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FINAL REPORT - PHASE I

for

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

(JUNE 1968)

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

The purpose of this contractual effort has been to develop a controller for a brushless, direct-drive, single-axis solar array reorientation system for earth-pointed, passively-stabilized spacecraft. A control system has been designed and breadboard circuits have been built and tested for performance. The results obtained meet the intent of the contract.

The controller is designed to take over automatic control of the array on command after the spacecraft is stabilized in orbit. The controller will orient the solar array to the sun vector and automatically track to maintain proper orientation. So long as the orbit is circular, orientation toward the sun is maintained even though the spacecraft goes into the shadow of the earth. Particular attention was given in the design to limit reaction between the array and the spacecraft.

The control system is capable of reorienting a simulated solar array having an inertia of 5 to 10 slug feet square from any position, smoothly within a three-minute period. Acceleration from rest to a speed-controlled return to proper orientation occurs with a minimum of speed oscillation. Acceleration is limited by the design of the controller to minimize reaction between the array and the spacecraft. Upon approaching proper orientation, anticipatory circuits in the controller act to prevent undesirable reactions caused by overshoot or hunting and thus cause a smooth transfer from the reorientation mode to the normal tracking mode.

Operating in the sunlit normal tracking mode, the controller tracks the sun vector at almost a constant error of 0.7 degree. There is no perceptible oscillation and the variation in tracking errors is about 0.1 degree. Transition of the system into the dark period has little effect on the average tracking error (a maximum of 1/2 degree). Total variation of the tracking error during dark period tracking was observed to be 1.2 degree, while the maximum deviation from the sun vector was less than 2 degrees.

In developing the circuits of the controller, it was necessary to compensate for irregularities in the magnetic sensor signals incorporated in the drive motor. It is therefore recommended that in further development of the system, the magnetic sensor outputs be specified to a tolerance of ±5% to provide a reliable interface between the motor and the controller. It is further recommended that the external command control, including the slewing signal, be specified in more detail.

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LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS - Continued

INTRODUCTION

This report covers the work performed on the subject contract which comprised design and building of breadboard circuits of a controller and system testing to prove feasibility.

The solar array reorientation system is intended primarily for use on earth-pointing, passively-stabilized spacecraft such as gravity-gradient stabilized satellites. The reorientation system is to be a brushless direct-drive system without gears or slip rings, capable of operating in a single-axis mode. The system is to consist of a solar array to convert solar energy to electric energy, a rotary transformer-inverter assembly for transmitting electric power to the satellite by brushless means, a brushless dc motor incorporating rate and position sensing for direct drive of the array, and a control system to maintain orientation of the array relative to the sun. The rotary transformer-inverter, brushless dc torque motor, and magnetic rotor-position-and-rate sensor have been developed on earlier NASA in-house and contractual programs. To complete the reorientation system, the controller is required. Work on the present phase of the contract included controller circuit design, building of breadboard circuits and system performance testing using a simulated array, but excluding the rotating transformer.

The function of the controller is to control operation of the brushless motor to maintain the solar array in a sun-oriented position at all times. When the satellite is in sunlight, the tracking error may be determined directly from photovoltaic sensors and used to control movement of the motor. Control of other modes of operation which are required are not as straightforward. Orientation during the dark portion of an orbit and reorientation from a large misalignment require limiting of the motor speed.

The magnetic sensor is designed with an offset-tooth configuration so that there is always one voltage available which changes linearly with motor rotation, as described in reference 1. Comparison of this sensor signal with a controlled input voltage can, therefore, be used as an error detector on a continuous angular basis. The idea of using the linearly changing signal from the offset-tooth sensor to achieve continuous angular position and rate control was first presented by L. J. Veillette of GSFC. This principle is employed in the reorientation control system described in this report in preference to a "run and coast" scheme initially considered.

Circuit diagrams showing functional blocks are referred to throughout the discussion section of the report. A composite of the functional circuits is provided in figure 34 showing all circuits and values used in the design of the controller other than the dark period control shown in figure 22.

DISCUSSION

OPERATING MODES

There are four distinct modes of operation required of the solar array reorientation system. Two of these modes may occur during each orbit: (1) normal tracking during the sunlit period and (2) programmed tracking during the dark portion of the orbit. When a large error exists, a speed-limited reorientation mode is required to restore the sunlit array to its proper position. The fourth mode required, which takes precedence over all other modes, is the external command mode which, on command, allows the array to be moved to any desired position at a controlled rate or to be stopped.

Normal Tracking Mode

The normal tracking mode of operation takes place during the sunlit portion of the orbit when the signal from the solar sensor is less than a predetermined value. In this mode the drive motor responds to two signals derived from the solar sensor: (1) a speed-torque signal and (2) a direction signal. The speed-torque signal varies in magnitude with the magnitude of the alignment error, having a null at the zero-error point. The direction of the alignment error determines the direction signal which responds to polarity of the difference in signal magnitude of two adjacent solar sensors.

Dark Period Operation

When the spacecraft moves into the shadow of the earth, the control signal from the solar sensors disappears and a shadow signal, SH, appears. The position reference for normal tracking is thus lost. To maintain tracking during the dark period, a substitute signal must be provided to the motor. It is necessary that a reference signal be received from the spacecraft. This reference is used to determine the motor speed. The control acts to maintain the average motor speed at the same rate as was present during the normal tracking mode.

Large Error Reorientation

If the position of the array is off target by a large amount, as may be the case after launch, it is desirable to orient the array in a relatively short period of time. This would require a speed much greater than that during normal tracking. As the array approaches proper orientation, however, it is desirable that the speed decrease to a value approaching the normal tracking speed to reduce overshoot and minimize undesirable reaction between the array and the spacecraft. Speed control is, therefore, employed in the control of reorientation from large errors.

External Control

External control may be gained at any time regardless of the operating mode in command. Three external commands are applicable in this mode, external forward EXF, external reverse EXR, and standby. An additional signal required is a speed signal, which is a pulse train, a direct substitute for the dark period control signal. The motor speed will respond to the pulse frequency, thus the speed may be controlled to any value desired. Thus, speed control is accomplished exactly as in the dark period control mode.

Mode Selection (Motor Drive Direction Logic)

The direction of the motor rotation can be controlled only by introduction of one of two signals, FWD or REV. In the normal tracking mode, forward or reverse signals to the motor are merely a function of the direction of the error signal. A positive error signal, for example, always applies a torque which tends to drive the motor in a forward direction.

In all other modes of operation, however, the motor speed is controlled and the direction of rotation is preprogrammed. The speed control circuit supplies a signal which tells whether the motor lags behind the commanded position or leads it. Thus, the speed control can supply direction information relative to the commanded direction. When the commanded direction is forward, for example, a lag condition from the speed control provides a forward (acceleration) signal to the motor, while a lead condition provides a reverse (braking) signal to the motor. The opposite is true for a reverse-commanded direction.

In the logic diagram, shown at the bottom of figure 17, the command direction signals, EXF, STF or SF, are used in conjunction with the LAG signal to produce the output signal, FWD. In the external command mode, either EXF and LAG or the absence of both produce an output, FWD. This same relation is provided between STF and LAG and between SF and LAG, so that either pair of signals, when not inhibited by other conditions, can produce a FWD output signal. The signals STF and LAG are inhibited under all operating conditions except for the dark-period mode, i.e., there is no external command $\overline{EX}$ and a shadow signal SH exists. Likewise, the signals SF and LAG are inhibited for all conditions other than the large-error reorientation mode, where a speed limit signal SL exists, but there is no external command $\overline{EX}$, and no shadow signal, $\overline{SH}$.

The normal tracking mode is indicated by the signal N which exists unless any of three conditions are present: (1) shadow, SH, (2) external command, EX, or (3) speed limit, SL. In this mode the signal SF determines the motor direction.

It will be noted in figure 17 that a STANDBY command overrides all motor direction commands by causing both FWD and REV to turn off.

REORIENTATION SYSTEM OPERATION

Two basic operational control methods are used in the reorientation system. The first, and by far the simplest, is a position control wherein the solar sensors look at the sun and give signals, depending upon the magnitude and direction of the misalignment of the solar array. The system response to such a signal is that the motor runs in the direction that will reduce the magnitude of the signal to zero. Rotation of the spacecraft which tends to increase misalignment also tends to increase the restoring signal, which causes the motor to run at whatever speed is necessary to maintain a minimal error. This method is used in the sunlit normal tracking mode.

The second method, used in all other operating modes, is one of speed control. Speed is controlled through use of magnetic sensors incorporated in the motor. Output voltages from the magnetic sensors vary as a function of motor position. Thus, motor position data, in combination with a function of time, are used as speed data for the control of motor speed.

A functional block diagram, figure 1, shows the main functions of the control and the primary signal flow routes. In the normal tracking mode, only the blocks in the upper portion of the figure are active. The signal is received from the solar sensors, amplified and fed to the motor control. Also, the dark-period control collects speed data from the magnetic sensor processing circuit to be used later.

The dark-period control takes over upon leaving sunlight and supplies the signal to the stepped-ramp generator as shown in

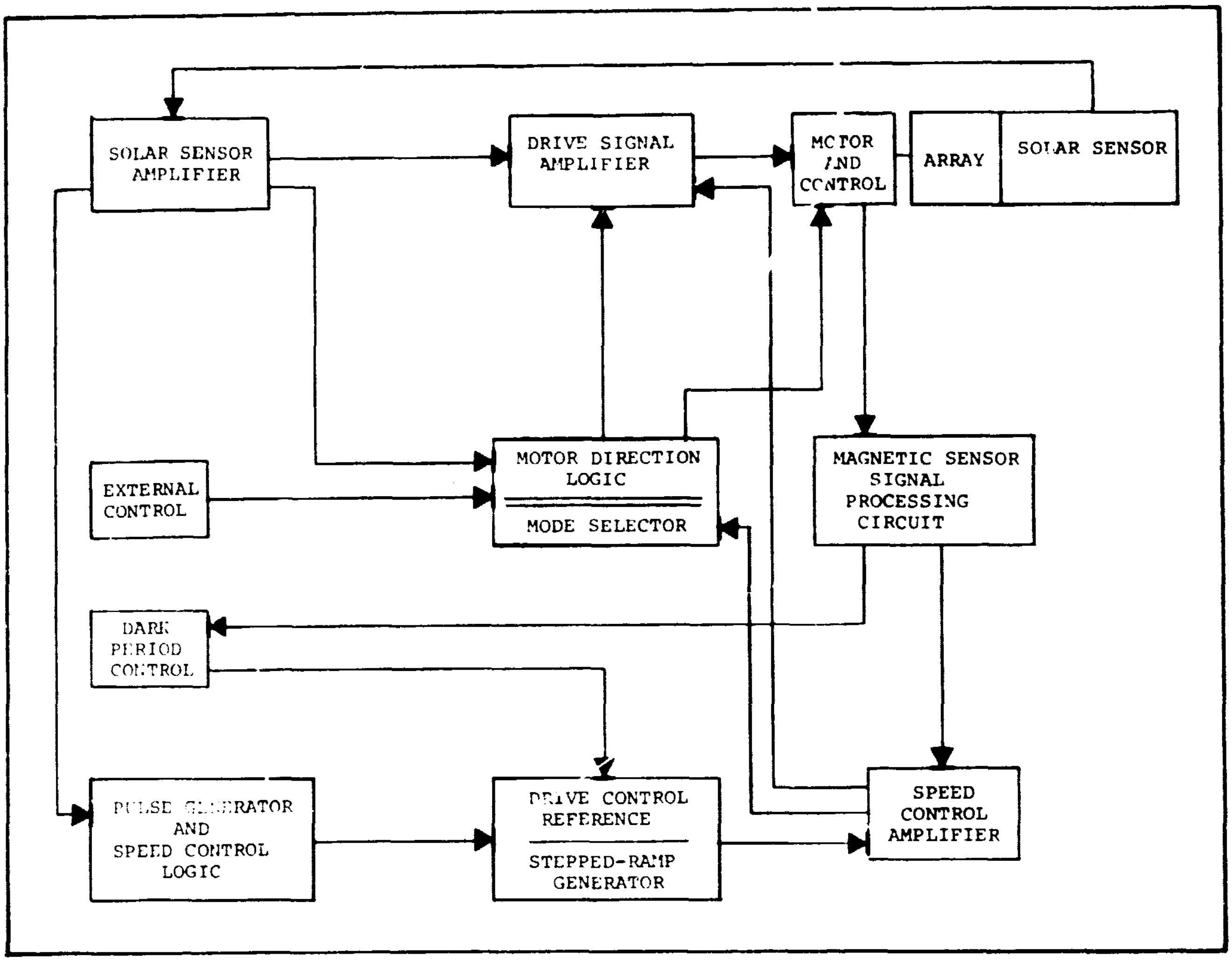


Figure 1. - Functional Block Diagram

figure 1. The speed control amplifier compares the stepped ramp to the magnetic sensor signal and supplies the motor drive signals through the motor direction logic and the drive signal amplifier.

During reorientation from a large error, the signal from the solar sensor amplifier is supplied to the pulse generator and speed control logic which in turn supplies the signal for the stepped-ramp generator, figure 1. Signals are processed in the same manner as in the dark period.

Also shown in figure 1, the external control supplies signals directly to the motor direction logic which controls the motor in response to the external control signals.

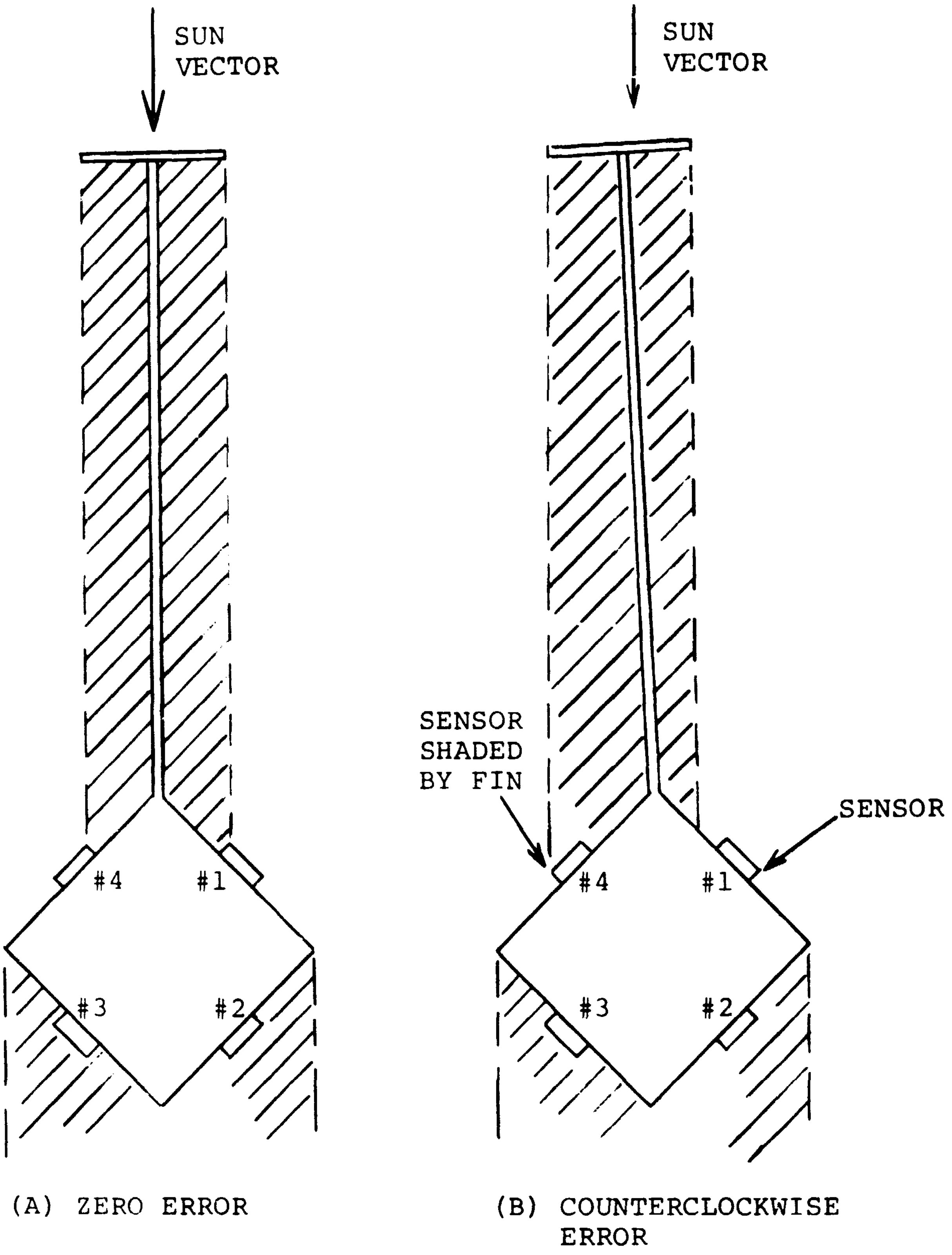
Solar Sensor Signal

Development. - Signals for tracking and reorientation are developed by the solar sensors. These signals indicate the position of the solar array relative to the sun. Figure 2 shows the arrangement of the solar sensors. Four similar sensors are mounted at 90 degree intervals on the axis of the motor shaft. The sensor system incorporates a shadow fin extending along the zero-error vector for the purpose of increasing the sensitivity of the tracking error signal. When the solar array is perfectly aligned, sensors No. 1 and No. 4 are both in view of the sun, at an angle of incidence of 45 degrees, figure 2(A). Both sensors have the same signal strength so that sensing their difference gives a null, indicating zero error. As the array is misaligned, the shadow fin casts a shadow on one of the sensors, reducing its signal strength to zero during a small rotation as illustrated in figure 2(B). The difference in signal strength thus increases rapidly providing a strong error signal. The sensitivity of the error signal depends on the length of the shadow fin relative to the diameter of the sensor. Sensors No. 2 and No. 3 are shaded during normal tracking, but provide an output when the error is greater than 45 degrees.

Each pair of solar sensors is connected in parallel. Sensors No. 1 and No. 2 provide a signal for counterclockwise errors, while sensors No. 3 and No. 4 provide the clockwise error signal. The output signals derived from the solar sensors are depicted in figure 3 for counterclockwise errors. The outputs for sensors No. 1 and No. 2 are shown in their relative positions. The outputs of sensors No. 4 and No. 3 (not shown) are symmetrical about zero on the error angle coordinate. The parallel connection of the solar sensors provides a composite signal equal to the sum of the individual signals. Two composite signals are thus processed by preamplifiers to give outputs E_{CC} and E_{CW}. A difference amplifier provides the signal (E_{CC} - E_{CW}), shown in figure 3(B). The magnitude of this signal is used to control the array position in the normal tracking mode, where the error is less than 2 degrees.

