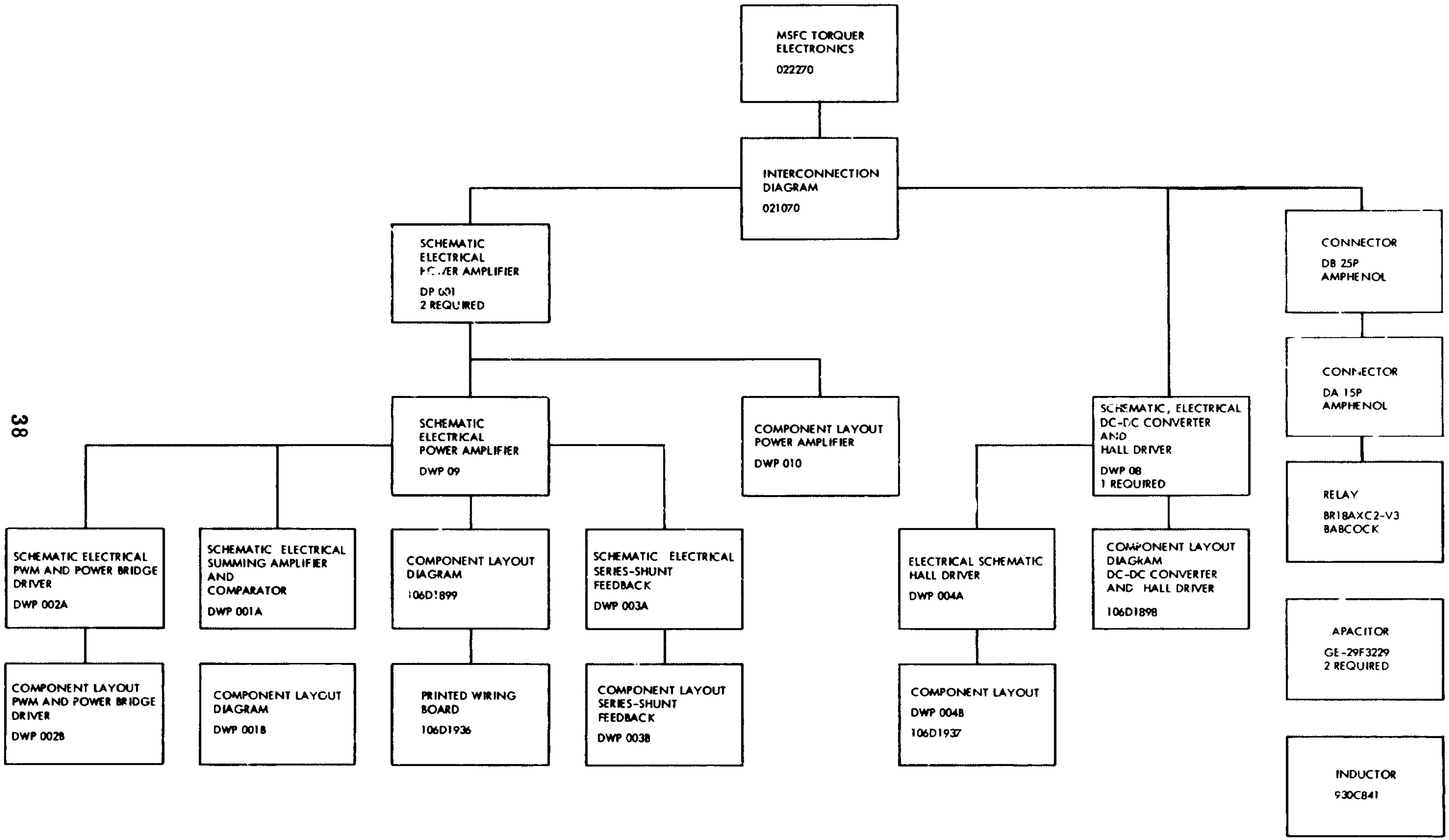
APPENDIX
DRAWING STRUCTURES



Brushless DC Motor and Test Fixture Assembly



Brushless DC Motor Drawing Structure



Electronic Controller Drawing Structure