FIRST QUARTERLY REPORT - PHASE II

for

DESIGN AND DEVELOPMENT OF A BRUSHLESS, DIRECT-DRIVE, SOLAR ARRAY REORIENTATION SYSTEM

(BRUSHLESS MOTOR COMMUTATOR-CONTROLLER DEVELOPMENT)

(June 1969)

Contract No. NAS 5-10459

Prepared by

Westinghouse Electric Corporation
Aerospace Electrical Division
Lima, Ohio

for

Goddard Space Flight Center
Greenbelt, Maryland

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ABSTRACT

Although work done in the first quarter covered several areas including design work on the transformer and the control unit, only the work pertinent to the drive motor is reported here. Several problem areas were left unresolved at the close of contract NAS 5-10263 covering the brushless dc torque motor. The motor was transferred to the present contract, NAS 5-10459, for resolution of these problems. Necessary modifications were made to correct the problems in the motor design and the changes and test results are contained in this report.

This report may be considered as an addendum to reference 1, the final report on the brushless dc torque motor built on contract NAS 5-10263.

CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

A brushless dc torque motor, described in reference 1,[1] was developed on Contract NAS 5-10263. Three motors were assembled. The first of these motors was used in the Phase I of the present contract, NAS 5-10459, for system tests. The second motor was transferred to Phase II of the present contract for modification to correct unresolved problems in the electronic controller-commutator of the motor. The third motor was assembled from left-over parts and is not expected to be as good as the second motor. Nevertheless, the controller-commutator of the third motor will be modified to conform to the findings of this study.

The problem areas as discussed in reference 1 are (1) magnetic sensor outputs are unequal and wave form irregular, (2) pulse width of the motor voltage varies as a function of rotor position, and (3) another area, not specifically pointed out as a problem, is torque variation. These problem areas were analyzed and modifications were made to correct the problems.

DISCUSSION

PROBLEM AREAS AND CORRECTIVE ACTION

Magnetic Sensor

The six output voltages of the magnetic sensor deviated from the intended design as reported in reference 1. The difficulty is shown in figure 41 of reference 1 where the magnitude of the sensor outputs, which should be equal, are not the same. The outputs, as shown in the figure, are alternately high and low. The second motor was tested and found to follow a similar pattern.

Investigation of the reason for the alternate high-low variation in magnitude led to the magnetic sensor wiring diagram, figure 13 of reference 1. It will be noted that the number of turns varies from 87 to 109. It was further learned that the magnetic sensor used in the first motor was tested in a fixture external to the motor and adjustments in the number of turns were made to equalize the outputs of the sensors. The results of the adjustment are shown in figure 40 of reference 1. There is evidence that the test fixture used was faulty, probably eccentric. Further, the magnetic sensor used in the second motor was wound having the same number of turns as the first. Hence, similar output variations existed in both motors.

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[1] See Bibliography

Inspection of figure 13 of reference 1 reveals that the lower group of coils have an average of almost 10 percent more turns than do the upper group. Analysis of the sensor does indeed show that alternate sensor outputs would be about 10 percent different in magnitude as shown in figure 41 of reference 1.

A second variation in magnetic sensor output was also observed. As the motor is rotated the sensor output should repeat eight times per revolution. There is, however, a variation of approximately 5 percent in the maximum value of each sensor output throughout a motor revolution. This variation is evidently caused by eccentricity of the sensor rotor, and no attempt was made to correct it.

The maximum output voltages of two sensors prior to modification are shown in figure 1 (A). Output B (from one of the coils in the lower group figure 13 of reference 1) was consistently higher than output E (from the upper group), because of a greater number of coil turns. Figure 1 shows the variation in maximum output as a function of rotation.

The magnetic sensor was modified by removing 16 turns from each of three lower coils having the greatest number of turns. This lowered the outputs B, D, and F. Figure 1 (B) shows the variation in outputs B and E after the modification was made. While there is still variation in outputs with rotation, the difference in sensor outputs was reduced from about 16 percent to approximately 6 percent, a variation that can be tolerated.

Pulse-Width Variation

As discussed in reference 1, the pulse width of the voltage applied to the motor windings by the electronic control varied with position of the rotor. The effect was to reduce the motor voltage in the region where commutation takes place. The motor torque normally is minimum at the commutation points. Thus, the reduction in pulse width accentuated the ripple torque, and made the motor run roughly at low speed.

In the original circuit (figure 17, reference 1) the drive transistor (Q11 or Q14, etc.) is turned on as a result of turn-on of the Schmidt trigger WM208T, which turns on when the magnetic sensor voltage reaches a preset positive level. The turn-on of Q11, Q14, etc. completes the circuit through the output winding of the magnetic amplifier, AR1, which supports voltage for a time depending on the current level in the magnetic amplifier control winding. When the magnetic amplifier saturates, base drive current is supplied to the power transistor (Q12, Q15, etc.) through the drive transistor (Q11, Q14, etc). The pulse to the motor continues until the magnetic sensor voltage goes negative, turning off the Schmidt trigger and subsequently the drive transistor. The magnetic amplifier is reset

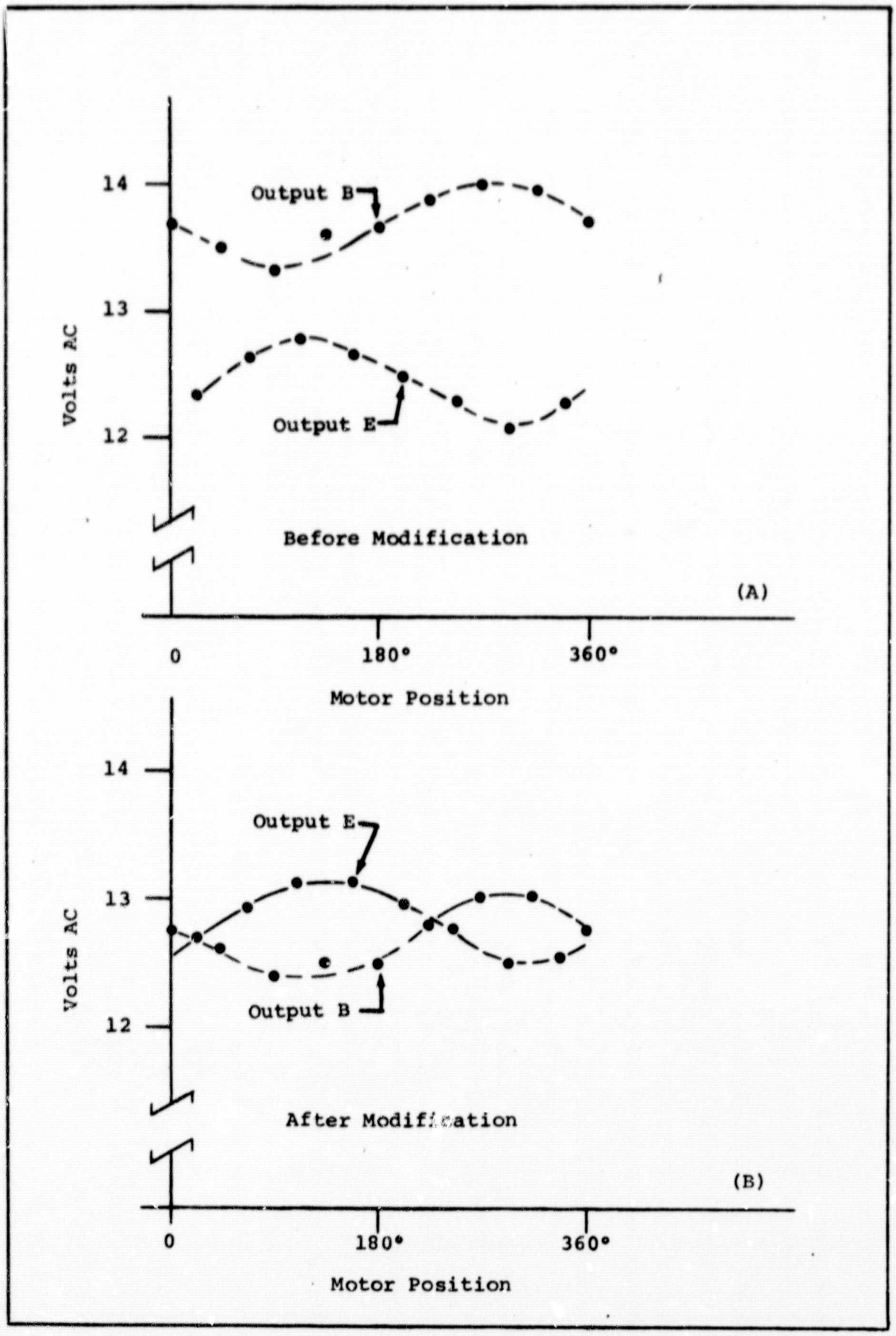


Figure 1. - Maximum Sensor Output Versus Motor Rotation

during the negative half cycle of the magnetic sensor output.