The signal used to control the motor speed during large error reorientation is shown in figure 3(C). The signal covers almost the entire error range, increasing from zero near the maximum error point (180°) to maximum strength at 90 degree error, and falling to zero near the zero-error point, where the normal tracking mode automatically takes control. As the error is reduced toward zero, the motor will slow down because the control signal is reduced toward zero.

Signal processing circuits. - The five signal processing circuits are described below.



(A) ZERO ERROR

(B) COUNTERCLOCKWISE ERROR

Figure 2. - Solar Sensor System Arrangement

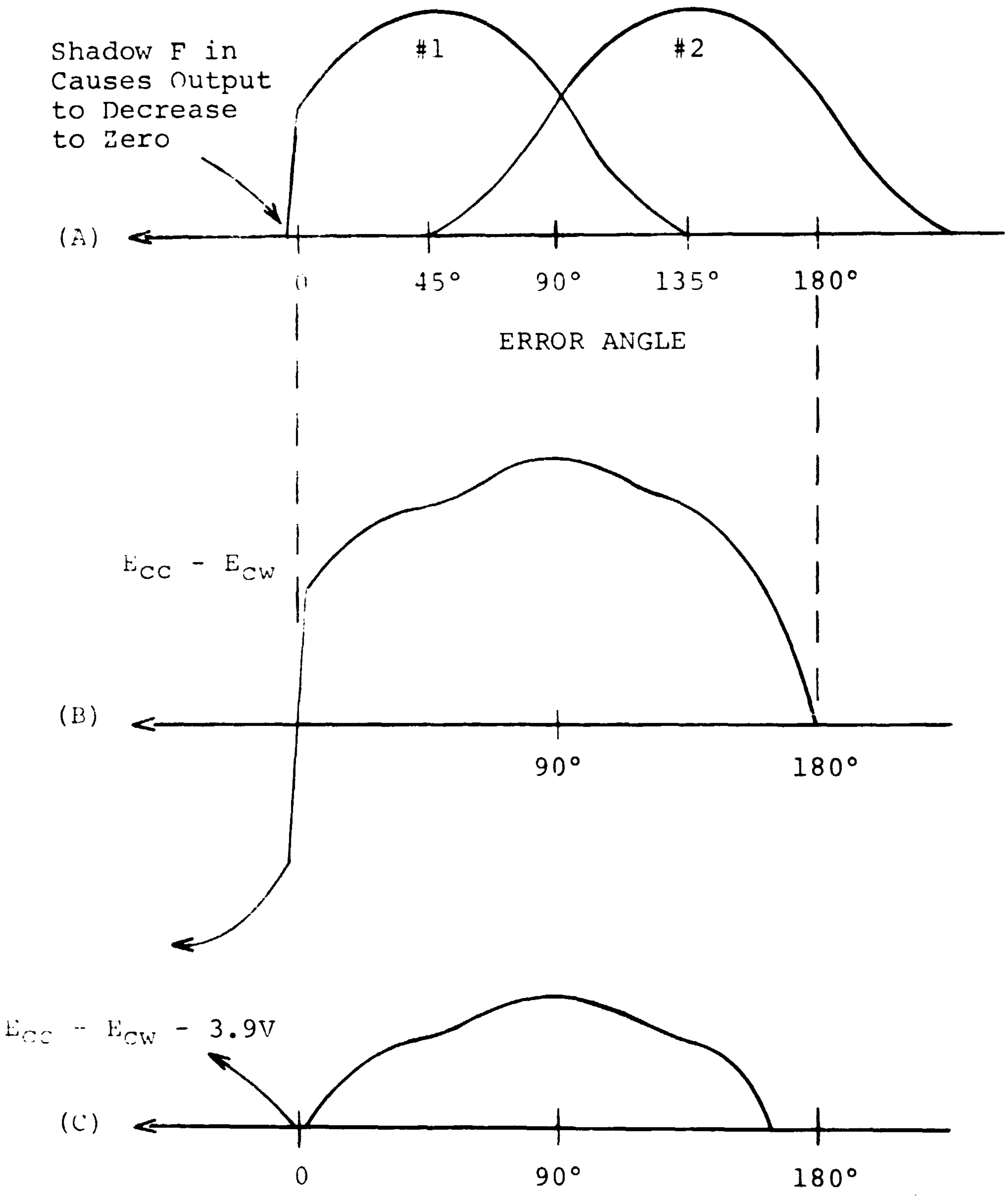


Figure 3. - Solar Sensor Signals

Solar sensor preamplifier: Solar sensors No. 1 and No. 2 are connected in parallel and sense a counterclockwise position error of the array. The sensor output is fed directly to the input terminals of an operational amplifier, as shown in figure 4(A). The operational amplifier, through its feedback resistor, acts to adjust its output voltage so that its differential input voltage is near zero. The sensor thus operates into a short circuit which gives a linear response with variation in light intensity. The output voltage level relative to input current is determined by the value of resistors connected to the amplifier inputs. The value chosen results in an amplification of approximately 32 millivolts per microampere. Thus, an error signal of 100 microamperes from the sensor provides a voltage, E_{CC}, of 3.2 volts. The preamplifier for solar sensors No. 3 and No. 4 uses the same circuit, figure 4(B), and the same calibration, but senses clockwise errors. The sensors are connected so that both E_{CC} and E_{CW}, are used to provide sensing for 1) the logic signal SH, 2) the normal tracking mode speed signal, and, 3) the direction-sensing comparator, SF.

Difference amplifier (E_{CC}-E_{CW}), figure 4(C): The preamplifier outputs E_{CC} and E_{CW} are supplied to an operational amplifier connected as a difference amplifier. With this connection, the output voltage is equal to the ratio of the feedback resistance to the input resistance times the difference in input voltages, approximately 1.34 (E_{CC}-E_{CW}). Variations in the magnitudes of E_{CC} and E_{CW} cause the output to vary both positively and negatively, depending on which of E_{CC} or E_{CW} is greater.

Error signal rectification $|E_{CC}-E_{CW}|$: The motor speed control operates from a positive signal only, as does the voltage-to-pulse converter stage which supplies the motor speed signal. The signal voltage, (E_{CC}-E_{CW}), must therefore be rectified. This is accomplished by an operational amplifier circuit. Connected through a resistor and diode network as shown in figure 4(D), the operational amplifier acts as a voltage follower when the input voltage is positive, and as an inverting amplifier when the input is negative. The resulting output voltage is always positive, approximately the absolute value of the input. Because of the forward voltage drop in the diodes, a dead zone occurs in the output when the input is less than 0.3 volt, which is desirable.

Signal transfer switch, figure 4(E): The motor speed control signal must be applied by alternate routes depending on the system operating mode. The signal $|E_{CC}-E_{CW}|$, is transferred to the motor control (V_O) through a resistor and an isolating diode when its control transistor is off, indicating the normal tracking mode.

Voltage-to-pulse-converter, figure 5: The motor speed control signal is converted to pulses in the circuit of figure 5.

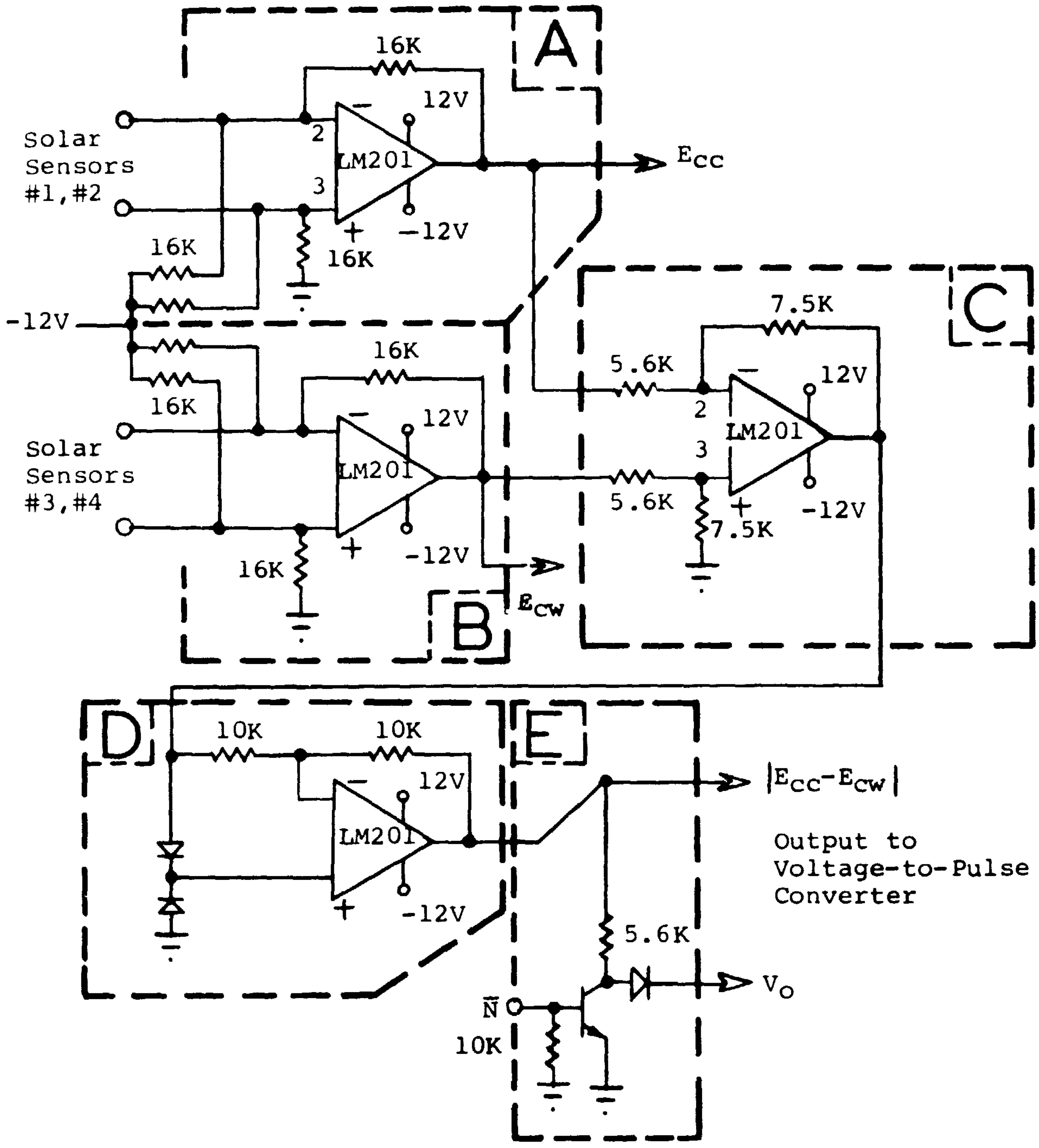


Figure 4. - Solar Sensor Signal Processing Circuit

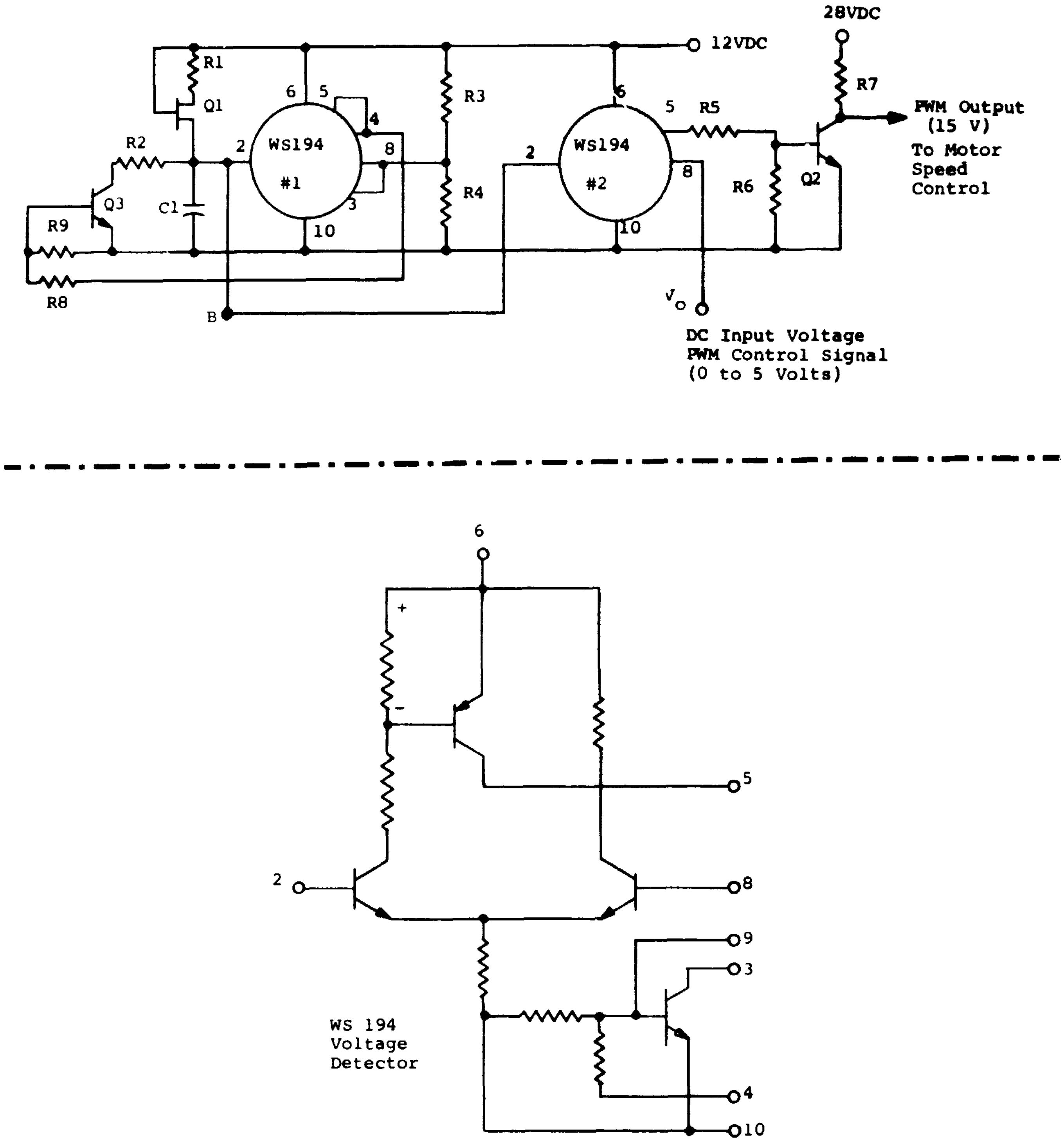


Figure 5. - Voltage-to-Pulse-Width Converter

The pulse rate is fixed by a ramp generator while the pulse width is determined by the voltage level of the input signal, V_O. A ramp voltage is generated by charging capacitor C1 from a constant current source consisting of R1 and Q1, a field effect transistor. The WS 194, No. 1 compares the capacitor voltage to the fixed reference voltage at pin 8. Whenever the capacitor voltage exceeds that of the reference, the capacitor is discharged through R2 and transistor Q3. Note that during capacitor discharge, the voltage applied to pin 8 is reduced to approximately 0.3 volt.

The WS 194, No. 2 compares the input signal at pin 8 to the generated ramp voltage (from B) at pin 2. So long as B, the ramp voltage, is less than the signal level, transistor Q2 is turned off and an output signal is available to the motor from the 28-volt source through R7. When the ramp voltage gets larger than the dc reference, Q2 is turned on and short circuits the output signal. The output signal therefore, has a pulse width which varies in proporation to the dc level.

Speed Control Method

Description. - A magnetic sensor, which supplies signals to the motor commutation control, is provided as an integral part of the motor.[1] Variation in sensor output voltages repeats each 45 degrees of rotation of the motor. The sensor outputs are variable-amplitude ac square-wave voltages, which are rectified and filtered for use in motor speed control. The variable amplitude envelopes of the six magnetic sensor signals are phase displaced 7.5 degrees in position. The positive half of the envelopes, as shown in figure 6, are used for speed control. The sensor voltages may be used as produced, (and discussed in quarterly reports), but a much more useful wave form is obtained by summing three adjacent sensor voltages. This produces a waveform symmetrical about its half-amplitude as shown in figure 7.

If the middle half of one side of these sensor signals are sampled in a sequence ABC while the motor is turned at a constant speed, a saw-tooth voltage waveform which rises linearly is obtained. Sampling the opposite sides gives a falling saw-tooth waveform. These waveforms are illustrated in figure 8 by the bold portion of the curves. By selecting the proper sensor signal then, a motor-position signal of constant volts-per-degree rotation is obtained. Such a signal may be compared to a time-varying, saw-tooth wave to derive a useful error signal for controlling motor speed.

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[1] See references 1 and 2 of Bibliography.