As the magnetic sensor output increases, the period of time between turn-on of the Schmidt trigger and turn-off of the drive transistor increases, while the saturation time of the magnetic amplifier remains constant, as reported in reference 1. The major cause of pulse-width variation was thus attributed to the non-square wave form of the sensor voltages. Attempts made to improve the magnetic sensor wave form were without much success. Another method of control was, therefore, developed to correct the pulse-width variation problem.

To eliminate the effect of the magnetic sensor wave form, it was decided to rectify the sensor output and thus turn on the Schmidt trigger for the full angular position of the rotor demanded by the logic. The pulse width is, thereby, divorced from the magnetic sensor outputs. The magnetic amplifier circuit was modified by connecting its output winding to the ac power supply transformer, through a diode. The magnetic amplifier output winding, which is energized when the transformer voltage goes positive, supports this voltage until saturation takes place, and subsequently conducts current to the drive transistor until the end of the positive half cycle. The pulse width is, therefore, determined by the supply voltage and the magnetic amplifier control current, but is not affected by magnetic sensor output. The pulse width of the applied voltage, and thus the average magnitude, is made independent of the position of the rotor.

Torque Variation Due To Irregularities in Switching Angle

Analysis of the motor and control circuit reveals three causes of incremental torque variation, (1) normal variation due to flux distribution, (2) transient variation due to commutation, and (3) variation due to error in switching angle.

The variation in torque with angular position is a function of pole shape, winding placement and magnetic flux distribution of the rotor poles. In this motor the torque varies approximately sinusoidally for a particular winding connection (i.e. between switching points). This variation is beyond the scope of the present contract, thus no modification was made to alter the characteristic.

The transient variation due to commutation is a normal function which occurrs following each switching point. During the commutation period the currents in the motor windings must change to new values. During the current change there is a momentary decrease in torque, which is restored following commutation.

The variation in torque due to error in switching angle is a function of both the magnetic sensor and the control circuit. Effort was confined to this area in reducing torque variations.

The first consideration in providing accuracy of switching points, of course, is to align the magnetic sensors so that the crossover points between adjacent sensor outputs occur at equal torque points of adjacent motor windings. This can be done with reasonable accuracy, provided the rotor poles are magnetized uniformly and the sensor outputs are well balanced.

In the original circuit the Schmidt trigger acts as a pulse amplitude comparator (as explained in reference 1, pp. 56-57) in conjunction with a lock-out circuit. Two magnetic sensor outputs are compared on the basis that the Schmidt trigger sensing the larger amplitude would turn on and lock out the others. Ideally this method should function well provided all Schmidt triggers have equal turn-on voltage, and good square-wave pulse signals are applied. It was found, however, that a fairly wide tolerance exists in turn-on voltage (4.2 to 6.4 volts). Unfortunately the circuit does not lend itself to convenient calibration and, as previously pointed out, the magnetic sensor does not produce quality square waves. As a result of these variations, the switching points deviate from the sensor crossover points causing transfer from one motor winding to another at points of unequal torques. Figure 2 illustrates how errors in switching points cause discontinuities in motor torque. If the control transfers the motor winding at the magnetic sensor crossover there is a minimum of change in torque.

Because of the difficulty in sensing the magnetic sensor crossover points by the original method, it was decided to try the direct approach. A circuit was devised to detect the crossover points by sensing the difference in amplitude between magnetic sensor outputs, and providing logic to switch the proper power transistor at the crossover points. The six Schmidt triggers were replaced by three type 710 voltage comparators. Integrated circuit NAND gates are used as logic elements.

The replacement control circuit is shown in figure 3. The magnetic sensor outputs from the direction control logic transistors are brought in to diodes which serve as rectifiers for the sensor voltages and also as OR gates. The output from each pair of diodes is a dc voltage proportional to the greater of two adjacent magnetic sensor signals. The output from sets of diode pairs are sensed by the differential comparators, thus detecting the crossover points of two sensor outputs.

The signal X, for example, in figure 3 is a logical "one" when the signal at either K or N is greater than that at either P or J. The sensor outputs appearing at K, N, P, J etc. depend on the direction control. Reversing the direction control simply interchanges the magnetic sensor signals appearing at K and N with those at P and J.