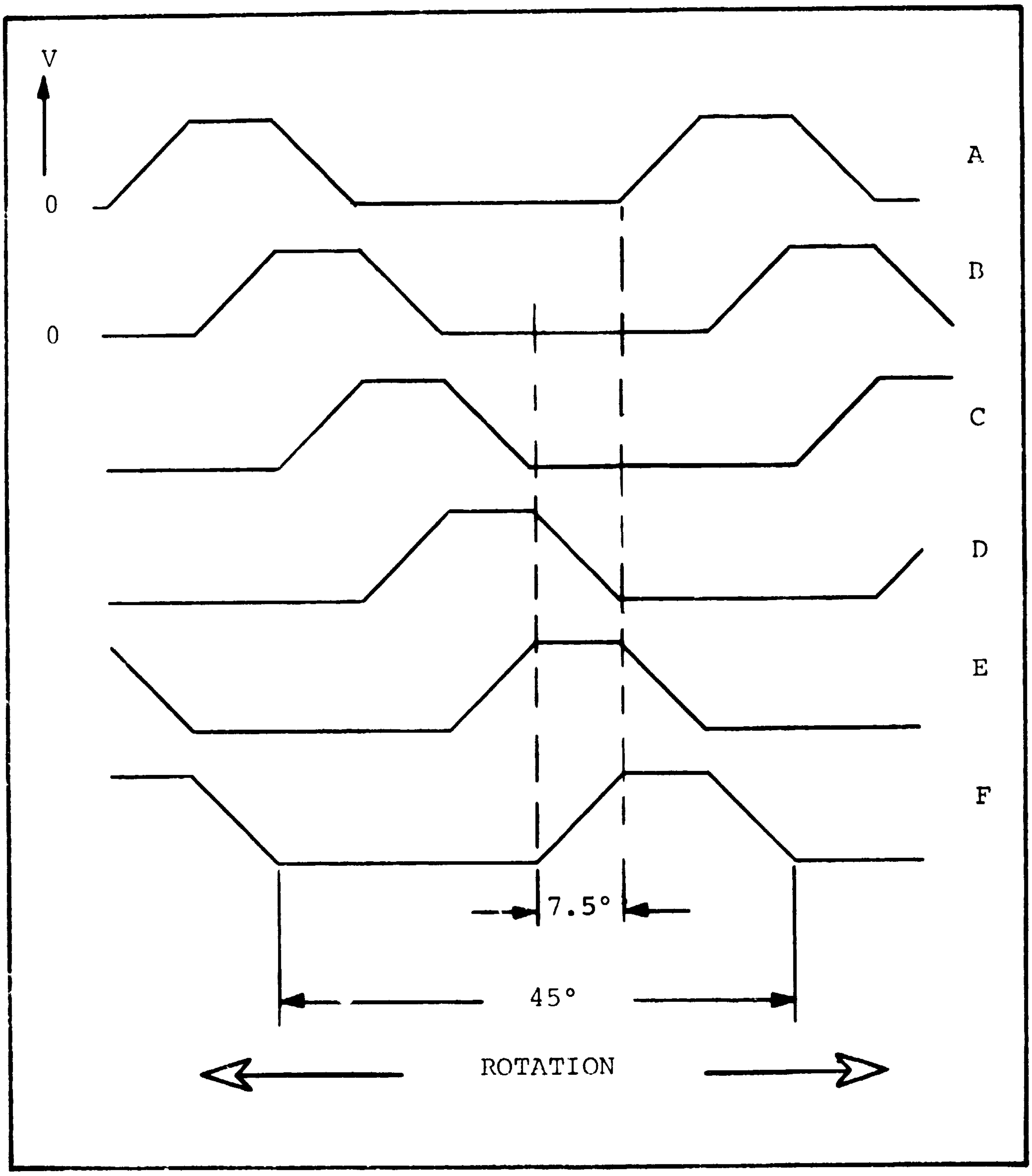


Figure 6. - Magnetic Sensor Output Signals
(Rectified Envelopes)

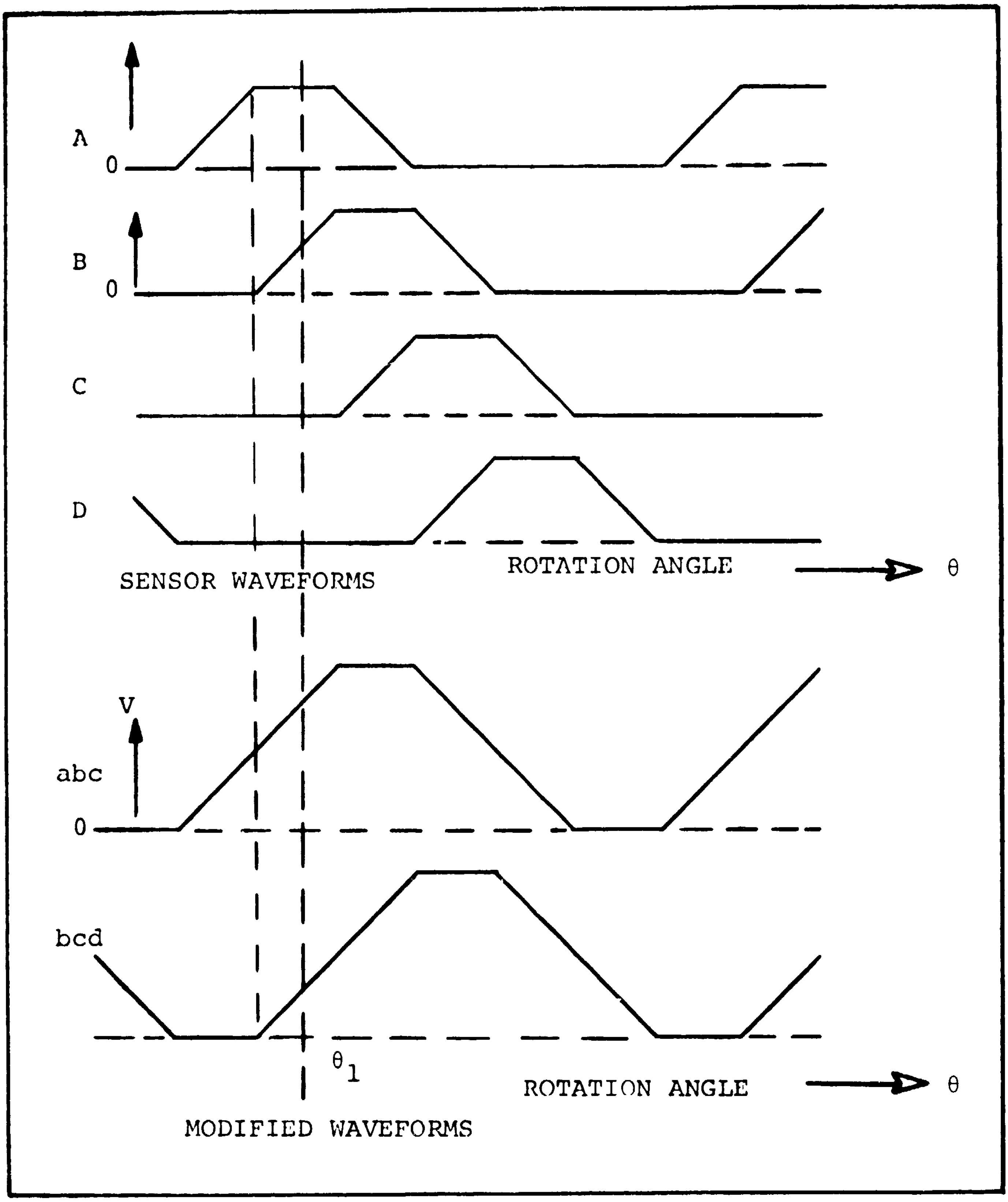


Figure 7. - Derivation of Waveforms Used in Speed Control Method

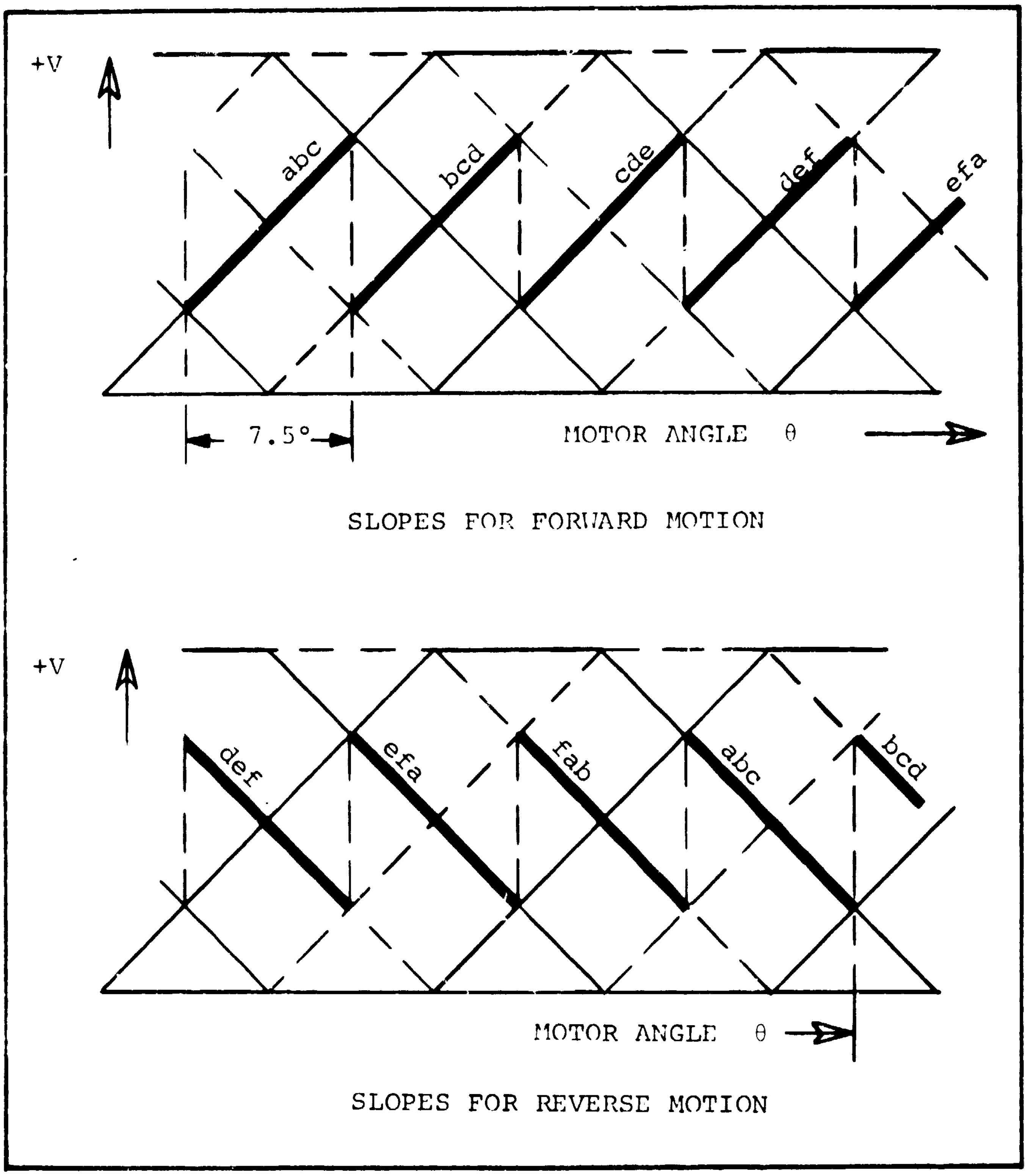


Figure 8. - Superimposed Magnetic Sensor Signals Showing Slopes Required for Forward and Reverse Motion Used in Speed Control

Consider the case where the motor is running at a constant speed. The sensor signals from the motor can be visualized as two time-varying, saw-tooth voltages, phase displaced by one-half a period, if we consider only the rising portion of the signals. These are shown as dashed lines in figure 9. A reference saw-tooth voltage, slightly higher in frequency and half

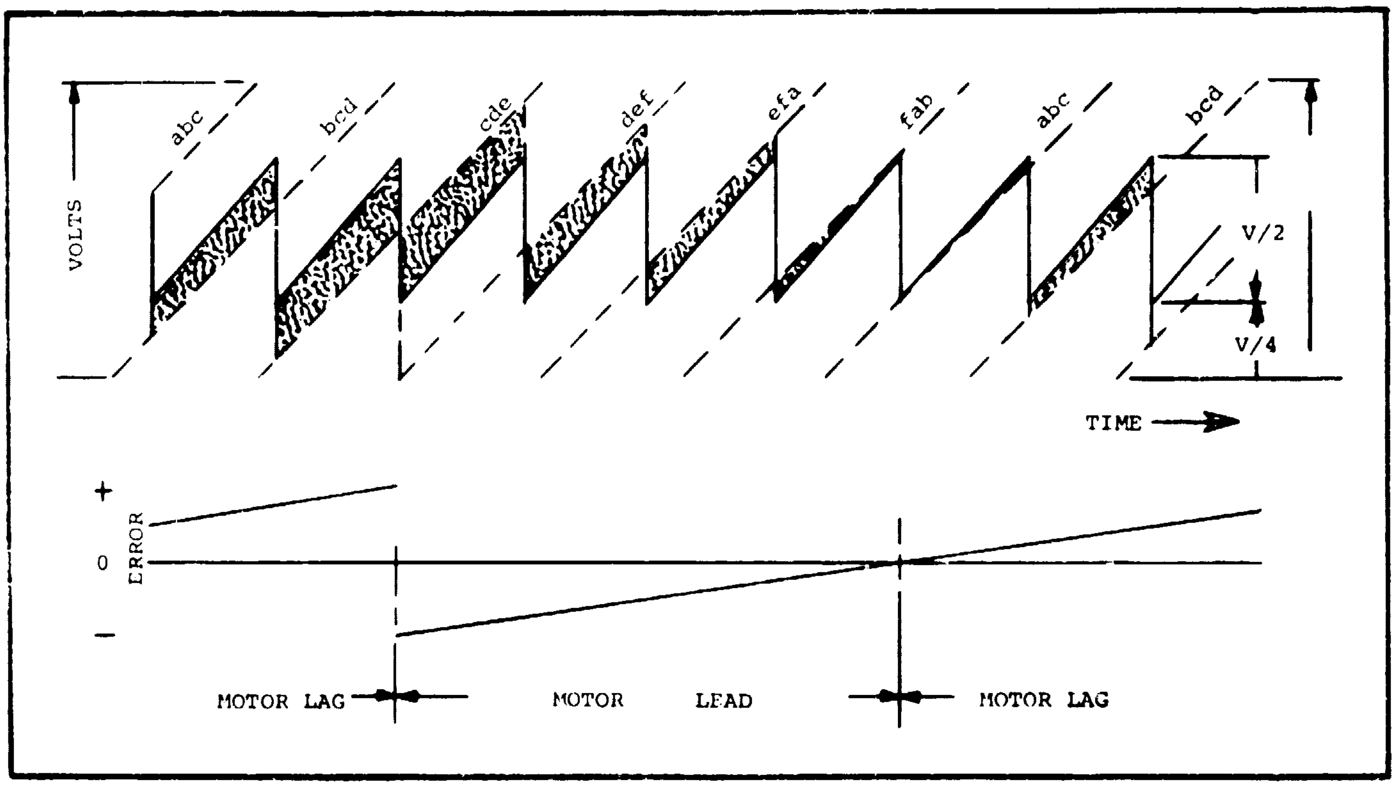


Figure 9. - Illustration of Error Signal Development for Forward Rotation of Motor

the magnitude of the sensor voltage swing is superimposed on the figure. The shaded area between the saw-tooth reference and the sensor signal represents the error voltage that would be generated by monitoring the difference between the two signals. The error is also plotted separately. The left side of figure 9 shows a positive error signal which indicates that the motor lags the reference ramp (saw-tooth wave). As time passes, a discontinuity occurs in the error signal which means that the error has exceeded the control limit. At this point the error becomes negative, indicating that the motor leads the reference ramp. As time goes on, the higher frequency reference ramp catches up with the sensor signals, reducing the error signal to zero. Once more the motor lags the reference ramp, producing a positive error signal. If the error signal were applied to the motor drive system, it would cause the motor to speed up when the error were positive so as to reduce the error signal. If, conversely, the error signal were negative, the motor would slow down, likewise reducing the error signal.

To produce the error signal for use as a speed-controlled drive signal, the following rules apply to its fabrication:

(1) Only one composite magnetic sensor signal may be on at one time.

(2) The sensor signal is selected at the beginning of each period of the reference ramp.

(3) The sensor signal must increase if the motor turns in the commanded direction.

(4) The magnitude of the sensor signal, when selected, must be less than approximately half its maximum.

(5) The sensor signal must stay on until a new selection is made at the beginning of a new ramp period.

(6) The reference ramp voltage must have a peak-to-peak magnitude equal to the difference between two adjacent rising sensor signals (half the maximum sensor signal) and centered between maximum and minimum sensor voltages.

Magnetic sensor signal selection circuit for speed control. - The magnetic sensor signal, which is selected for use at any time, appears at a point referred to on the circuit diagrams of this report as BUS. The logic circuit for developing the signal, BUS, is shown in figures 10 and 11. The circuit consists of six identical interconnected channels, one for each magnetic sensor signal. One channel is shown in figure 11. The output from a resistor-summing junction which sums three adjacent sensor voltages is fed to BUS through an isolating diode when the control transistor is controlled by a NAND gate flip-flop.

To analyze operation of the sensor selection logic, refer to figure 7 and assume the motor position is θ_1. The comparator signals A', B', C', etc. (see figure 12) are in the high state when A is greater than D, B is greater than E, and C is greater than F, etc. Assume a forward command (FW=1, FW'=1) when the reference ramp starts and produces signals T and T', both of which are pulses, T being of much longer duration. The signal T' trips all six flip-flops to assure that only one

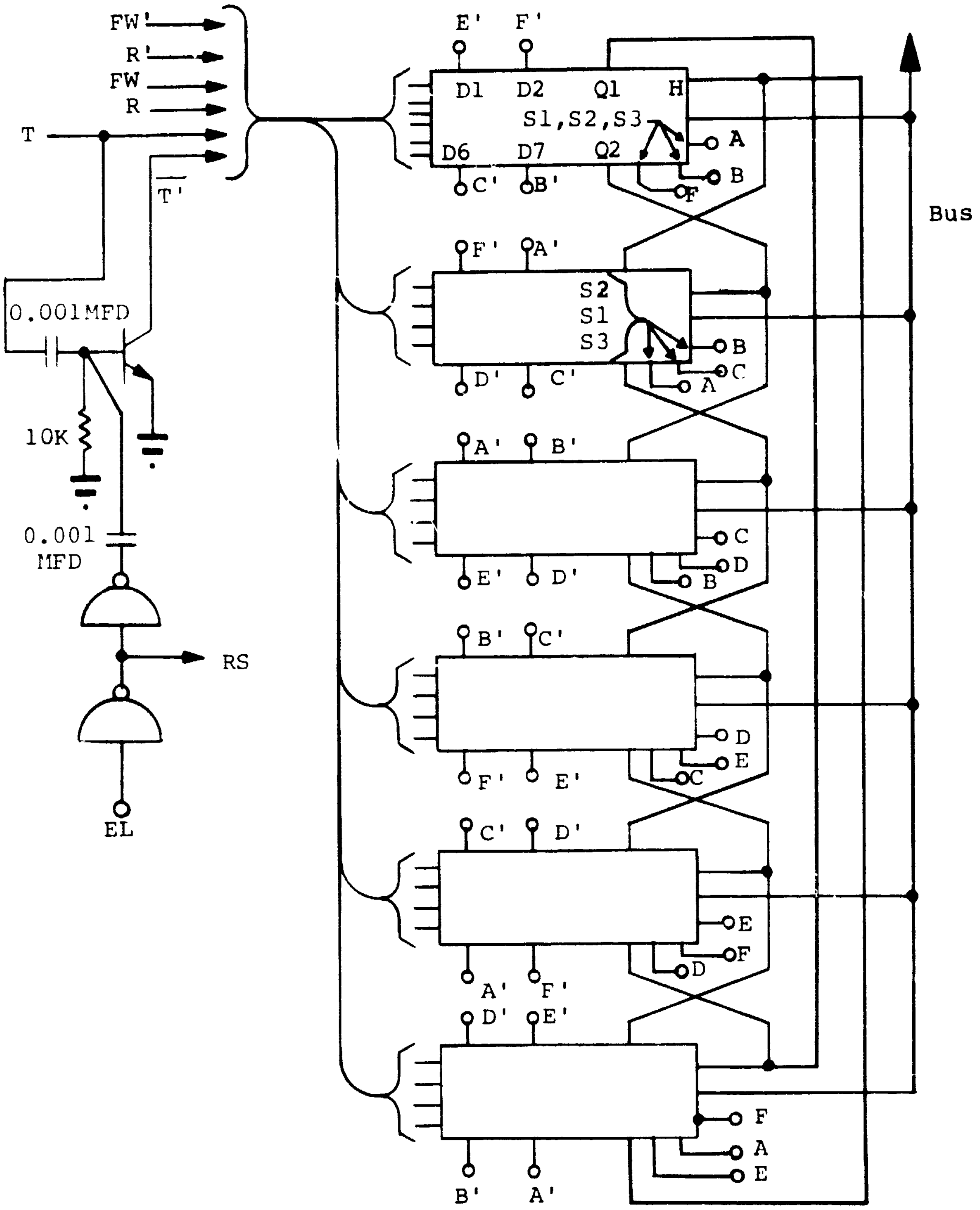


Figure 10. - Connection of Six Channels for Drive Logic and Magnetic Sensor Reference