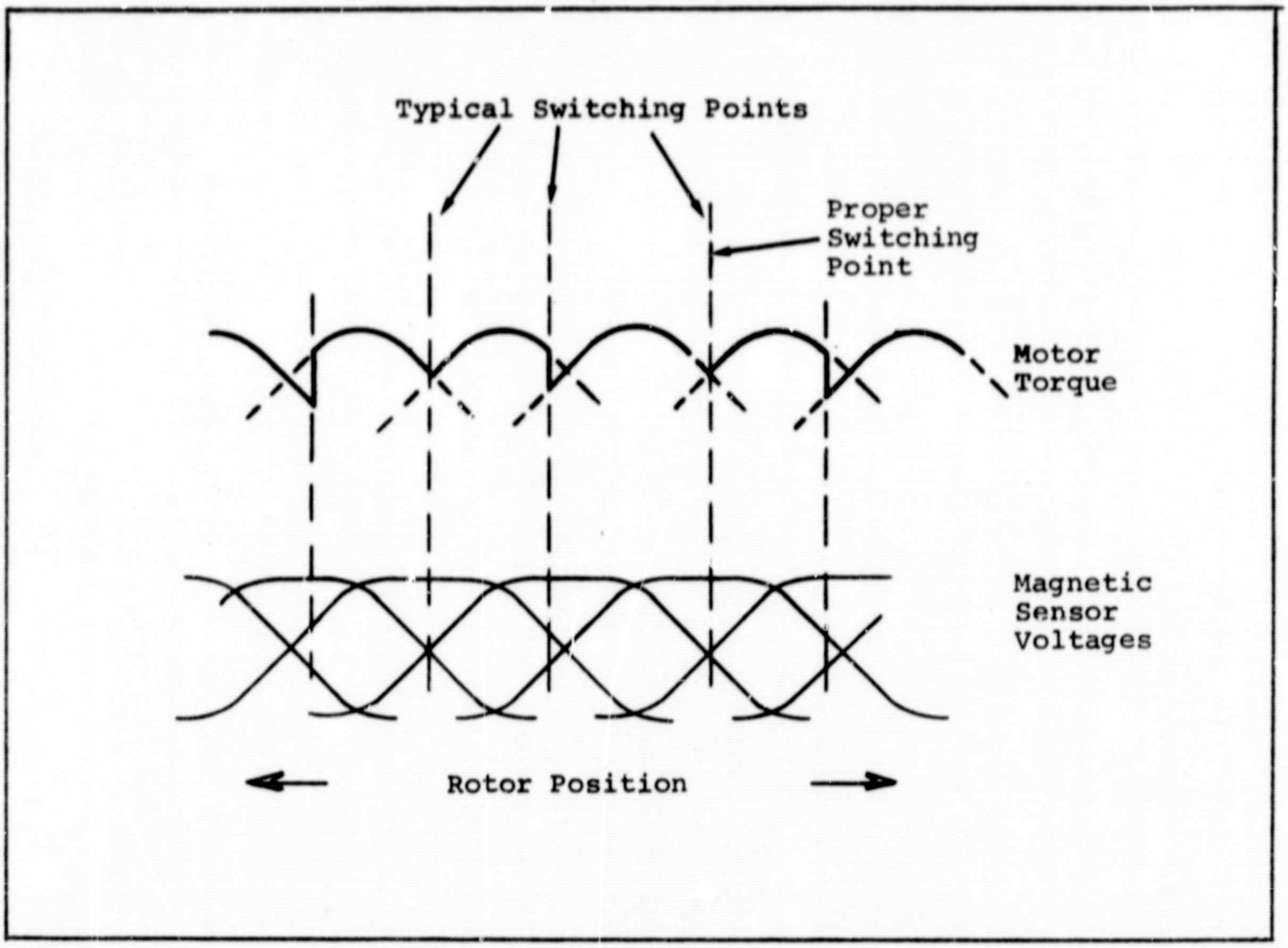


Figure 2. - Motor Torque Variation versus Switching Points

The signals Y and Z are derived from appropriate sensor signals in the same manner as is X. The signals X, Y, and Z are used to form control signals for the steering transistors Q1, Q13, etc. A signal to turn on transistor Q1 is developed when both X and Y are low ($Q_1 = \overline{X} \cdot \overline{Y}$). Likewise, $Q_{13} = \overline{Y} \cdot \overline{Z}$, $Q_7 = \overline{Z} \cdot X$, $Q_{10} = X \cdot Y$, etc. The output of the NAND gates to the transistors form wired AND logic. Thus two NAND gates must be in the high state to turn on the transistor, which is driven through the collector resistors of both NAND gates.

Referring once again to figure 3, note that filter capacitors are provided at the inputs of the comparators and that feedback resistors are connected from $\overline{X}$, $\overline{Y}$, and $\overline{Z}$ to the input of the comparators. This circuitry serves to provide a clean transfer from one state to another, eliminating dither or instability. The capacitors eliminate the effect of differences in sensor wave form, while the feedback resistors increase slightly the difference voltage applied to the comparator after the comparator has changed state.

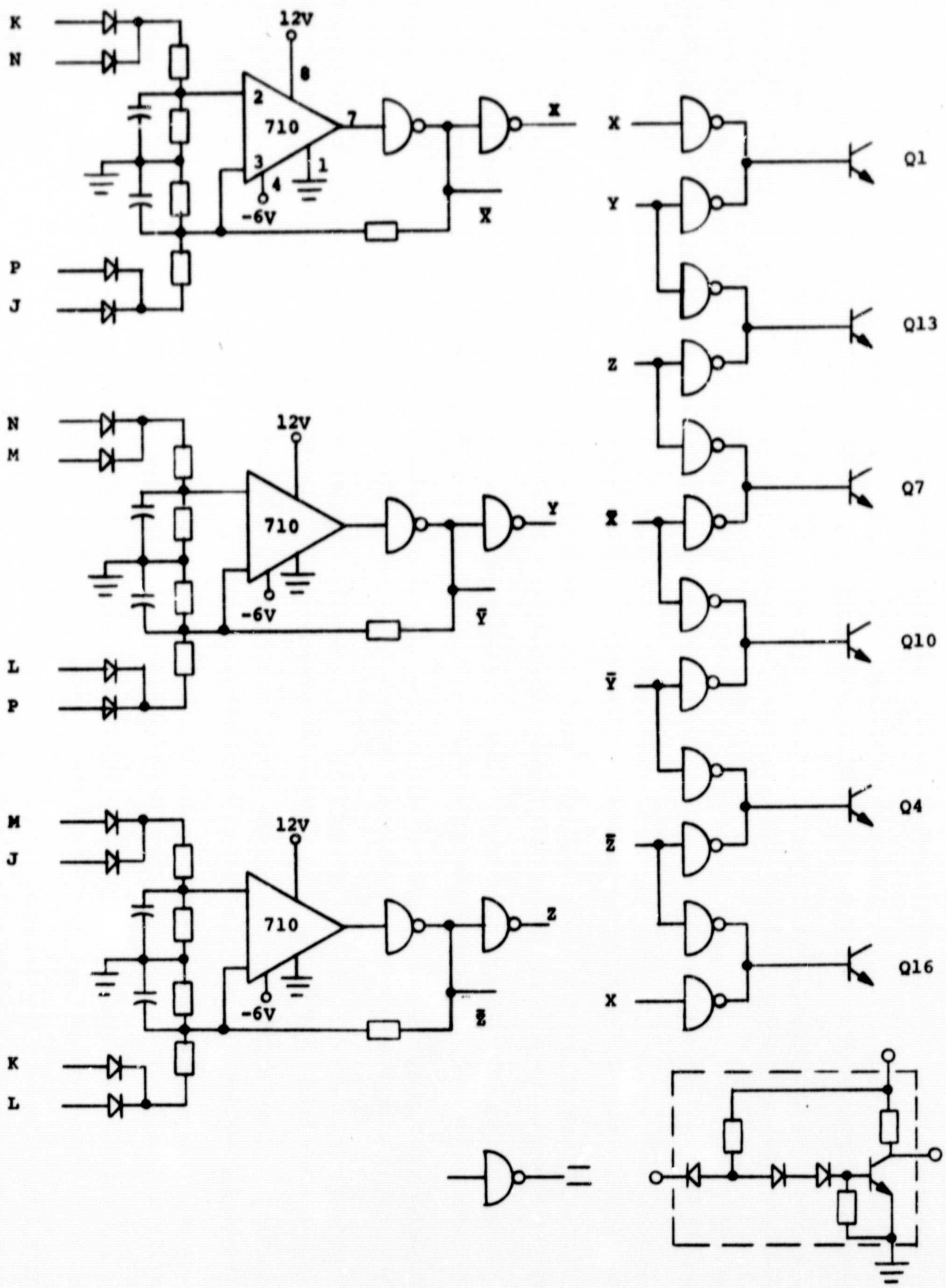


Figure 3. - Brushless Motor Commutator Control Logic

Derivation of the commutator control signals is shown in figure 4. The sensor outputs which appear at points P, L, K etc. are shown at the top of the figure. The diode output from K or N is shown in bold lines as is the output from J or P. When K or N is greater than J or P the signal X appears. It will be noted that X is "on" for an angular rotation equal to that for which it is "off" (a square wave, relative to position). The same is true for Y and Z. One of these signals changes state at each of the sensor crossover points. By combination of these signals as shown in figure 3, the drive signals are thus derived.

A revised schematic diagram of the modified controller-commutator is shown in figure 5, which incorporates the circuit of figure 3 into the complete circuit. Connections between signal points have been omitted for clarity. These connections are indicated by symbols (signal symbol or terminal marking). Although no change was made in the direction control logic, some space economy could be made in a redesigned unit by using NAND logic for direction control.

TEST

The tests conducted on the motor were the applicable performance tests outlined in reference 2. The initial test consisted of adjustment of the magnetic sensor assembly. Once proper alignment was accomplished the following tests were conducted.

(1) Oscillator (28-volt input)

Wave Form - The wave form was observed to be a reasonably good quality square wave.

Frequency - 10620 cps

Output Voltage (peak reading of square wave)

Terminals	Volts
12-13	6.1
13-14	6.1
15-10	9.0
10-16	9.0
8-10	6.1
10-11	6.1

(2) Magnetic Sensor (28-volt input)

Wave Form - The wave form is substantially the same as previously reported in reference 1. A good deal of ringing is apparent but suppression resistors have not been used since this ringing is not troublesome.

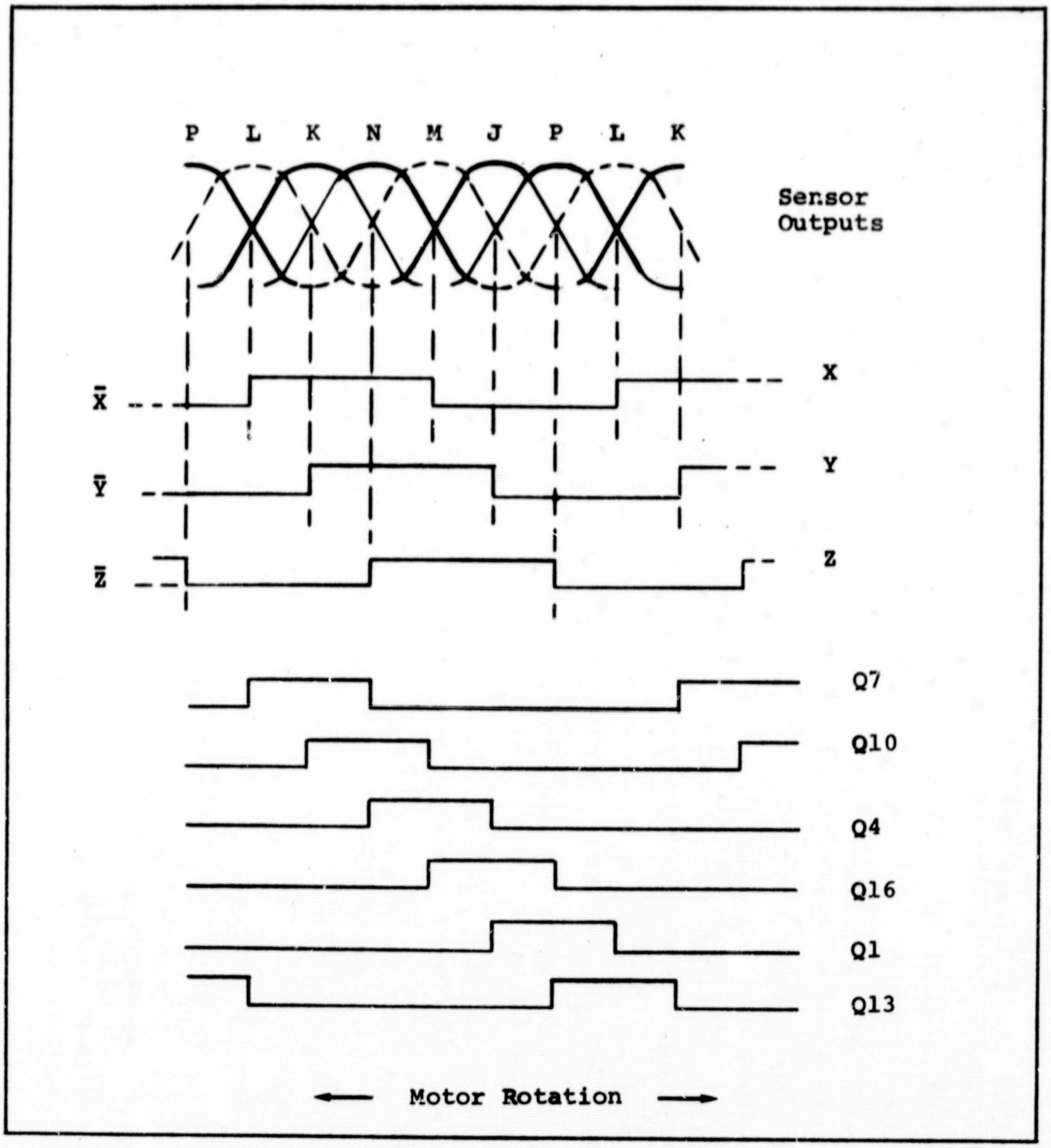


Figure 4. Derivation of Commutator Control Signals

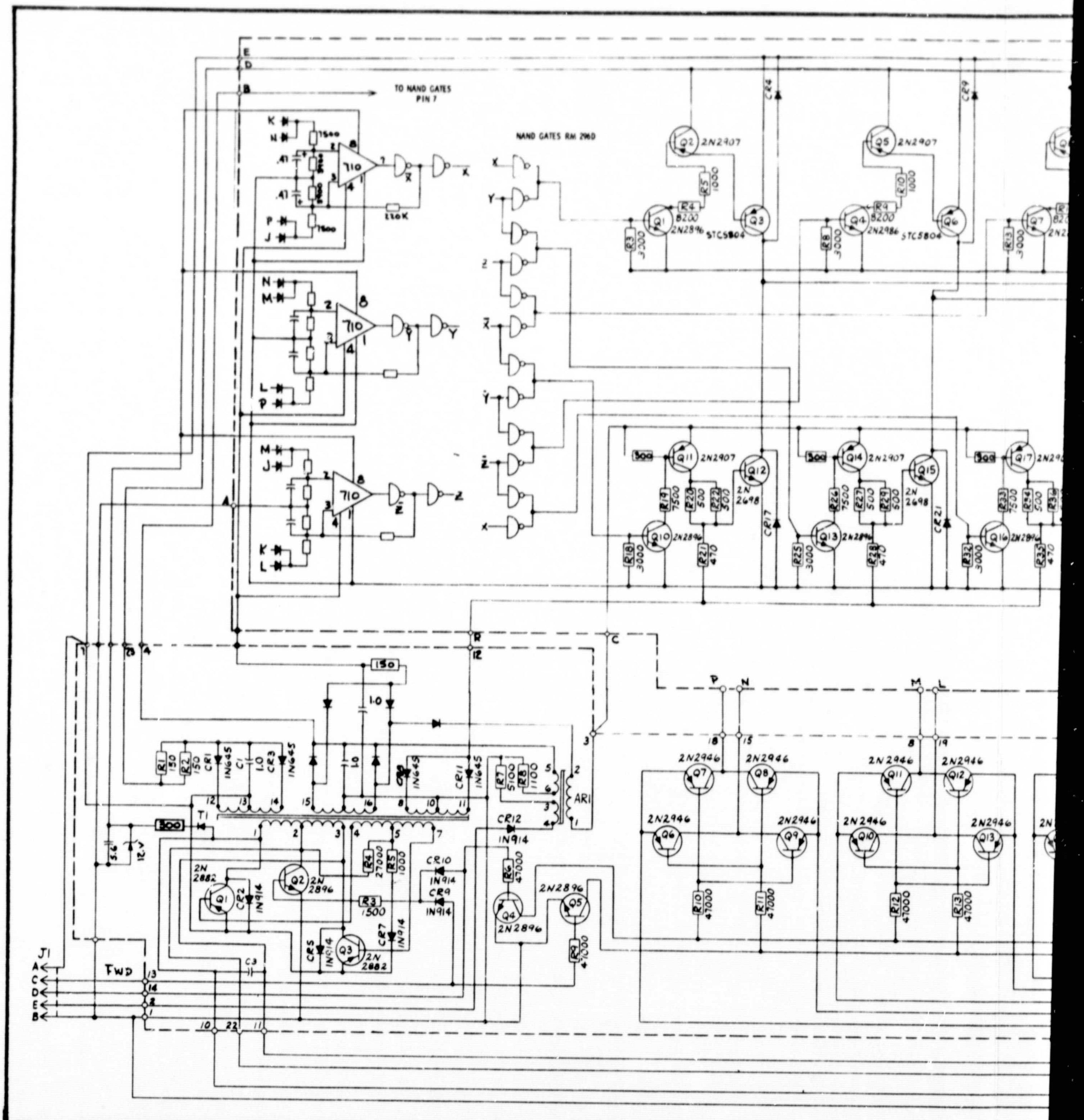
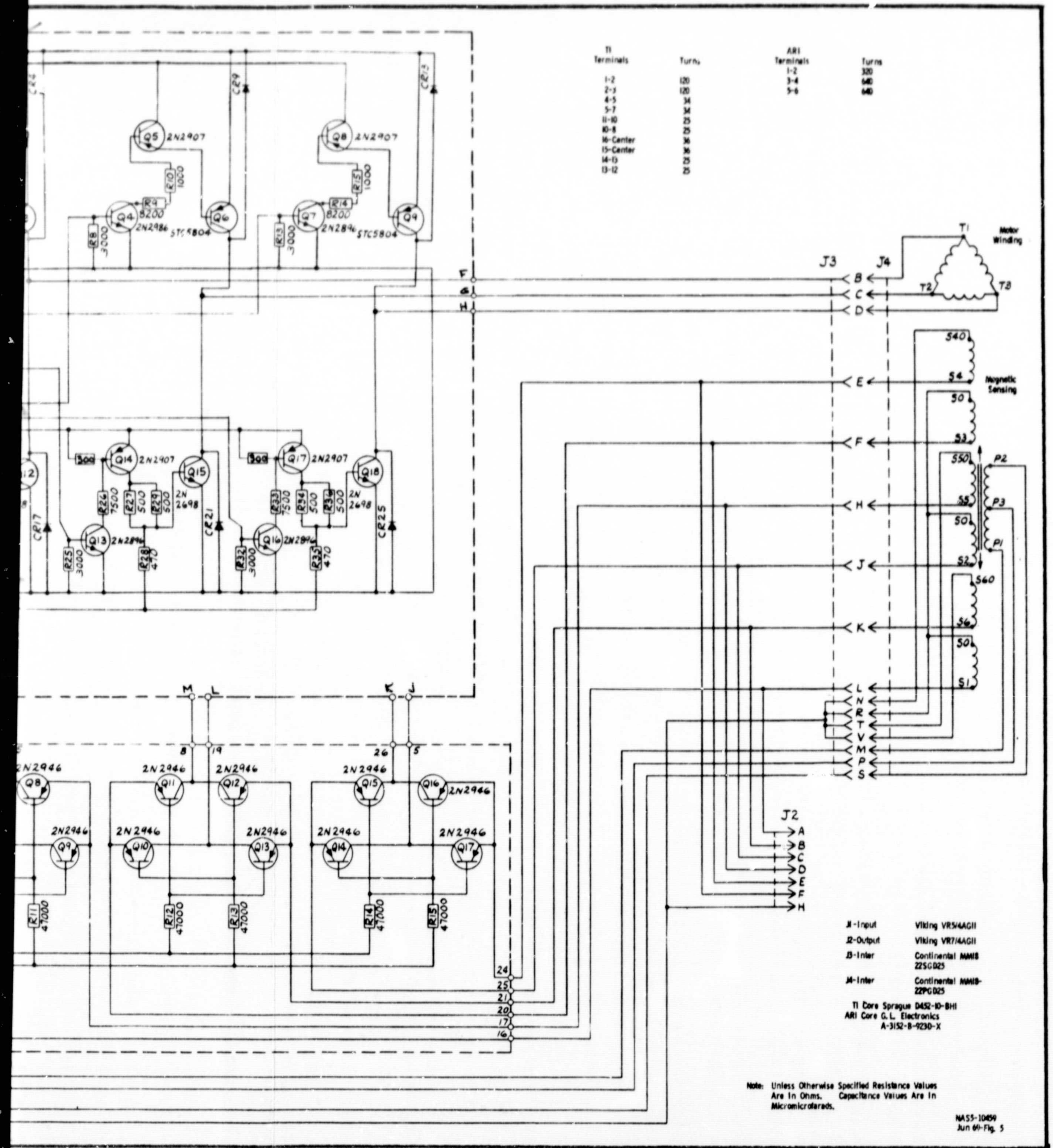