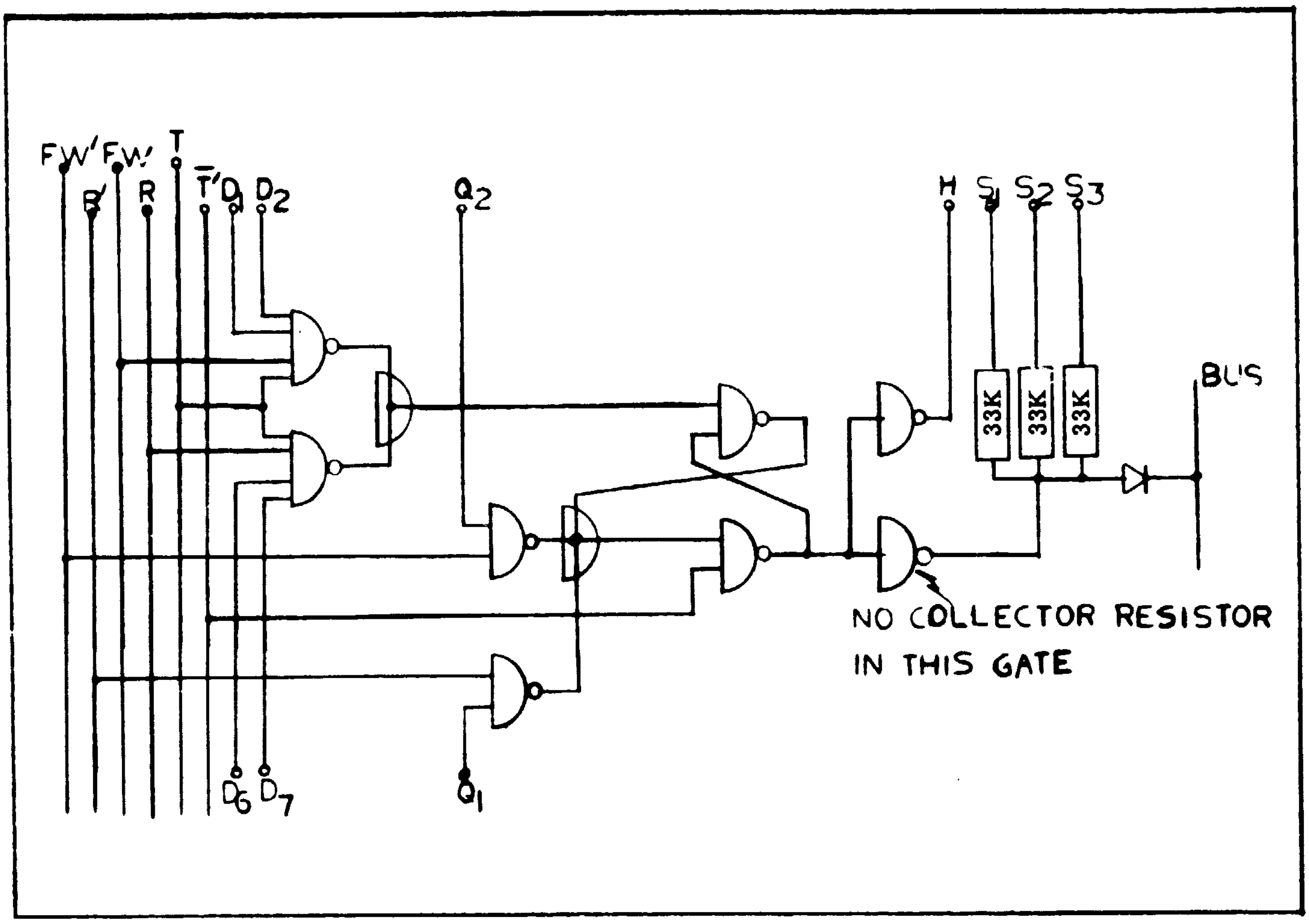


Figure 11. - Drive Logic and Magnetic Sensor Reference - One Channel

channel can be connected to BUS at one time. Logic signals A', B', and F' are high (F not shown in figure). In figure 10, the second and third channels receive signals at terminals D_1 and D_2. (Terminals D_6 and D_7 need not be considered because R = 0.) Both the second and third channels are turned on as soon as T' disappears, and a signal appears at terminal H of both channels. Signals appear at terminal Q_2 of the second channel and at Q_1 of the third channel. Since FW'=1, the signal at Q_2 immediately trips out the second channel and leaves the third channel to supply the signal to BUS. Thus the signal bcd is selected in agreement with the rules set down.

Reference ramp. - The extremely low speeds at which the motor must operate requires a very low frequency reference ramp for speed control. The speed range demands ramp frequencies of about 12 ramps per minute to as low as two ramps per hour. It is, therefore, logical to use a digital approach, fabricating a stepped ramp rather than a continuous one. To do this, a pulse counter operates into a resistor network such that each input

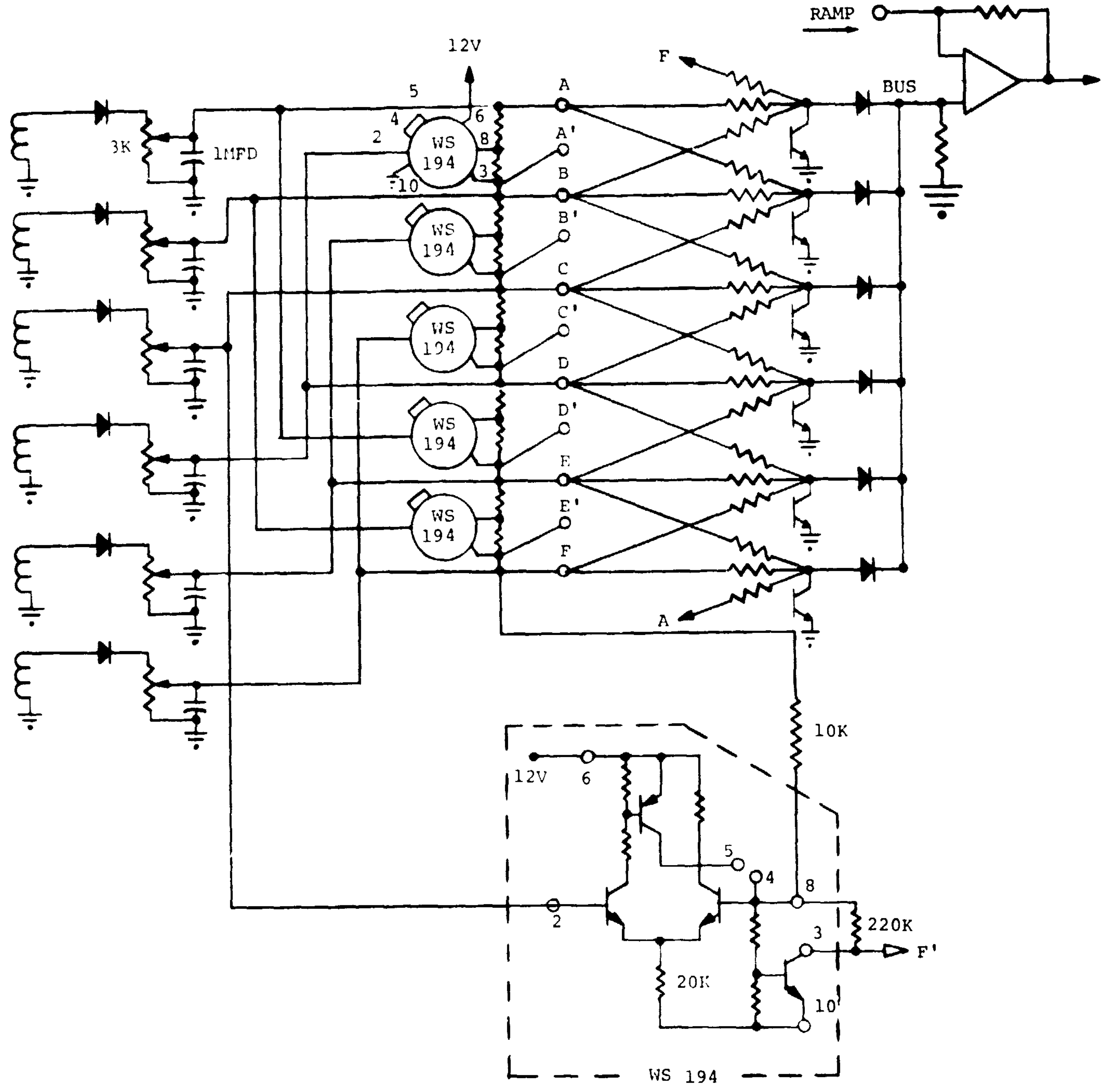


Figure 12. - Magnetic Sensor Signal Processing Circuit

pulse raises the voltage at the output terminal of the resistor network by one step. The average rate of rise of the ramp and thus its frequency is, therefore, controlled by the input pulse frequency. The counter selected for the system produces a 16-step ramp. Each step drives the motor slightly less than 0.5 degree. More steps could be used if finer motor control is desired.

The circuit for the ramp generator is shown in figure 13. The circuit consists of four binary counters (WM 213G) connected

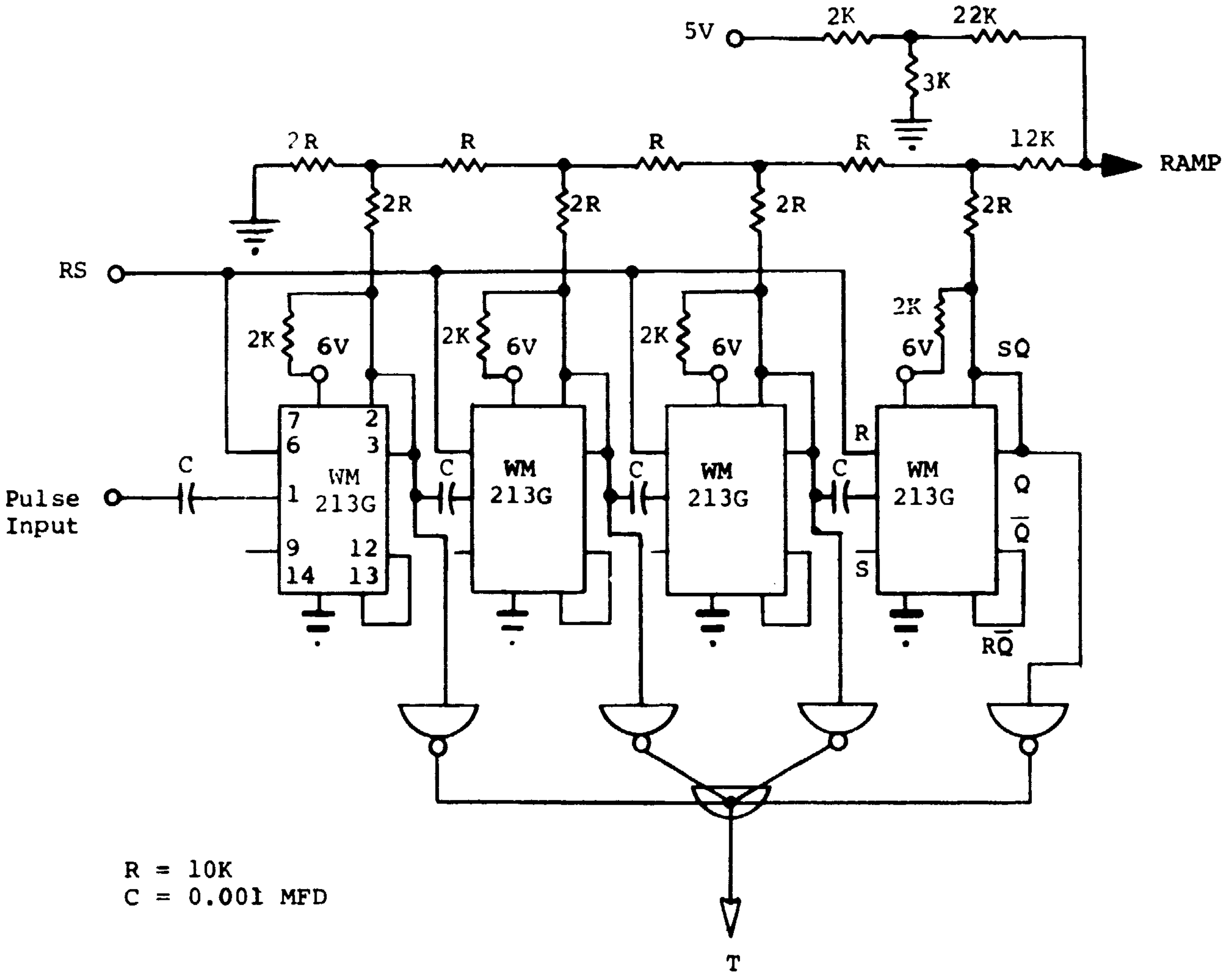


Figure 13. - Speed Reference Ramp Generator

serially and operating into a resistor network. Each counter changes state when the input signal goes from high to low, but is not affected by a rising signal. The first stage receives the unit pulse and changes state with the fall of each pulse.

The second stage receives a signal from the first stage, and changes state each time the first stage output goes low. Similarly, the third and fourth stages change state when the output of the previous stage goes low. Thus, the first stage counts units, the second counts two's, the third four's, and the fourth eight's. The resistor network is designed so that each stage, when on, contributes twice the voltage at the ramp output as does the previous stage. Input to the network from the counters is either approximately six volts or zero. The network presents a constant resistance as viewed from the output terminal. This resistance represents an input resistance of the operational amplifier in the following stage, figure 14. The output of the counter is connected to a summing junction so that the output signal, RAMP, is the sum of the counter output and a fixed reference. The fixed reference is used to center the reference ramp between maximum and minimum voltage of the magnetic sensor output as shown in figure 9.

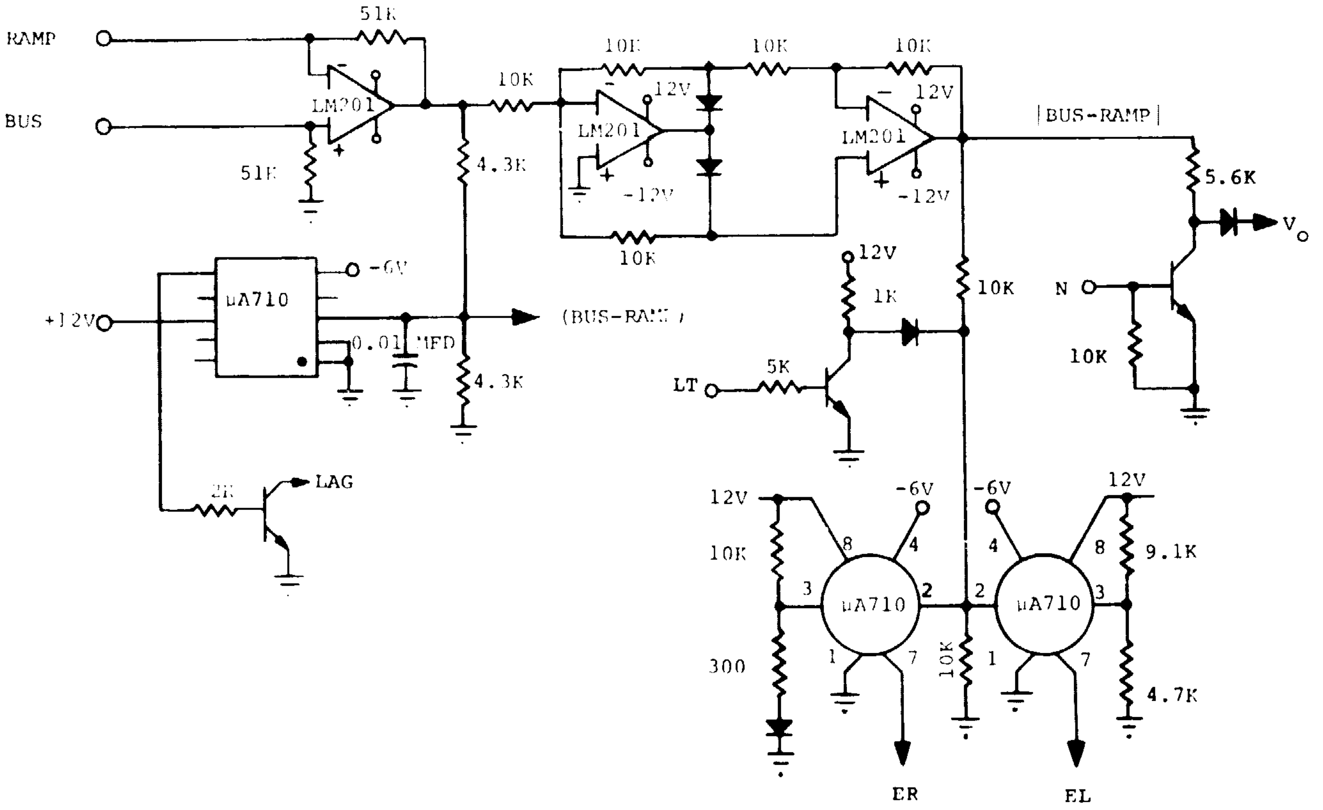


Figure 14. - Speed Control Amplifier Circuit

A logic circuit is included in figure 13, the output (T) of which signals the beginning of a new ramp. This signal is used to trigger the drive logic of figure 10.