Figure 5. - Controller-Commutator Circuit Schematic - Revised

FOLDOUT FRAME 1



Revised

FOLDOUT FRAME 2

Voltage Level - The ac output voltages were plotted for one full cycle (45 degree rotation). The results are shown in figure 6. In other rotor positions these curves will vary slightly as discussed previously.

(3) Reversing Bridge

Operational check - performance is normal.

(4) Voltage Comparators and Switching Logic.

Operational check - Switching occurs in proper sequence at proper points.

(5) Speed Control (28-volt input)

A speed control voltage was applied to pin E of connector J1 and varied to determine the no-load speed characteristic. These data are plotted in figure 7. Minimum no-load speed was 15 to 20 rpm at 2 volts control voltage. Maximum speed is slightly higher than 150 rpm at 12 volts. Higher control voltage increases the speed only slightly.

(6) Control Losses

The input power with the motor inoperative was measured.

Supply voltage -	28 volts
Control voltage -	15 volts
Input current -	24 ma
Power dissipation -	672 milliwatts

(7) Power Dissipation, Motor Operating

The input power was measured at maximum speed-control voltage at both no load and locked rotor.

Supply voltage -	28 volts
Control voltage -	15 volts

	No Load	Locked Rotor
Input Current	150 ma	500 ma
Input Power	4.2 watts	14 watts

(8) Operating Voltage Range

Supply voltage was varied over a range of 12.5 to 34 volts. The motor operated satisfactorily in both directions throughtout the voltage range. The minimum voltage at which the motor would run was 12.5 volts.

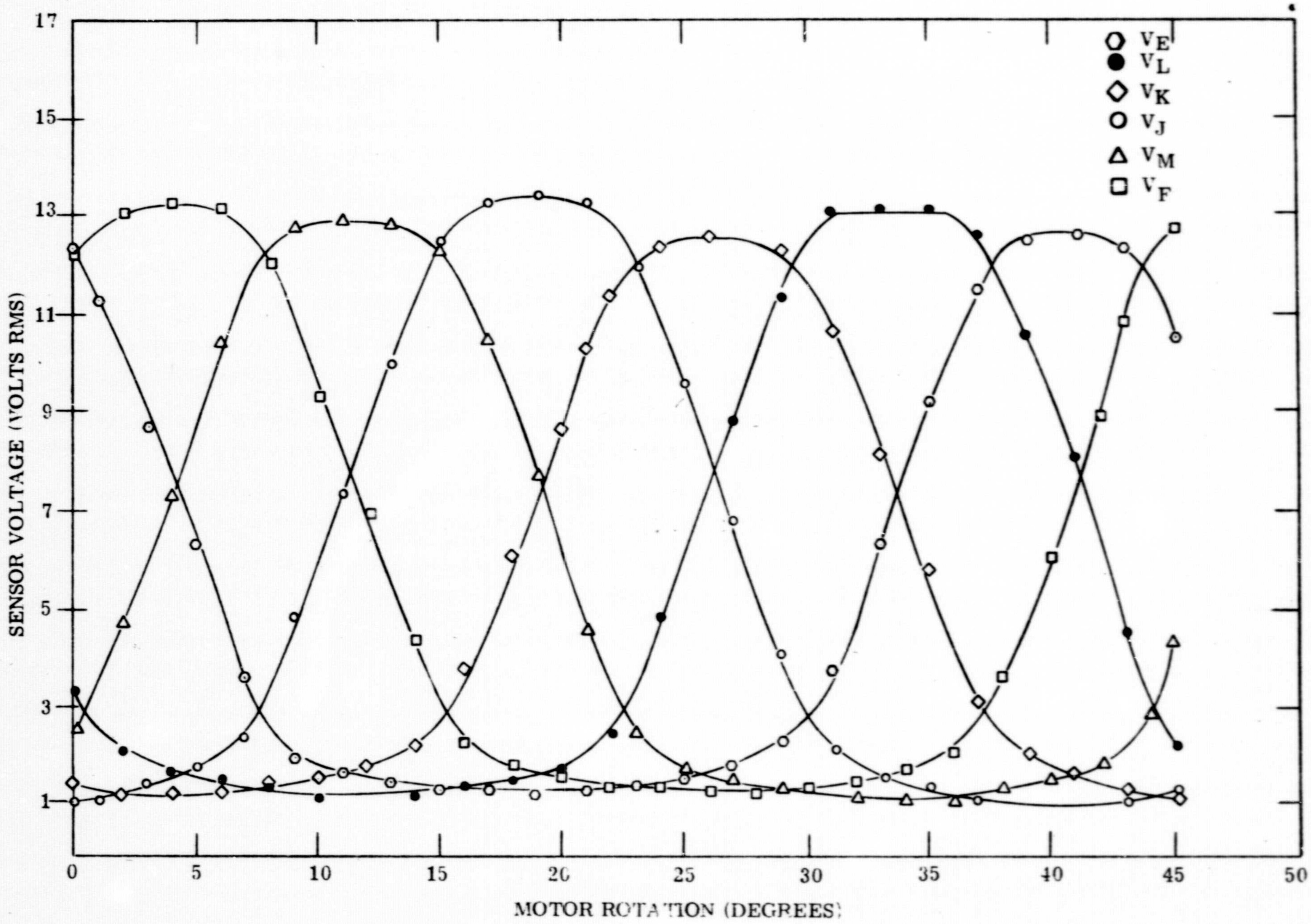


Figure 6. - Magnetic Sensor Characteristics - Test Curves

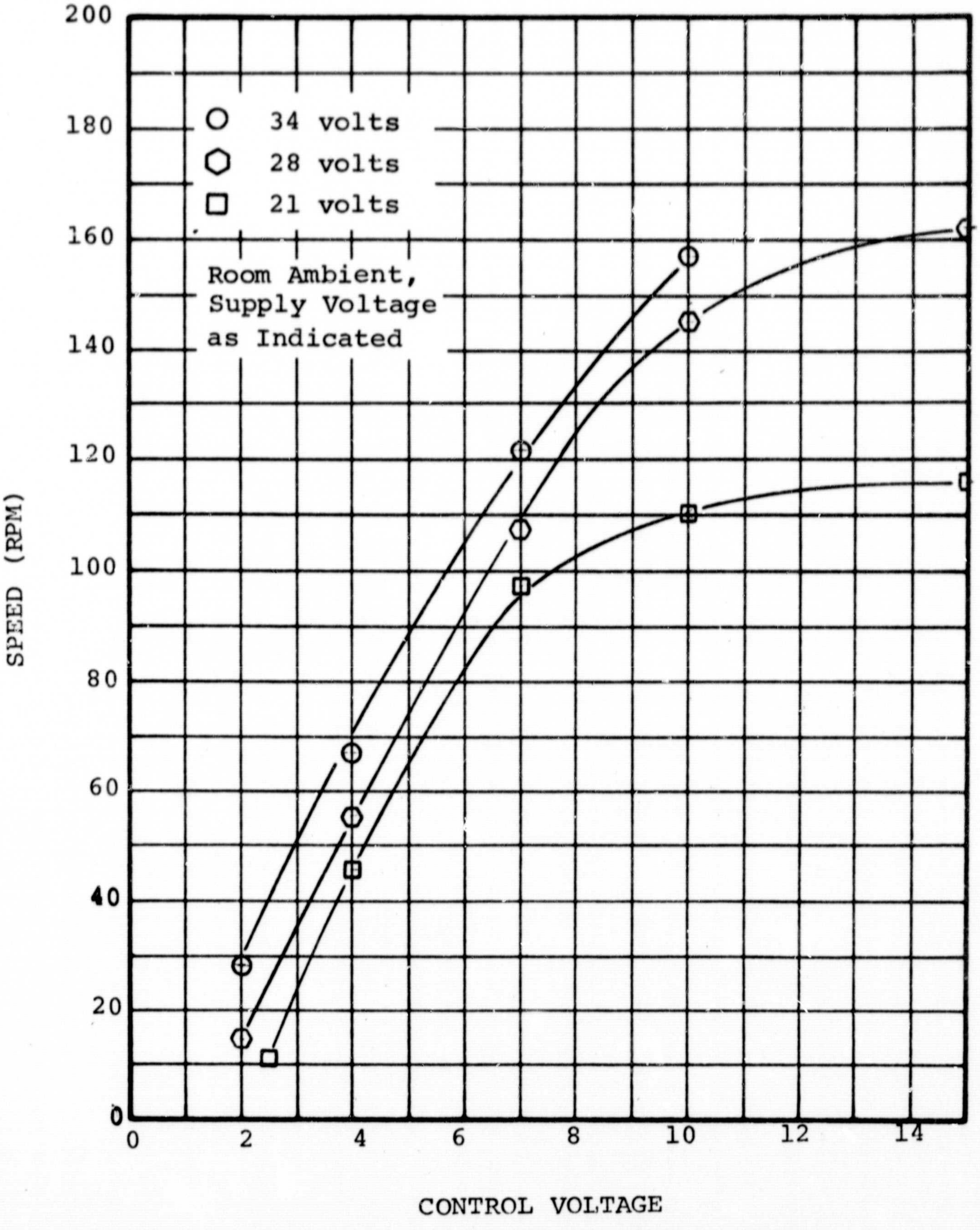


Figure 7. - No Load Speed Control Characteristics

(9) Forward Drop In Power Transistors

The conduction voltage drops in the power transistors were measured at locked rotor as follows:

	Volts
Q3	0.2
Q6	0.15
Q9	0.15
Q12	0.4
Q15	0.7
Q18	0.6

These values indicate that the transistors were operating within their saturation region as designed.

(10) Winding Resistance

Winding terminals are identified by terminals of connector J4.

Motor Winding	Ohms
B-C	15.2
C-D	15.19
B-D	15.2

Magnetic Sensor

Primary	Ohms
M-P	0.84
S-P	0.84

Magnetic Sensor

Secondary	Ohms
E-N	3.00
F-R	2.94
H-T	3.01
J-R	3.00
K-V	2.96
L-R	2.90

(11) Break-Away Torque

Break-away torque, which includes both friction and cogging torque, was measured as the torque required to start the motor with power turned off. This torque was 3.37 ounce-inches, both directions.

(12) Torque Variation With Rotor Position

Locked rotor torque data were taken on the motor at 28 volts supply voltage and 15 volts control voltage. Figure 8 shows torque as a function of rotor position for 45 degrees of rotation. This curve shows approximately 15 percent variation in torque due to ripple, which is caused by near sinusoidal flux distribution in the rotor poles.

Additional data were taken over a complete revolution, measuring the maximum and minimum torque points. The total variation in torque measured was 72 to 90 ounce-inches.

(13) Speed-Torque Curves

Torque-speed data were taken at various control voltages with supply voltages of 21, 28, and 34 volts, in both forward and reverse rotation. The data shown in figures 9 and 10 for forward rotation result in practically linear curves. Reverse rotation values were within 3 percent of the forward values.

(14) Miscellaneous Tests

Tests were made using various combinations of spring and mass loads to determine if instability existed at any point. The general procedure was to wrap a length of cord around the motor shaft to form a windlass, to load the windlass with a weight and spring, and lift the weight by running the motor at minimum speed. The motor was started by increasing the control voltage enough to lift the weight. Once the weight was lifted, the motor continued to run with no sign of instability or dither. Although many combinations of spring and mass were tried, no instability was found in the motor under any condition when it was loaded with a linear continuous type load. An unstable loading condition such as holding the motor shaft by hand can result in oscillatory motion of the rotor, but this is not considered a practical load.