Speed control - output stage (figure 14). - To make use of the two derived signals, BUS and RAMP, it is necessary to derive the difference between the two. This is done by means of an operational amplifier connected as a difference amplifier. The output signal is rectified and transmitted to the motor speed control.

A comparator (μA 710) is used to detect the polarity of the difference amplifier. A positive output indicates that the reference ramp signal (RAMP) is greater than the magnetic sensor reference (BUS) and thus the motor lags its command signal. The motor is, therefore, driven in the commanded direction because of the presence of the comparator signal (LAG). Should the motor be driven too fast, the difference amplifier output would become negative and the comparator signal (LAG) would go to zero, causing the motor to get a reverse command and slow down.

The fact that the reference ramp is generated by means of discrete pulses makes the speed control, in reality, a position control when operating at orbital rotational speeds. At these very low speeds, each pulse provides a signal causing the motor to turn just enough to reduce the signal below its threshold. The motor comes to a stop at a stable position where it remains until another pulse (seconds or minutes later) causes an error signal to be developed to drive the motor through another increment.

Operation in the upper end of the speed range, as during reorientation of the array, is somewhat different. In this case, the inertia of the array and the speed are great enough to cause the array to coast through the zero-torque areas with little change in speed. Once steady-state speed is reached, the system rotates rather smoothly.

Speed control pulse generation. - Inasmuch as motor operating speed is controlled by incremental rotational response of the motor to a stepped-ramp signal, it is necessary to convert the speed-control signal to a pulse train. The frequency of the pulse train determines the motor speed. A pulse generator having a pulse frequency proportional to its input signal level is, therefore, required. Figure 15 shows the circuit of the pulse generator, which consists of an operational amplifier connected as an integrator, and a unijunction transistor (UJT) used as a pulse

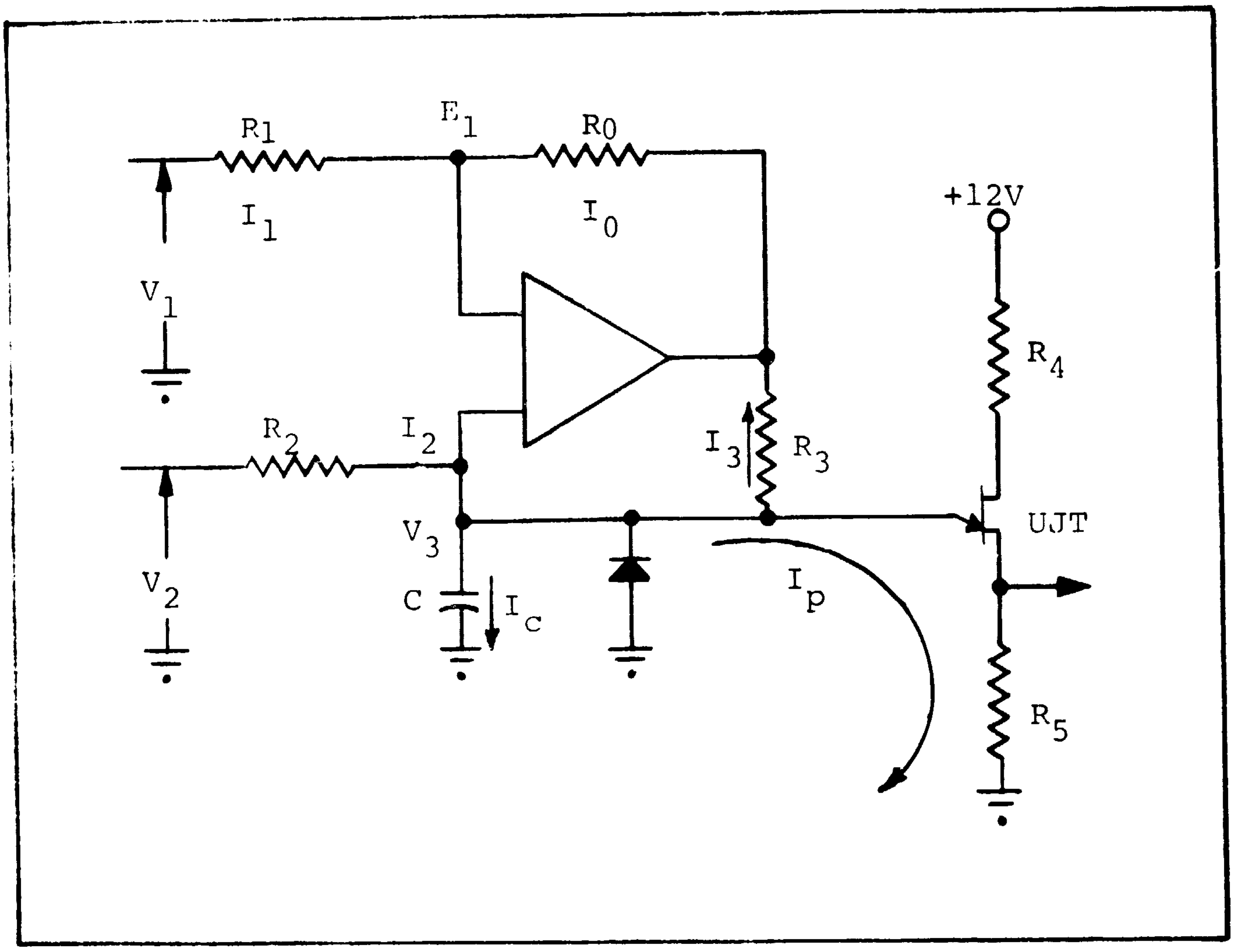


Figure 15. - Voltage-to-Frequency Pulse Generator

trigger. If the pulse current, Ip, is neglected in figure 15 the equation for capacitor voltage may be developed as

$$V_3 = \frac{1}{R_2C} \int_0^t (V_2 - V_1)dt$$

where

$$R_1/R_2 = R_0/R_3.$$

The capacitor voltage, V_3, rises until it reaches the voltage determined by the intrinsic standoff ratio of the UJT. At this point the UJT turns on, applying the capacitor voltage across R_5, the output point. The capacitor discharge current, I_p, flows through R_5 until the UJT emitter voltage falls to the valley point where the UJT turns off. The integrator circuit then starts a new charge cycle. Thus, the output pulse frequency is determined by the charge time constant, R_2C, and the UJT characteristic, and varies with the input signal voltage. A diode connected across the capacitor serves to prevent saturation of the operational amplifier when the input signal is negative.

An important feature which is used in the control circuit should be noted. The input circuit to the operational amplifier may be replaced by its Thevenin equivalent, utilizing any number of voltage sources desired. By so doing, summing junctions are formed so that input signals may be added together. The pulse generator as used in the reorientation system is shown in figure 16. Several system functions are performed by varying input voltage and capacitance as will be seen in later discussions.

Large-Error Reorientation

When the position of the array is off target by a large amount, as may be the case after launch, it is desirable to orient the array in a relatively short period of time. This requires a speed much greater than that during normal tracking. As the array approaches proper orientation, however, it is desirable that the speed decrease to a value approaching the normal tracking speed to reduce overshoot and minimize undesirable reaction between the array and the spacecraft. Speed control is, therefore, employed in the control of reorientation from large errors.

Acceleration from rest. - When the array starts from rest at some arbitrary position the difference in the two control signals, BUS and RAMP, may be at any value within their range, unless special provisions are made to prevent it. A large difference in these signals at the beginning of reorientation produces a relatively high rate of acceleration of the array and subsequent oscillation in array speed. On the other hand, if the initial signal difference is small, the acceleration is low and speed builds up smoothly. It is, therefore, desirable to start the reorientation cycle with as small a difference signal, |BUS-RAMP|, as possible.

With normal speed control logic, the magnetic sensor voltage selected in the fabrication of the signal, BUS, has a magnitude between zero and half the maximum value. The signal, RAMP, may have any value between one-fourth and three-fourths of the maximum sensor voltage. The chances are 50 percent then, that BUS will be below the minimum value of RAMP, and thus it may not be possible to obtain the small error signal desired by varying RAMP.

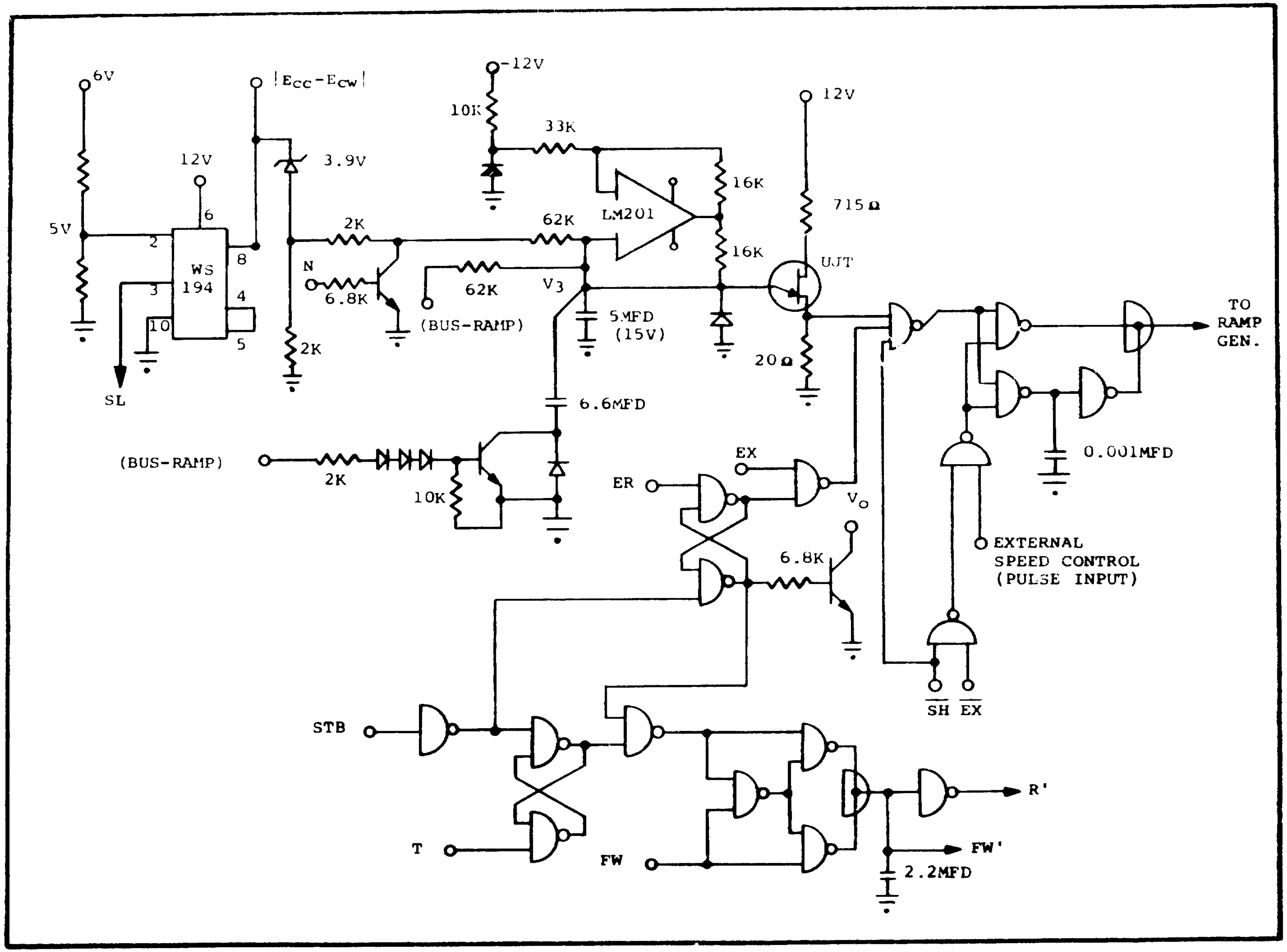


Figure 16. - Acceleration and Speed Control Circuit

To assure that a minimum difference in BUS and RAMP can be obtained, a special control is included which selects the magnetic sensor next in reverse normal sequence. After the selection has been made the special control is disabled. The signal, BUS, then will be at a level between the maximum sensor voltage and one-half maximum. When the reorientation cycle is started, the counter is reset and made to count. This causes RAMP to start at its minimum value and increase by steps until it reaches the level of BUS. If the level of BUS is greater than the maximum level of RAMP, the counter counts through a full cycle and resets. The reset causes the normal selection of a magnetic sensor voltage, reducing BUS to a level within the range of RAMP. As the counter continues, RAMP again increases from its minimum level to the level of BUS. Once this level is reached, the speed control signal is applied to the motor, starting acceleration.

Reorientation starts from standby: It is assumed that the control system will be in the standby condition when the spacecraft is launched. In addition, external commands, forward, reverse, and track should be preceded by the standby command. This assures that the reorientation operation starts from the standby condition, which sets up control for proper acceleration of the array.

The primary function of the standby command is to remove power from the motor. This is accomplished by removing both FWD and REV signals from the motor control terminals (see figure 17). The result is to stop the oscillator in the motor commutation control, which in turn de-energizes the magnetic sensors. Consequently, the signal, BUS, (figure 10) goes to zero, and since RAMP is always substantially greater than zero, the signal, |BUS-RAMP|, (figure 14) goes to its maximum value, causing the two comparators to turn on, producing signals ER and EL. The error-limit signal, EL, resets the ramp generator counter so that RAMP goes to its minimum value. At the same time a signal T' is produced which resets the magnetic sensor logic (figure 10).

The signal ER is produced when |BUS-RAMP| is slightly greater than the normal level during reorientation. The purpose of ER is to prevent acceleration of the array until the controls have reduced |BUS-RAMP| to an acceptable value for starting reorientation.

Starting circuit (see figure 16): The logic circuit for performing the special control function of starting the reorientation cycle is shown in figure 16. When the system is in STANDBY, logic signals STB, T, ER, and EX are high. Two significant results are obtained in this condition: (1) the transistor is turned on making the motor drive signal, $V_O = 0$, and (2) the direction signal is reversed, $FW' = \overline{FW}$. The system remains at

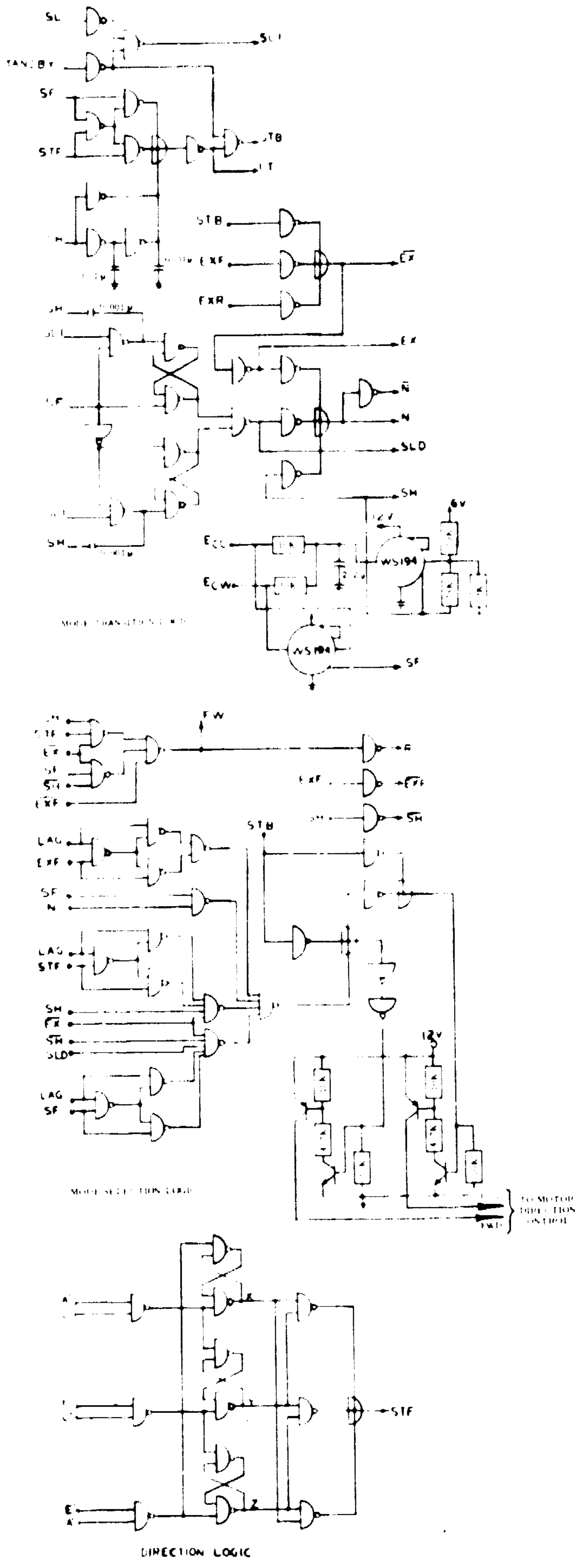


Figure 17. - Logic Circuits for Mode Selection and Transition

rest so long as this condition exists. The counter is not counting because the magnetic sensors are not energized in STANDBY, causing the signal (BUS-RAMP) to be at maximum negative voltage. Consequently, the pulse generator has no output to the counter.

The reorientation cycle is actuated by transferring the external command from STANDBY to TRACK. Logic signals STB and EX go low. The magnetic sensor voltages rise to normal. The drive logic makes the selection of the magnetic sensor voltage. Since the signals FW' and R' are at this point opposite the normal direction signals FW and R, the selection sequence is reversed (see figures 10 and 11 for logic), assuring that BUS is greater than RAMP. The signal (BUS-RAMP) thus becomes positive and the pulse generator resumes operation causing the counter to increase RAMP, unless the spacecraft is in the shadow. At the first count, T goes low, releasing the latch causing FW' to change state so that FW' = FW. This returns the magnetic sensor selection logic to normal. Note that the motor drive signal V_O is still short circuited by the transistor and remains in that state until ER goes low. The counter continues until RAMP becomes nearly equal to BUS, at which time the error signal $|BUS-RAMP|$ is low enough to cause ER to go low, and release the latch holding the transistor on. When the transistor turns off, V_O assumes the value of $|BUS-RAMP|$, to which the motor now responds.

Speed-controlled reorientation. - Speed-controlled reorientation is described below.

Speed determined by pulse rate: The speed at which the solar array moves toward proper orientation depends on the rate at which pulses reach the counter. The pulse rate of the pulse generator is primarily a function of the solar sensor signal strength. When the solar sensor signal is first applied, the motor speed is zero. Obviously, the motor cannot respond instantaneously, so immediately falls behind its command. The further behind the motor gets, the larger the error signal becomes and the higher the acceleration force. If the motor accelerates the array too rapidly, speed will get higher than the control signal demands. The control then will cause deceleration of the system. Successive acceleration and deceleration will continue until damped out by motor friction which is relatively small.

To minimize the speed oscillation, a feedback signal is employed. The feedback signal is the error between the motor position and the commanded position, BUS-RAMP. The effect of the feedback is to slow down the pulse rate whenever the motor lags behind the position demanded by the speed control and to raise the pulse rate when the motor leads the command. This allows the motor to catch up with the position reference while the pulse rate is low. As the motor catches up, the error signal, BUS-RAMP, gets smaller and allows the pulse rate to increase. If the motor speeds up more than necessary, the feedback-error signal reverses polarity and increases the pulse rate above normal, thus the motor is allowed to coast down to normal speed without appreciable braking. When the motor is running at the commanded speed, the feedback is negligible and the normal pulse rate drives the motor at normal speed.

Once up to normal speed, the motor runs at a speed proportional to its control signal, such as shown in figure 3(C). As the orientation error approaches zero, the motor speed gradually reduces to zero, following the speed signal.

Speed control circuit: Refer to figure 16 which shows the pulse generator circuit. The solar sensor signal, $|E_{CC}-E_{CW}|$, is fed into the non-inverting (+) input of the operational amplifier (LM201) through a 3.9-volt Zener diode. Use of the Zener diode modifies the solar sensor signal figure 3(B) into the speed control signal figure 3(C) so that the speed signal decreases gradually as the proper orientation angle is approached.

The feedback signal, BUS-RAMP, is also applied to the non-inverting input. The resultant signal input is, therefore, the sum of the two signals $(|E_{CC}-E_{CW}|-3.9)$ + (BUS-RAMP), and the equivalent input resistance to the operational amplifier is the parallel combination of the individual resistances.

In addition to the capacitor (5 MFD) permanently connected to the operational amplifier, a second capacitor (6.6 MFD) is connected through a transistor when the magnitude of the error |BUS-RAMP| is large. This slows down the charge rate (and thus the pulse rate) during acceleration of the array asisting the feedback and giving the motor more time to catch up with its drive signal.

In figure 16, also note that the inverting (-) input of the operational amplifier is negatively biased by a diode drop. During the final approach to zero-orientation error, the speed control signal, figure 3(C), goes to zero. The function of the negative bias voltage is to cause the pulse generator to continue operation slowly to assure movement of the array to zero reorientation error.

Transfer to normal tracking mode. - The following describes the transfer to the normal tracking mode.

Making a smooth transfer: When the system operates in the sunlit normal tracking mode, the motor drive signal is derived directly from the solar sensor output. The sensor is designed to give a high rate of change in signal strength about the null, figure 3(B).

Suppose the system were being reoriented and the array were approaching zero error. The speed control signal would be also approaching zero. Now suppose that at some small error (one or two degrees) the control were transferred to the normal tracking mode. A large signal, $E_{CC}-E_{CW}$, would be applied to the motor control, causing the motor to accelerate. As the array moves to the zero-error position, the error signal would go to zero, but the speed of the array would be substantial and the array would go on past the zero-error point. A restoring signal would then be applied, bringing the motor to a stop and accelerating it in the reverse direction. Thus, an oscillation would be set up. While such an oscillation would be within the normal tracking bank and die out after a few cycles, it is undesirable and can be avoided.

The means for preventing the problem is simply to prevent the initial acceleration upon transfer of the normal tracking mode. By making the system stay in its speed-controlled mode until the array has moved past the zero-error position, the initial force applied upon transfer will be a decelerating force. In addition, the transfer can be controlled to take place when the magnitude of the signal, $E_{CC}-E_{CW}$, is low. Thus, reorientation ends in a smooth transition to the normal tracking mode.

The transfer circuit: The logic for the transition is shown in figure 17. Control signals are derived from two conditions: (1) direction and (2) magnitude of the orientation angle. When signal, SF, is high the array is misoriented in a counterclockwise direction ($E_{CC}>E_{CW}$) and forward movement is demanded. When SL (figure 16) is high, the array is misoriented by an appreciable angle as indicated by the magnitude of the solar sensor signal, thus speed-limited control is commanded.

The normal tracking mode is in operation when the signal, N, is high, otherwise the speed control is in effect. From the logic diagram, figure 17, N will be low if there is an external command, EX, or if the system is in the earth's shadow, SH, or if signal SLD is high. During reorientation, there is neither a shadow nor an external command signal, so SLD determines the state of N.

The signal, SLD, is developed any time speed-limited control is indicated by SL1 which is high when either SL or STANDBY is high. The signals SL1 and SF operate into two flip-flops producing the output, SLD, any time SL1 is high, regardless of the state of SF. The flip-flops remain latched-up after SL1 goes low, until SF changes state and causes SLD to go low, which in turn produces the signal N.

The result is that the system operates in a speed-controlled manner until the orientation error has been reduced to zero. Since the array is brought to proper orientation of a controlled speed, overshoot and oscillation are negligible.

Dark Period Speed Control

When the spacecraft moves into the shadow of the earth, the control signal from the solar sensors disappears and a shadow signal, SH, appears. The position reference for normal tracking is thus lost. A substitute signal must therefore be provided to the motor to maintain tracking during the dark period. The method available for control in the dark period is the speed-controlled method of operation described previously in the paragraph entitled "Speed Control Method".

It is assumed that the spacecraft orbit is circular. Thus, a sun-oriented array mounted on an earth-oriented spacecraft turns at a constant average speed. The problem of dark-period control is essentially one of supplying a series of pulses at the proper rate to drive the motor at the same average speed as that in sunlight. Allied problems involve the transient conditions encountered when entering and exiting the shadow.

Speed-control pulse requirements. - Recall from the discussion on the speed control method section "Reorientation System Operation", "Speed Control Method", paragraph "Description", several facts concerning the magnetic sensor signals, and the signal, RAMP.

(1) The sensor signal repeats each 45 degrees of motor rotation.

(2) There are six sensor signals each of which are sampled in sequence during 7.5-degree increments of motor rotation.

(3) The signal, RAMP, varies in amplitude in 16 increments.

The speed control causes the motor to move 7.5 degrees for each cycle of the signal, RAMP, which requires 16 pulses. Thus, during a complete cycle of one magnetic sensor signal, 96 pulses are required. The problem of speed control during the dark period is to produce pulses at the rate of 96 pulses in the time required for 45 degrees of rotation.

Assume that a pulse source of constant frequency is available to be used as a timing reference. Suppose that while the spacecraft orbits in sunlight in the normal tracking mode, the number of pulses produced by the reference source during 45 degrees of rotation is counted. Call this number n. Now, suppose the system is operated by the speed-controlled method at the same average speed. Since 96 pulses are required to drive the motor 45 degrees, there are n/96 reference-source pulses developed for each speed-control pulse. The digital control employed in the speed-controlled method makes it possible, therefore, to make use of a pulse-counting system to maintain accurate position control of the array during the dark period. Knowing the number of source pulses per control pulse, one can design a counter to give a control pulse each time the proper number of source pulses is counted.

A hypothetical case. - A simplified block diagram of a dark-period control is shown in figure 18. During a selected 45-degree interval of rotation in sunlight, the reference pulse, P, is transmitted to counter No. 1 which counts 96 pulses, resets, and repeats the count. Counter No. 2 counts the number of times counter No. 1 counts a complete cycle of 96 pulses. If n pulses, P, are developed during the 45 degree rotation, then counter No. 2 will contain the number n/96 at the end of the 45-degree rotation. This number represents the average interval between output-control pulses in terms of source pulses. The number n/96 in counter No. 2 is stored in a memory as a reference during dark-period control.

Entering the shadow allows the source pulse, P, to be transmitted to counter No. 3. The number in counter No. 3 is compared to that in the memory (n/96). When the two numbers become equal, the comparator puts out a pulse to the speed control and resets counter No. 3 to zero. The counting continues, each time counting n/96 source pulses. Thus, the time interval between output pulses is determined by the number (n/96) stored in the memory, and is of the proper timing to drive the motor at the same rate as in sunlight.

One of the main considerations in the design of the counting system for dark-period control is the required accuracy. In the system of figure 18, it will be noted that the number left in counter No. 1 at the end of the 45-degree counting period is disregarded in determining the output pulse interval. The number stored in memory is thus an integer which may have an error of one. For example, assume that the number of source pulses, P, during the 45-degree counting period were 1055. Counter No. 1 would count through ten times, and have a count of (1055-960) = 95 at the end of the period. The number 10 would be stored in the memory, while the fraction 95/96 is dropped. The error is, therefore, almost 10 percent.

To achieve a tracking accuracy of two degrees requires that the dark-period control hold the average speed to within approximately 0.5 percent. This means that the minimum number required

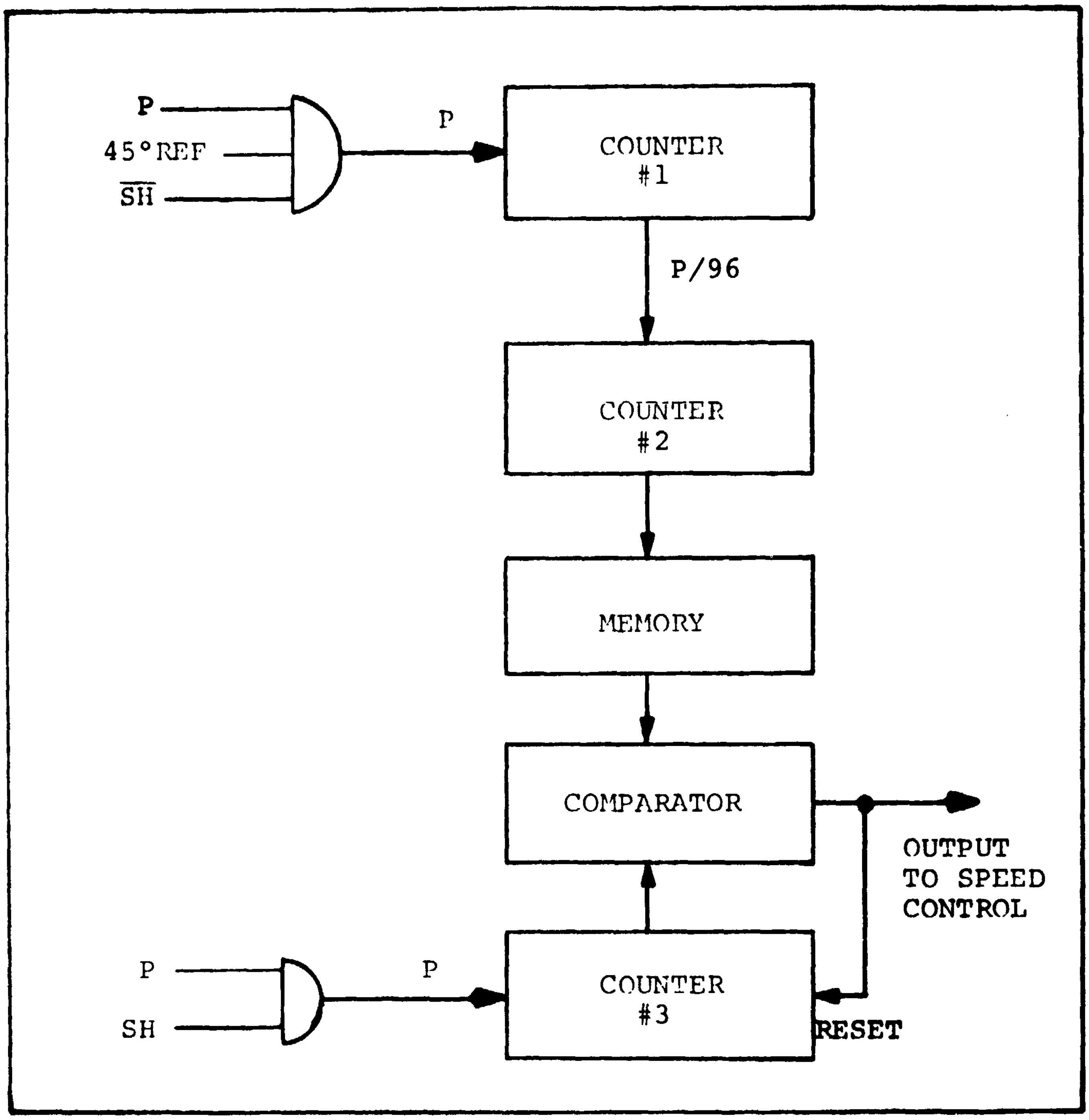


Figure 18. - Block Diagram for Simplified Conceptual Dark-Period Speed Control

in memory be 200. This requires an eight-stage binary counter and memory, with a capacity of 256.

The number of source pulses per 45 degrees rotation is a function of source frequency and of the orbital altitude. For example, suppose a source-pulse frequency is chosen to generate the reference number 200 at the minimum 90-minute orbit. Suppose further it is desired to use the same pulse frequency at a 24-hour orbit. The pulse-counting time is increased by a factor of 16. This requires an additional four stages in counter No. 2 and memory as well as in counter No. 3.

It is recognized that the functions of counter No. 2 and counter No. 3 may be combined since these counters are used at different times. In a practical circuit, a further reduction in counter stages can be made by making use of the most significant stages of counter No. 1, to develop a fractional remainder which can be added to the integer number generated by counter No. 2.

A practical control scheme. - The counting system designed for the dark-period control uses the integer and remainder concept, and thereby requires a lower frequency pulse rate than otherwise necessary. A block diagram of the system used is shown in figure 19. The diagram is shown in two parts for simplicity. Figure 19(A) shows only those functions necessary during the sunlit portion of the orbit. Although the logic functions are not shown, at the beginning of each 45-degree rotation period, the contents of counters Y and Z are transferred to the memory and all counters are reset to zero. The source pulses, P, are counted until the end of the 45-degree period. At the beginning of each new 45-degree period, the memory is updated by the contents of counters Y and Z. The total count of counter Z is the integer number n/96. The final count in counter Y represents the numerator of the fractional portion to be added to the integral number n/96. In this design, counter Y consists of four binary stages and contains the remainder fraction to the nearest 1/16 at the end of each counting period.

Figure 19(B) shows the connections of the counters after the spacecraft has gone into the shadow. The counters are initially reset to zero and source pulses are transmitted simultaneously to both counters Y and Z. Counting continues until the number in counter Z equals that in memory Y, at which point comparator Y senses the equality, and gives a "stop" signal to a flip-flop. The flip-flop output inhibits further pulses, P, reaching counter Y which holds its last count until a "start" signal is received by the flip-flop. Counter Z continues to count until its number becomes equal to that of memory Z, at which point comparator Z senses the equality and gives an output pulse. The output pulse

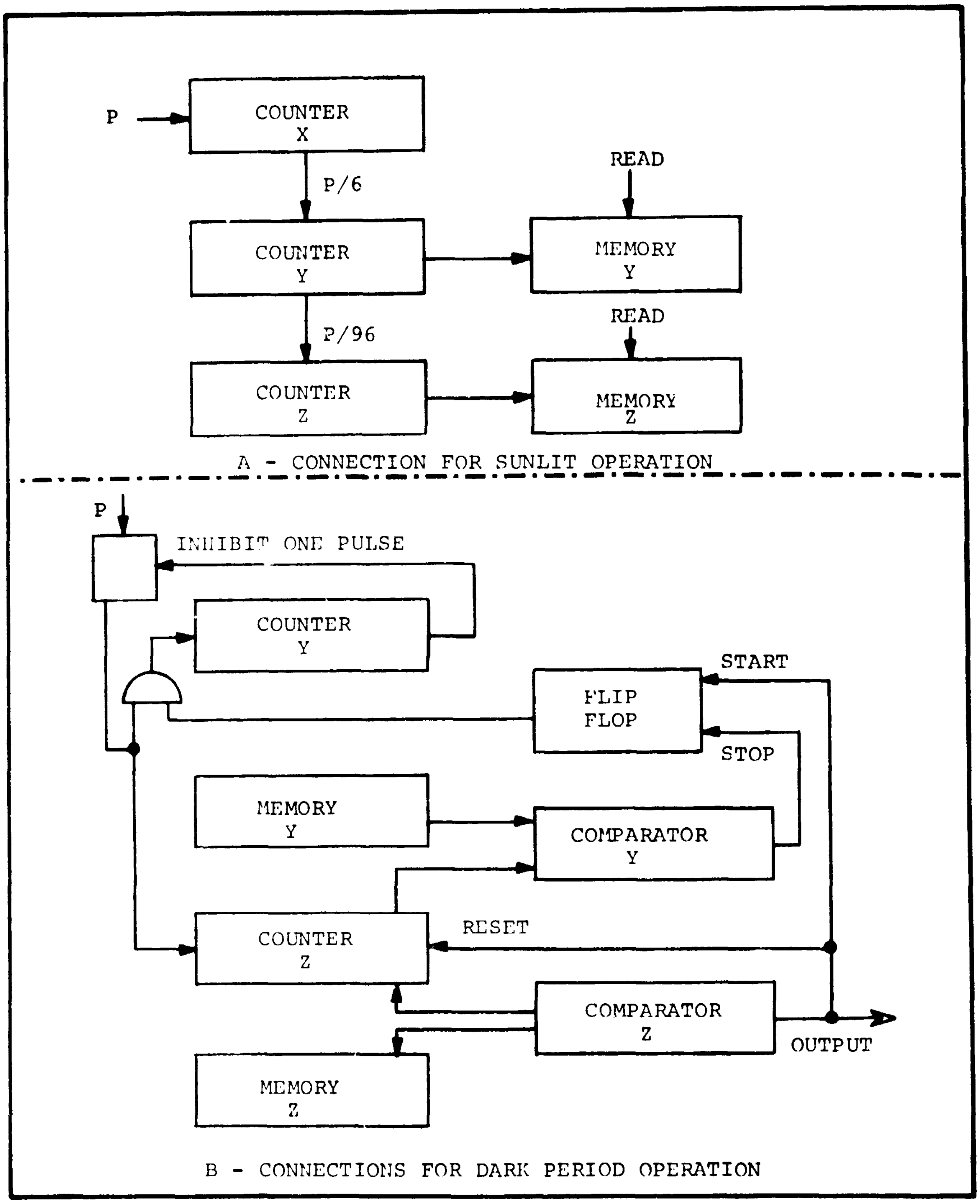


Figure 19. - Block Diagram of Dark-Period Speed Control

is sent to the motor control causing approximately 0.47 degree rotation. In addition, the output pulse resets counter Z to zero and sets the flip-flop to "start". Counter Y resumes counting with the next pulse, P, while counter Z continues from zero. Counting continues as in the previous cycle until counter Y reaches its full count (15) and resets to zero. On the reset pulse, an inhibit signal is applied at the pulse, P, input point. The next pulse P merely removes the inhibit condition but does not get through to the counters. With the inhibit command removed, subsequent pulses, P, are transmitted normally until counter Y once again completes its full count.