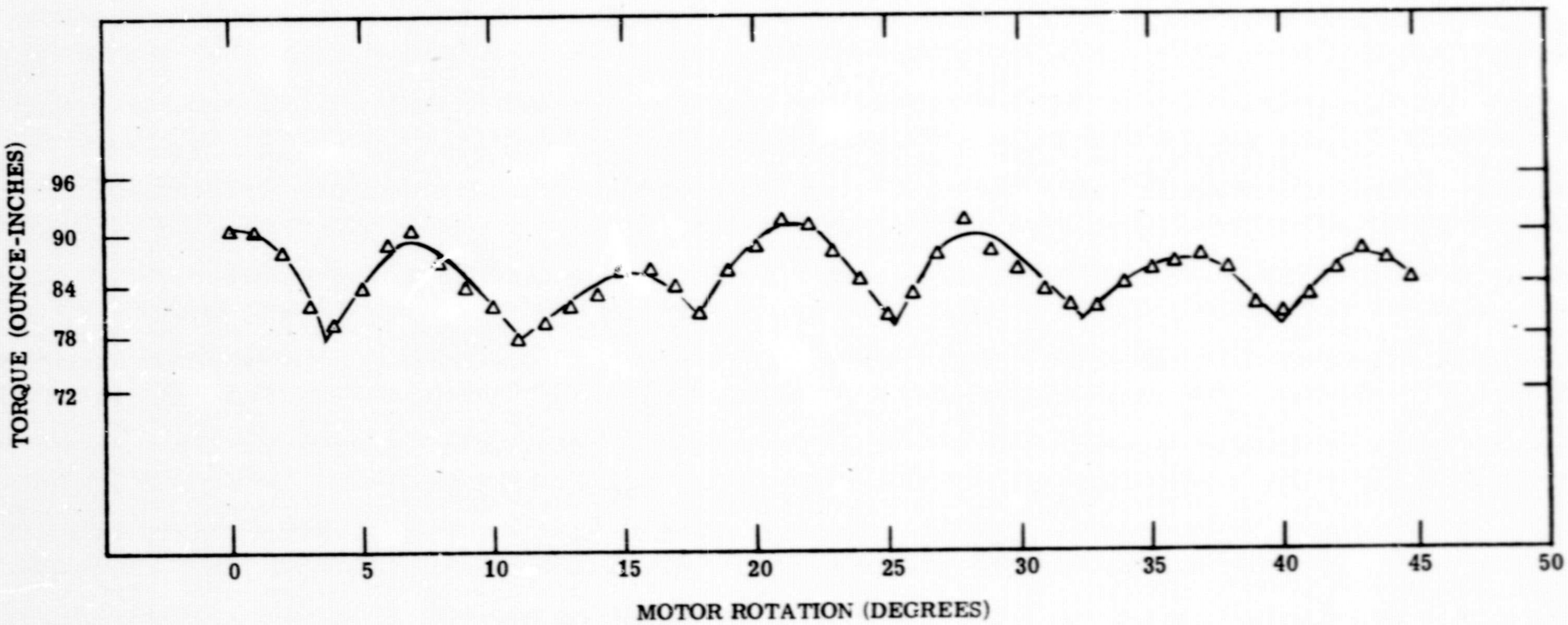


Figure 8. - Torque Versus Rotor Position

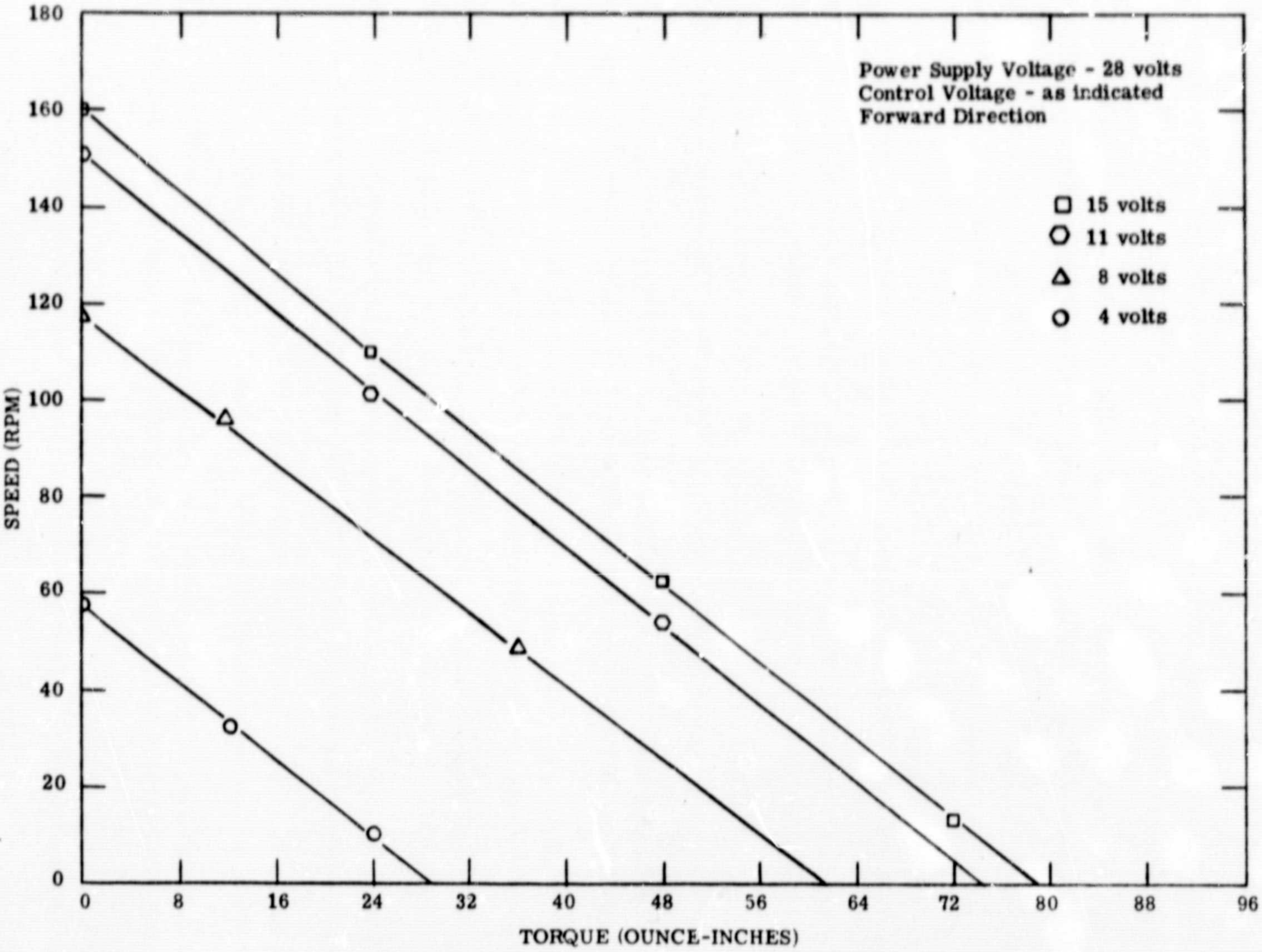


Figure 9. - Speed-Torque Curves

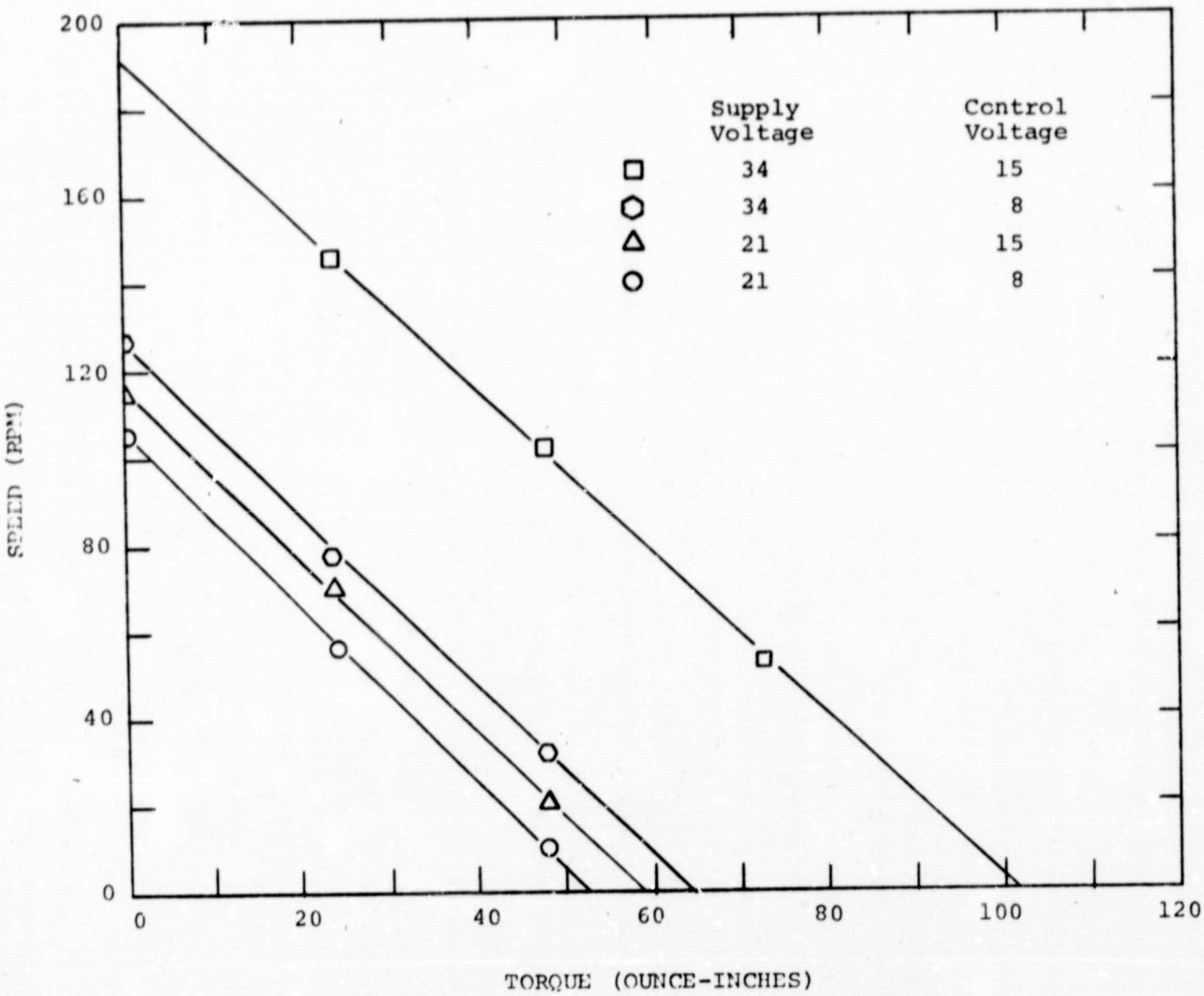


Figure 10. - Speed-Torque Curves

(15) High And Low Temperature Tests

The motor was run at the specified temperature extremes of -10° C and +70° C. Performance checks were made at both temperatures. The motor ran normally in both cases indicating that there was no malfunction in the commutator-control circuit. No-load speed was tested as a function of control voltage over a range of supply voltage 21 to 34 volts. The speed characteristics at nominal supply voltage are plotted in figure 11 for temperatures of -10° C and +70° C. Speed increases slightly with temperature for any control voltage.

CONCLUSIONS AND RECOMMENDATIONS

The problem areas outlined in reference 1 were analyzed, and development work was done to correct these problems. The inequality of signals from the magnetic sensor (reluctance switch) was corrected by modification of the output windings so that each pair of poles (for each of the six output signals) have approximately the same number of turns per pair. It is recommended that all sensor output coils be identical in future motors.

The major problem area involved the electronic commutator and speed control system. Variation in pulse width of the voltage applied to the motor windings as a function of rotor position aggravated torque variations and caused erratic low-speed operation. The primary cause of pulse-width variation was irregularities in the magnetic sensor wave form. After analysis and testing it was decided to eliminate the effect of the magnetic sensor wave form by rectifying the sensor outputs and to revise the circuit to operate from the resultant dc signals. The primary consequence of the circuit revision was the replacement of the six Schmidt trigger circuits with three differential voltage comparators and integrated circuit logic modules.