The result of operating the counters in this manner is perhaps best explained by numerical example. Assume that the average number of source pulses per output pulse were 18-34/96, for example. The total number of source pulses counted during the 45-degree counting period would be 96 x 18-34/96 = 1762. The number would be distributed among counters X, Y, and Z as follows at the end of the period.

(1) Counter Z = 18

(2) Counter Y = 30/96 = 5/16

(3) Counter X = 4/96

The contents of counters Y and Z are stored in memories Y and Z, while counter X is disregarded. The counters are set to zero and counting begins. On each of the first three passes (or counting cycles of counter Z), counter Y counts five pulses and stops while counter Z counts 18 pulses and gives an output pulse. On the fourth pass, counter Y receives its 16th pulse and resets, preventing the next pulse from reaching either counters. Thus, 19 pulses are required to drive counter Z to its reset point on the fourth pass. Note, however, that counter Y counts five pulses as usual. Similar action continues through 16 passes. The result is that five times during each 16 passes, one extra pulse is required to complete the count of counter Z. A running score on the counters is tabulated below for 16 passes.

PASS	NUMBER IN COUNTER Y	INHIBIT PULSE	SOURCE PULSES PER OUTPUT PULSE
1	5	0	18
2	10	0	18
3	15	0	18
4	4	1	19
5	9	0	18
6	14	0	18
7	3	1	19

PASS	NUMBER IN COUNTER Y	INHIBIT PULSE	SOURCE PULSES PER OUTPUT PULSE
8	8	0	18
9	13	0	18
10	2	1	19
11	7	0	18
12	12	0	18
13	1	1	19
14	6	0	18
15	11	0	18
16	0	1	19

As seen in the table, the average number of pulses per output pulse is 18-5/16 for 16 passes. Also note that the extra pulses are distributed as evenly as possible, which gives minimum variation in the average speed.

The minimum number of source pulses per output pulse which can be reliably used with this counting method is equal to the storage capacity of memory Y, which is 16 in this design. The maximum error that can be developed in the average output-pulse interval is therefore 1/16 part in 16, or 0.39 percent.

The logic circuit. - Logic circuit diagrams for the dark-period control are shown in figures 20, 21, and 22. The basic control elements are the pulse counter (WC213D) and the NAND gate. A single counting stage is shown in figure 20. The output, Q, changes state each time the input pulse at C goes to the zero state. The output, Q, goes to the zero state at any time the reset, R, goes to the zero state. The counter output may be transferred to the memory flip-flop only when so commanded by the signal GO which is normally in the zero state. The comparator output is in the high state only when the signal at X is the same as the output of the memory.

The counters, memories, and comparators Y and Z are made up of single stages, interconnected as shown in figure 21. The counters are serially connected as binary counters. The comparators are completed by connection of the single-stage comparators to NAND gates. Thus, a comparator output is possible only when all stages of the comparator are in the high state.

The logic circuit for the complete dark-period control is shown in figure 22. It shows, in addition to the basic counting functions shown in figure 19, the control functions necessary for operation in the proper mode. When operating in sunlight, the signal $\overline{SH}$ is high and SH is low. The signal P, a function of the input pulse, is transmitted only to counter X, which gives one

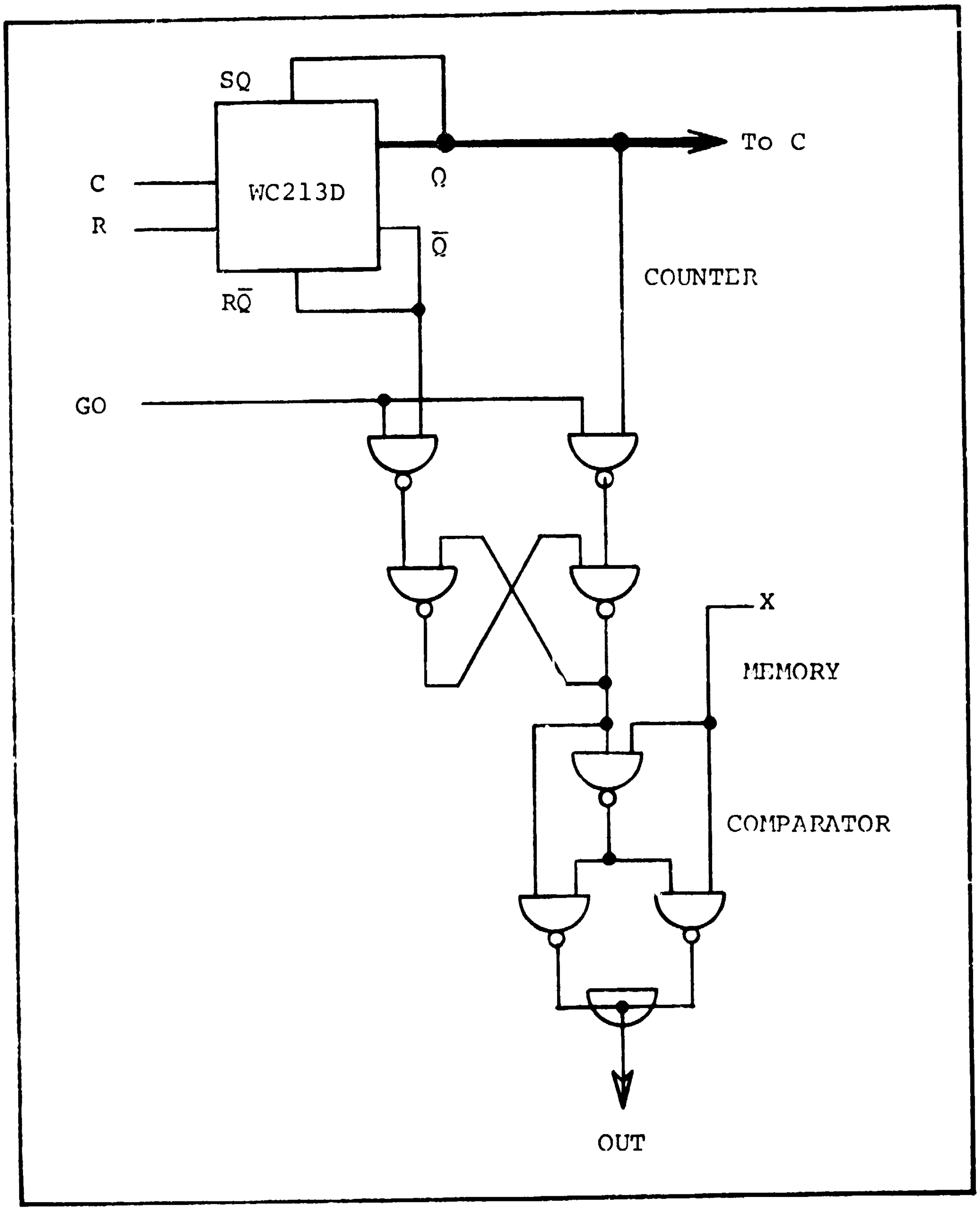


Figure 20. - Logic Diagram for Single Stage of Counter, Memory and Comparator for Dark-Period Speed Control

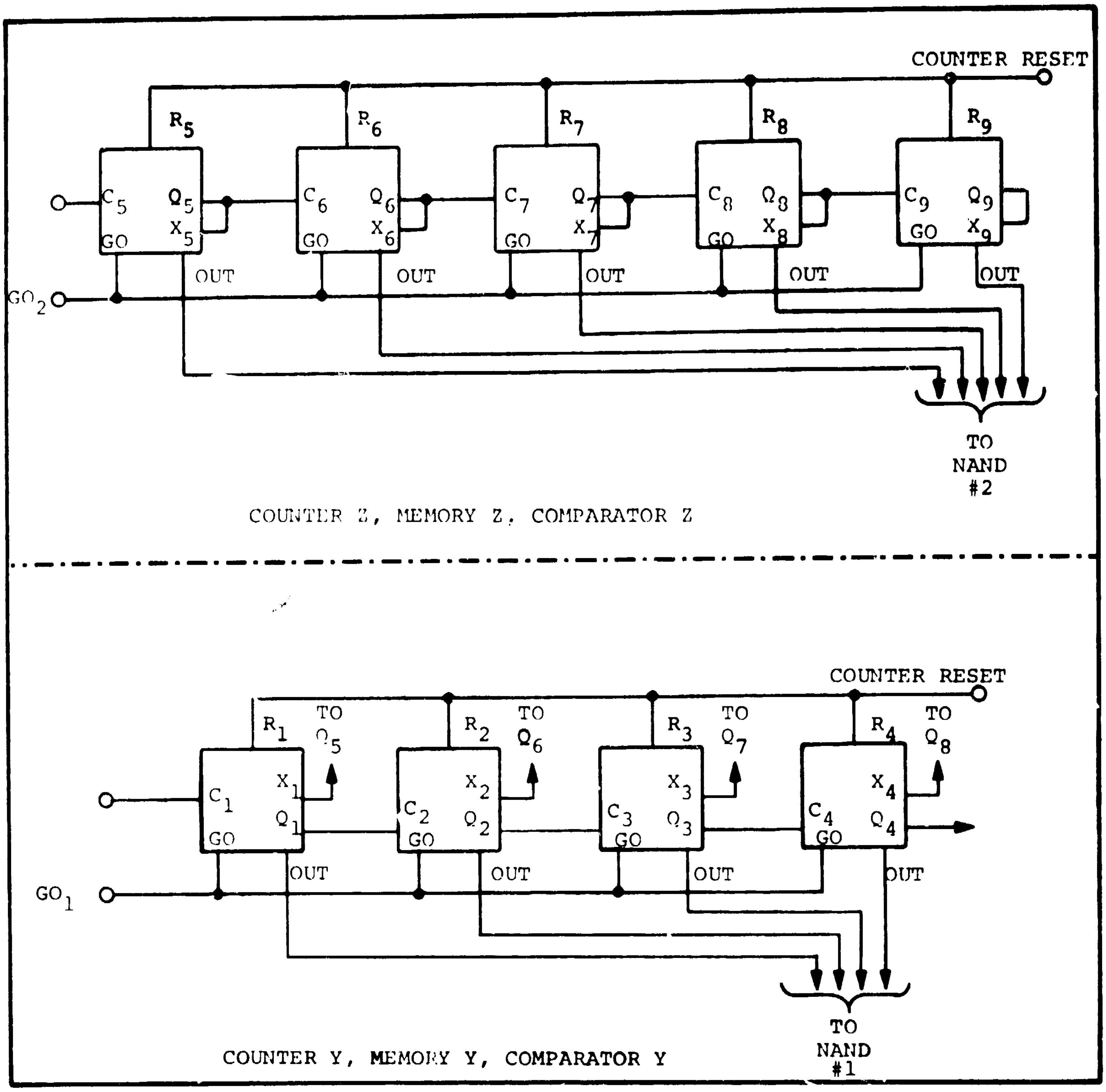


Figure 21. - Interstage Connections for Counters, Etc.

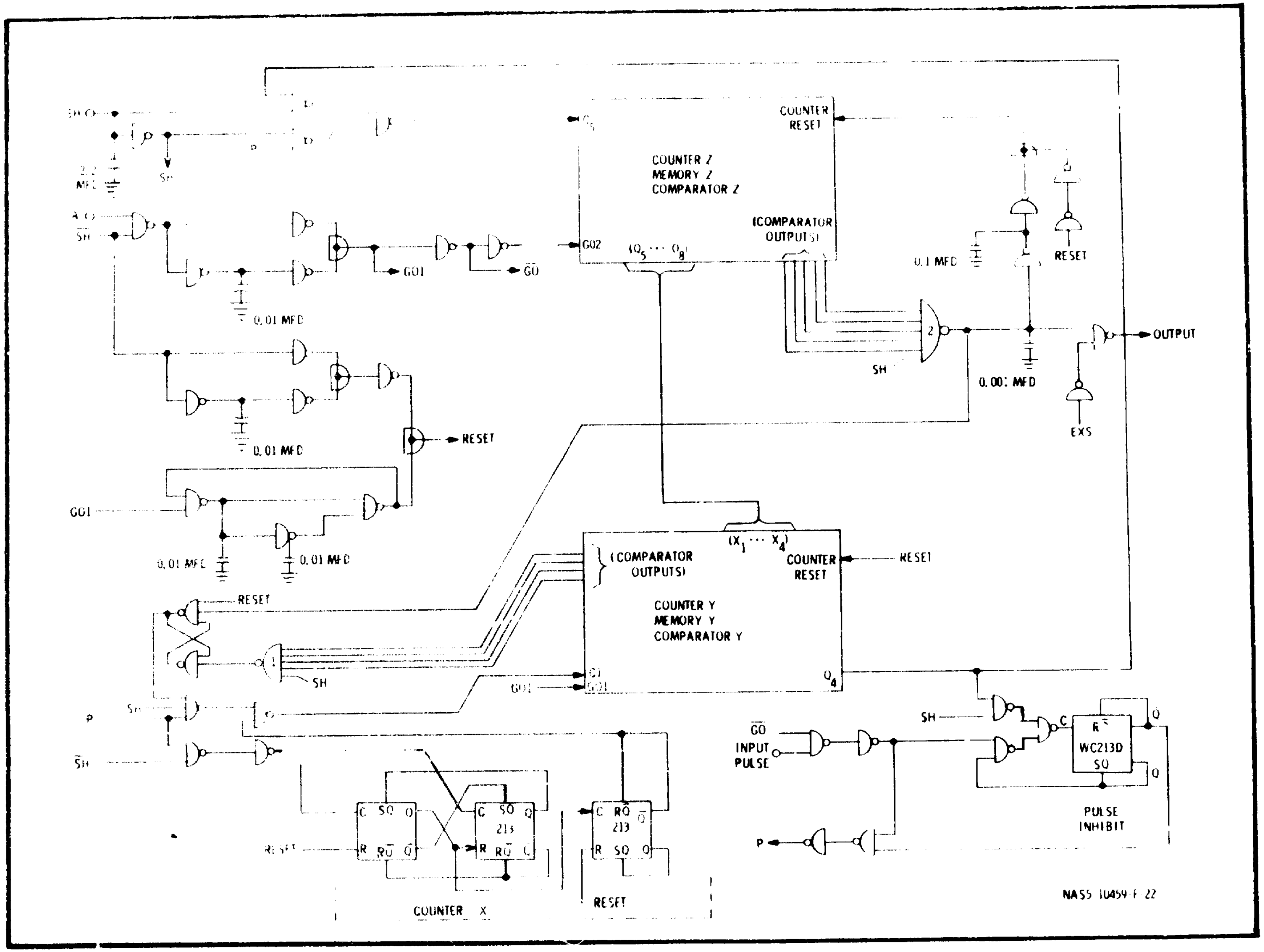


Figure 22. - Dark-Period Control Logic Circuit

output pulse for each six input pulses. This output is transmitted through a NAND gate to counter Y which requires 16 pulses at C1 to produce one output pulse. The output of counter Y is transmitted through two NAND gates to counter Z. The capacity of counter Z must be great enough to hold 1/96 of the maximum number of pulses generated during 45-degree rotation of the motor. Five stages are used in counter Z which is the minimum number required in this design.

During operation in sunlight, the only function of the controls is to develop a speed reference. The signal A' is high when magnetic sensor A has an output greater than that of sensor D. Thus, A' controls the counting interval to 45 degrees of rotation of the motor. In figure 22, it may be seen that A' operates into a pulse-forming circuit.

A pulse is formed at GO1 when A' goes to the high state. (When A' goes low there is no effect on GO1.) The signals GO1 and GO2 cause the contents of counters Y and Z to be transferred to the memories. The pulse GO1 also operates into a second pulse-forming circuit, the output of which is a counter-reset signal. The signal, RESET, which is normally high is delayed in going low until the signal GO1 has gone low. This assures that the numbers in the counters at the end of a 45-degree interval are transferred to the memories before the counters are reset to zero. Once reset, the counters begin counting a new set of data during the next 45-degree interval. In this way, the speed reference is periodically updated during sunlit operation.

Going into the shadow causes the signal $\overline{SH}$ to go low and SH high. This causes the pulse, P, to be rerouted from counter X directly to counters Y and Z. Thus, counters Y and Z count in parallel and counter X no longer counts. Also, the signal $\overline{SH}$ is applied to a pulse-forming circuit, which provides a negative going pulse at RESET, so that counting begins from zero. In addition, enable signals, SH, are provided for the comparators and for the pulse inhibit circuit.