The changes made in the circuit corrected the problem areas cited in reference 1. The pulse-width variation with rotor rotation is nil. Torque variation (or ripple torque) was reduced to a minimum. The remaining ripple torque is caused almost exclusively by variation in rotor permanent magnet flux distribution.

Circuit changes required the elimination of some parts and substitution of other parts. The original printed circuit boards could not be fully utilized in the revision, thus it was necessary to add a board to complete the circuit modification. It is, therefore, recommended that new circuit boards be designed when additional motors are built. This will eliminate the need for the additional board and simplify the wiring.

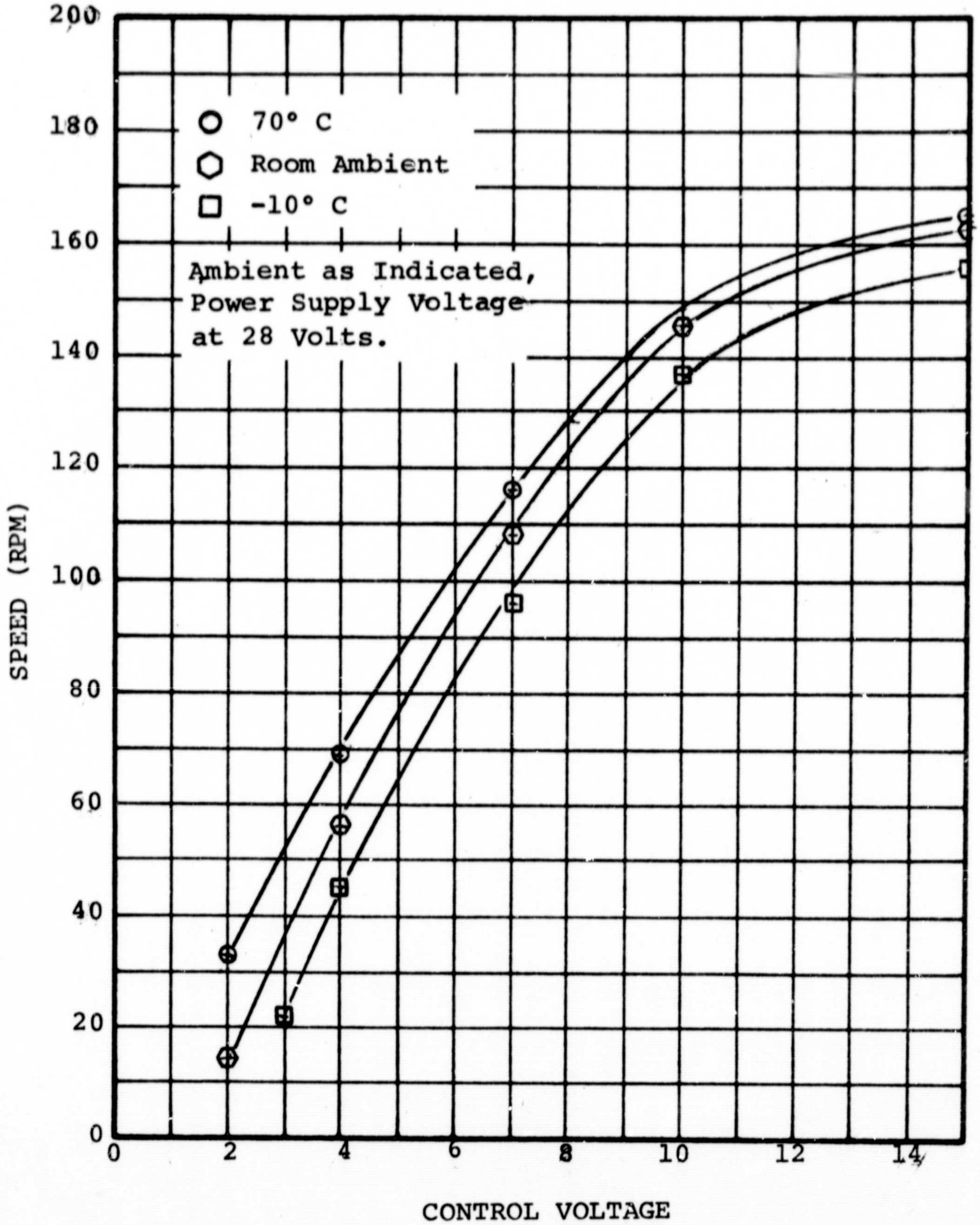


Figure 11. - No Load Speed Control Characteristics

If it is desirable to have a brushless dc motor having less ripple torque it is recommended that further development work be undertaken to produce such a motor. Techniques such as pole shaping might be employed to obtain a flat-topped, rather than sinusoidal, torque curve relative to each motor winding. It is believed that further work with the electronic commutator-control circuit will bear minimal results relative to ripple torque.

PROGRAM FOR NEXT REPORTING INTERVAL

During the next reporting period the following things are to be accomplished:

(1) Complete the design of the control unit and begin assembly.

(2) Reassemble the original laboratory set-up and check out circuit revisions made in the control-unit circuit.

(3) Begin assembly of the rotary transformer.

(4) Complete the mechanical design of the laboratory set-up to incorporate the rotary transformer and other modifications.

NEW TECHNOLOGY

None.

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1. Yates, W. W. et al, Final Report, Advanced Brushless DC Torque Motor, 30 November 1968, Contract NAS 5-10263, Report No. WAED 68.45E.

2. Yates, W. W. et al, Second Quarterly Report for an Advanced Brushless DC Torque Motor, Contract NAS 5-10263, Report No. WAED 66.69E.