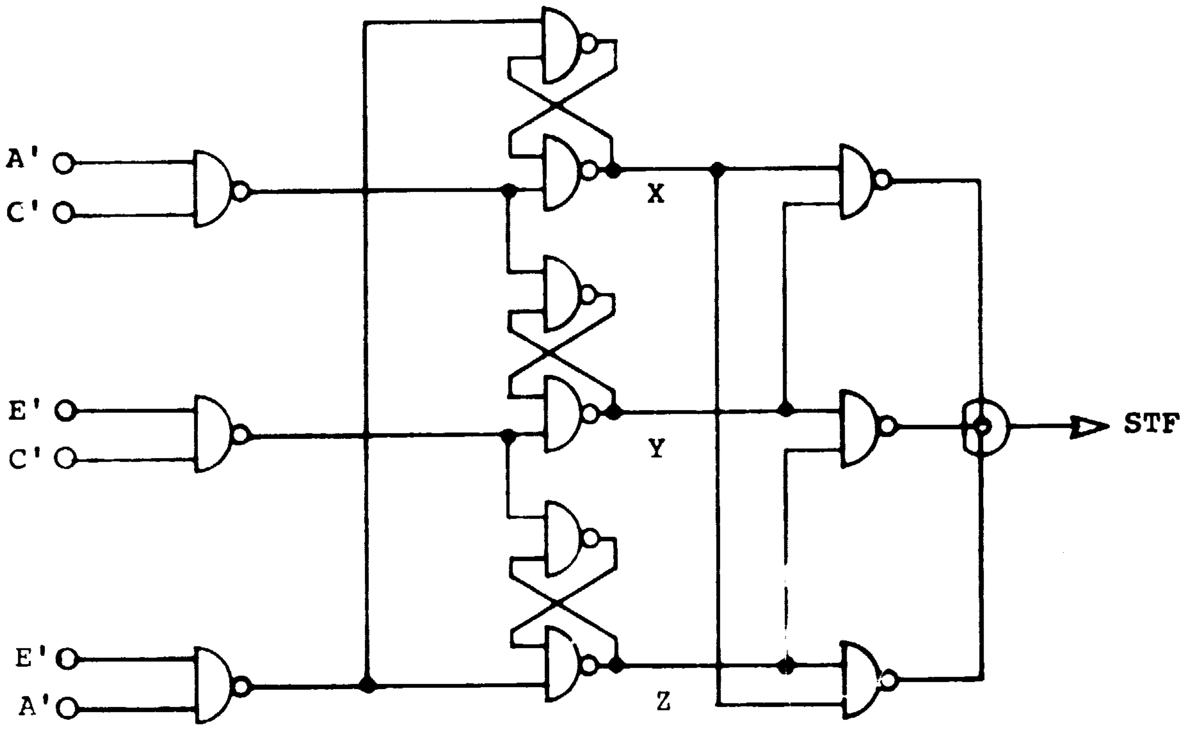
Starting at zero, both counters Y and Z count until the number in memory Y is reached. Comparator Y senses this condition and NAND gate No. 1 latches a flip-flop which then inhibits P being transmitted to counter Y. Counter Z continues to count until the number in counter Z matches that in memory Z, at which point comparator Z gives an output via NAND gate No. 2. Besides providing an output for motor operation, counter Z is reset to zero and the flip-flop inhibiting pulses to counter Y is reset, so that counter Y resumes counting. This cycle of operation is repeated until counter Y reaches its full count and the output at Q4 falls to zero. This causes the signal at C on the pulse-inhibit counter to fall to zero, changing the state of the output, Q, from low to high, and $\overline{Q}$ from high to low. The next input pulse cannot get through the NAND gate to P because it is inhibited by the zero state of $\bar{Q}$. The high state of Q, however, allows the input pulse to reach C on the pulse-inhibit counter. When the input pulse returns to zero, the counter once again changes its output state, and subsequent pulses are routed directly to P without effect on pulse-inhibit counter. One input pulse has thus been rejected and the interval between output control pulses increased by one count.

The return of the satellite to sunlight merely reconnects the counters serially and inhibits output pulses. No attempt is made to preserve the reference numbers in memory, as they are regenerated within the next 90 degrees of rotation.

Entering the shadow. - While the reorientation system is operating in the sunlit normal tracking mode, the speed control, of course, is not in operation, and thus the magnitude of (BUS-RAMP) makes no difference. Once in the shadow, however, the system responds to the signal (BUS-RAMP). It is necessary, then that the controlling signal (BUS-RAMP) be near zero at the time it assumes control, else a tracking error will be immediately introduced.

The magnetic sensor signals continually change during rotation of the motor causing the signal, BUS, to likewise change. To maintain a low error signal (BUS-RAMP), it is necessary to cause a change in the signal RAMP corresponding to the change in BUS during the normal tracking mode. Such a change is accomplished in the control system through the feedback signal used to smooth speed transients during reorientation from large errors. Referring to figure 16, it will be seen that the feedback signal (BUS-RAMP) is the only signal applied to the non-inverting input of the integrating operational amplifier. (In the normal tracking mode the signal, N, operates a transistor, short circuiting the other signal.) When (BUS-RAMP) is positive, its voltage is integrated by the operational amplifier circuit, eventually triggering the unijunction transistor (UJT) which gives a pulse to the ramp generator and raises the signal RAMP. This, in turn, reduces the signal (BUS-RAMP). As motor rotation continues, the signal, BUS, continues to increase, again increasing the feedback signal (BUS-RAMP). Once again the integrating circuit responds as before. In this manner, pulses are supplied to the ramp generator at just the proper rate to cause the signal, RAMP, to follow the signal, BUS. Thus, when the shadow is encountered, the control signal (BUS-RAMP) is near minimum.

It should be noted at this point that the motor-direction control during dark-period operation is determined by the signal, STF, which depends on the direction history. The logic circuit shown in figure 23 requires a rotation of 7.5 to 15 degrees after



IN	▨	E'			▨	A'			A'			▨	E'			▨	E'			▨
OUT	A'		▨	C'			▨	E'		▨	C'			▨	A'			▨	C'	
X	-	0	0	0	0	1	1	0	0	0	1	1	1	1	0	0	0	0	0	0
Y	-	0	0	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
Z	-	1	1	0	0	0	0	1	1	1	1	1	0	0	1	1	1	1	0	0
STF	-	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1
	REV →									FWD →								REV →		

Figure 23. - Direction Logic Circuit

a reversal to change the state of the output signal, STF (see truth table). This means that the system must operate in the normal tracking mode for 15 degrees to assure proper direction control and minimum error signal (BUS-RAMP) upon entering the shadow.

Leaving the shadow. - After the orientation system has operated in the shadow for some time, it is expected that a small error would have accumulated within the normal tolerance. Should the motor drive control be arbitrarily switched to the normal tracking mode, a large restoring signal would be applied to the motor. The reaction would be a tendency to overshoot the zero error point and oscillate. This is exactly the same problem as discussed in section "Reorientation System Operation", "Large Error Reorientation", paragraph "Transfer to Normal Tracking Mode", concerning the final approach to reorientation from a large error. Since we are dealing with the same problem, we also use the same solution. When the signal, SH, goes low the controls are made to momentarily simulate a large error and a standby condition.

Recall that when the controls are set in the STANDBY command, the magnetic sensors are not energized and that this results in a low signal, BUS. As may be seen in figure 14, the signal, |BUS-RAMP|, is therefore high, and comparators produce signals ER and EL. In addition, STANDBY produces the signals SL1 and STB (see figure 17). Recall also in figure 17 that SL1 causes the controls to be removed from the normal tracking mode (by producing $\overline{N}$) until the solar sensor signal SF changes state. When STANDBY is removed, the speed control takes over and moves the array slowly into proper orientation where the normal tracking mode takes over, as discussed in section "Reorientation System Operation", "Large-Error Reorientation", paragraph "Transfer to Normal Tracking Mode".

Simulation of the standby condition upon leaving the shadow may be seen in the upper portion of figure 17 where SH is applied to a pulse-forming circuit, the output of which is normally zero. When SH goes low, the pulse causes LT to go low and STB to go high. In figure 14 the low state of LT turns off a transistor which applies a voltage simulating a high signal, |BUS-RAMP|, at the inputs of two comparators which produce signals, ER and EL. To complete simulation of STANDBY, the signal, SH, is also used to simulate SL1 in the center portion of figure 17 where SH is applied through capacitors directly to two flip-flops. When SH goes low, the input to the two flip-flops goes low momentarily, assuring a high output at $\overline{N}$.

If, during the dark period, the array were driven a bit too slowly so that the solar sensor signal, SF, comes on in agreement with the stored direction signal, STF, the simulation of standby is omitted. In figure 17 $\overline{SF}$ and STF are applied to a NAND gate comparator which inhibits the pulse when SH goes to zero if SF=STF. The system is thus kept in speed-controlled operation until it catches up and reduces the tracking error to zero. If the simulated standby condition were allowed, the motor would be stopped until RAMP is counted through one cycle. This would increase the tracking error because of this waiting period.

TESTS

Performance Testing

Testing of the solar array reorientation system was limited to performance testing of the control system in its various modes of operation. During the course of testing, several modifications were made in the breadboard circuits to improve performance. Particular attention was given to smooth operation to minimize unnecessary accelerations, and to providing a reasonably realistic test setup.

Test setup. - The laboratory test setup was designed to simulate the operating conditions of its intended application. The motor was mounted on a rotatable fixture to simulate the rotation of the spacecraft. The mounting fixture, and thus the motor frame, may be rotated in either direction, driven by an electric motor at speed simulating orbital rotation. The speed is approximately 0.01 rpm, simulating the minimum orbital altitude. It was found that a single drive motor (a small-geared timing motor) allowed a great deal of backlash in the system. A second drive motor was coupled to the rotatable fixture through a gear ratio slightly different from the original. The difference in normal output speeds of the two drive motors took up the backlash so that virtually none was left in the system.

The solar array was simulated by a cylinder having an inertia of approximately five and ten slug feet square. The weight of the cylinder was supported by suspension by a cord from an overhead support. The motor was mounted with its shaft in a vertical position and connected to the simulated array through a sliding coupling so that the motor bearings support only the weight of the rotor assembly.

The solar sensor assembly was mounted on the simulated array such that a view of the light source is available through a vertical angle of 30 degrees or more. The light source used for performance tests was a photographic projector located about four feet from the sensors. A sketch showing the arrangement of the test setup is shown in figure 24. A photograph of the controller breadboard is also included in the figure.

Normal tracking mode. - Tests conducted in the normal tracking mode were primarily observations of steady-state conditions.

The system was set initially so that the output signals of the two pairs of solar sensors were equal when the light source was turned on. The drive motors were run in a clockwise direction simulating orbital rotation. The drive motors were later reversed. The maximum deviation during this test was ±0.7 degree from the zero-error vector.

Operation was observed during continuous operation in each direction. Movement of the simulated array was so slight that it was very difficult to see. Total variation in position relative to the light source during operation in a single direction was less than 0.1 degree.

Reorientation mode. - Reorientation of the array ordinarily starts from any arbitrary position when the external command is changed from standby to track. Reorientation tests were made using simulated-array inertia of both 5 and 10 slug feet square.

Typical startup characteristics are shown in figures 25 and 26. These tests were made, starting from a 30-degree error, by plotting the angular displacement from the starting point versus time. The speed curves were calculated from the displacement-angle data and plotted on the same time scale. Comparison of the two figures shows that the higher inertia array has a slightly higher peak speed and settles down quicker. The speed and displacement are approximately the same for both arrays after nine seconds.

Figures 27, 28, 29, and 30 show typical characteristics of the end of reorientation. In making these tests, reorientation was started at an error of 40 degrees or more and position data versus time were taken starting at the 30-degree error point. Data were taken for both the 5 and the 10 slug feet square arrays approaching from each direction. Here too, the speed curves were calculated from displacement versus time data. It will be noted in all four figures that the array comes to a stop before reaching the zero error point. The reason for this is the slow speed control designed into the circuit to prevent overshoot when reorientation begins at a 4 to 8 degrees error. It will also be noted that the approach from a reverse (ccw) error takes more time than does the approach from a forward (cw) error. The reason for this is the difference in solar sensor characteristics, as there was no attempt made to match them.

A test was made to determine the reorientation time, starting from the maximum error of 180 degrees. Moving in the forward direction, the restoring time was 2-3/4 minutes, while moving in the reverse direction it took 2-1/4 minutes. The time difference was due to the mismatch in solar sensors. In our test setup, the reorientation speed will normally slow down as the projector lamp ages. Therefore, a test made with an old lamp will show a longer reorientation time. The effect on other modes of operation however, is negligible.

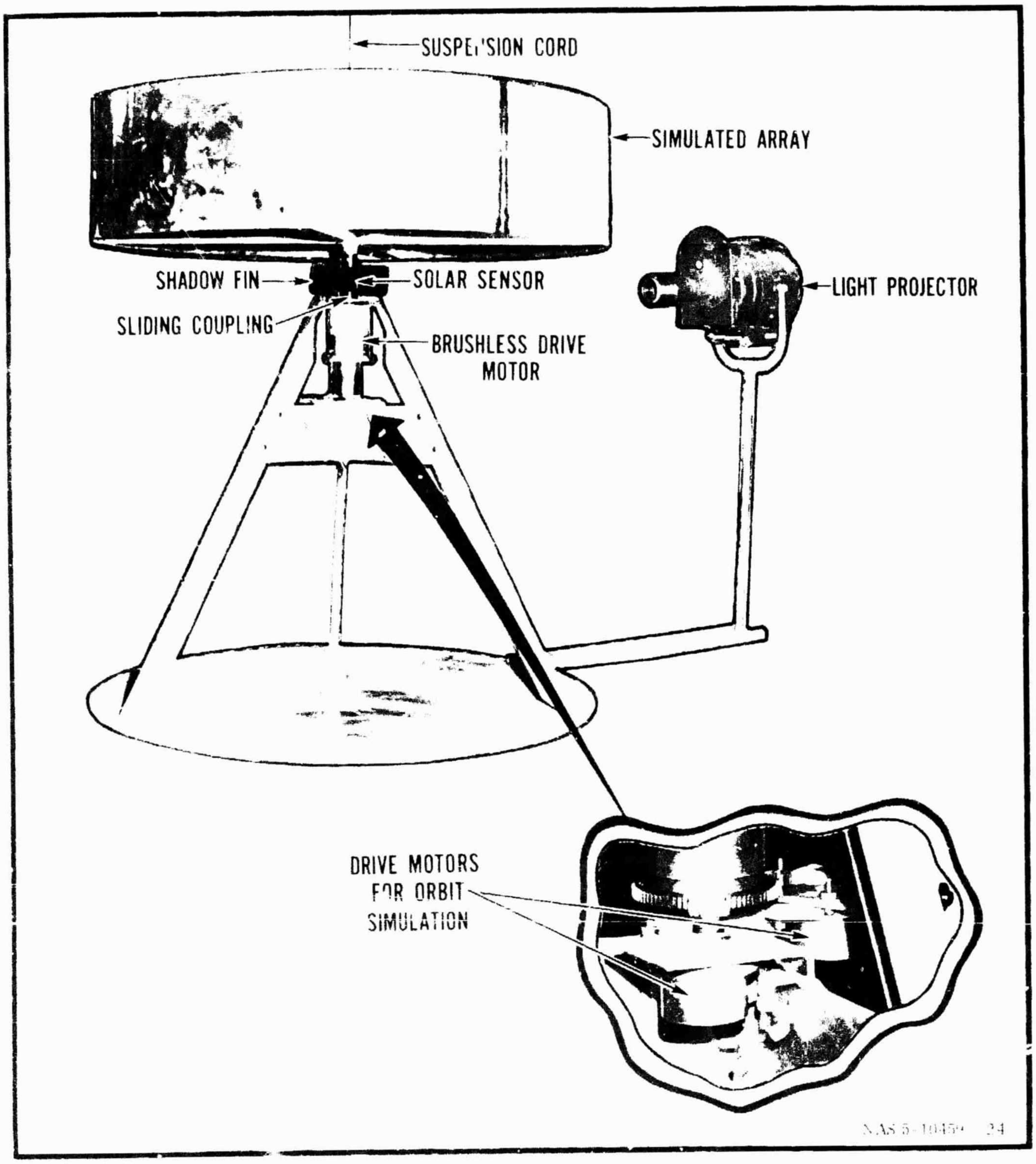


Figure 24. - Mechanical Test Setup

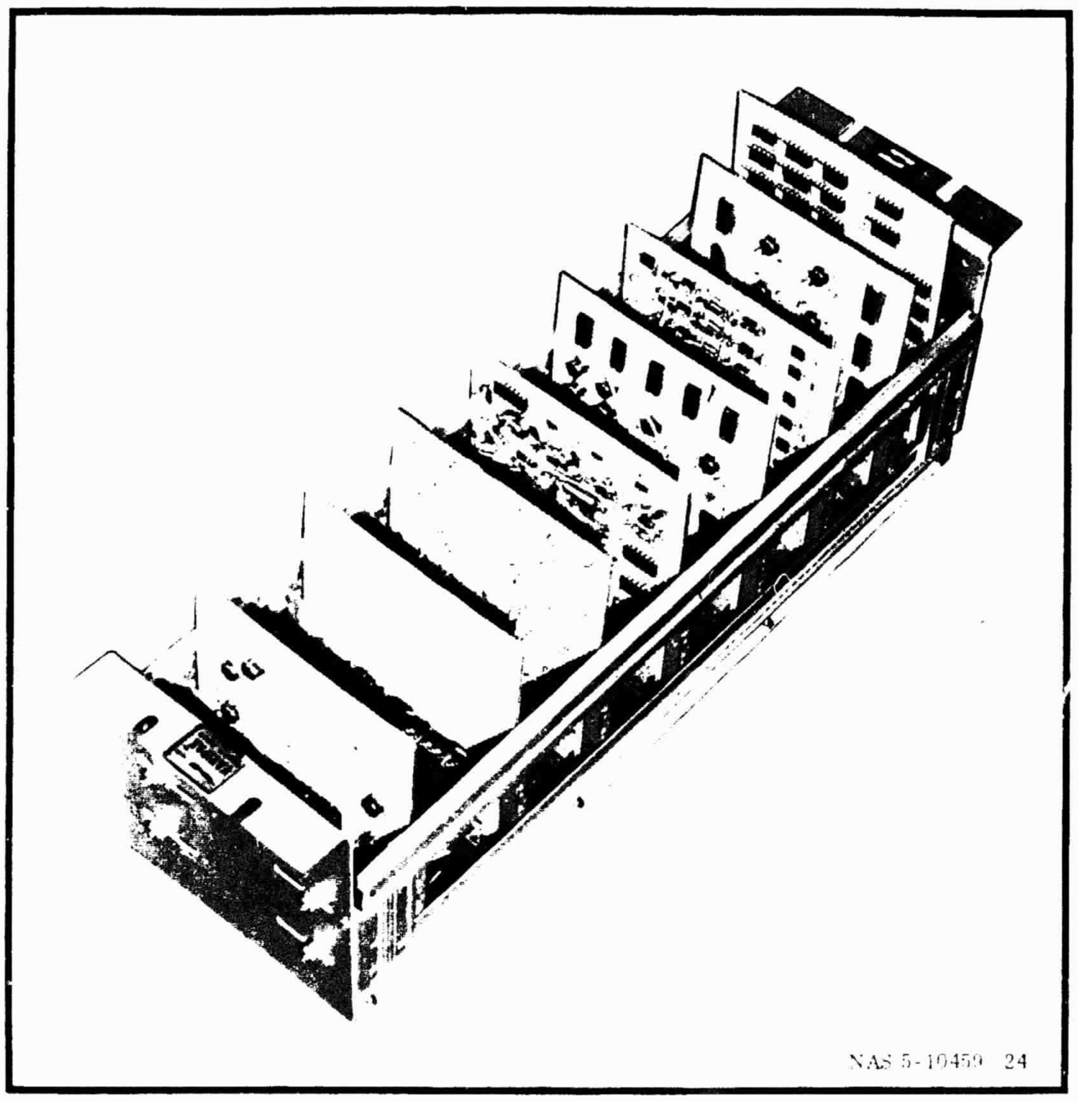


Figure 24. - Continued

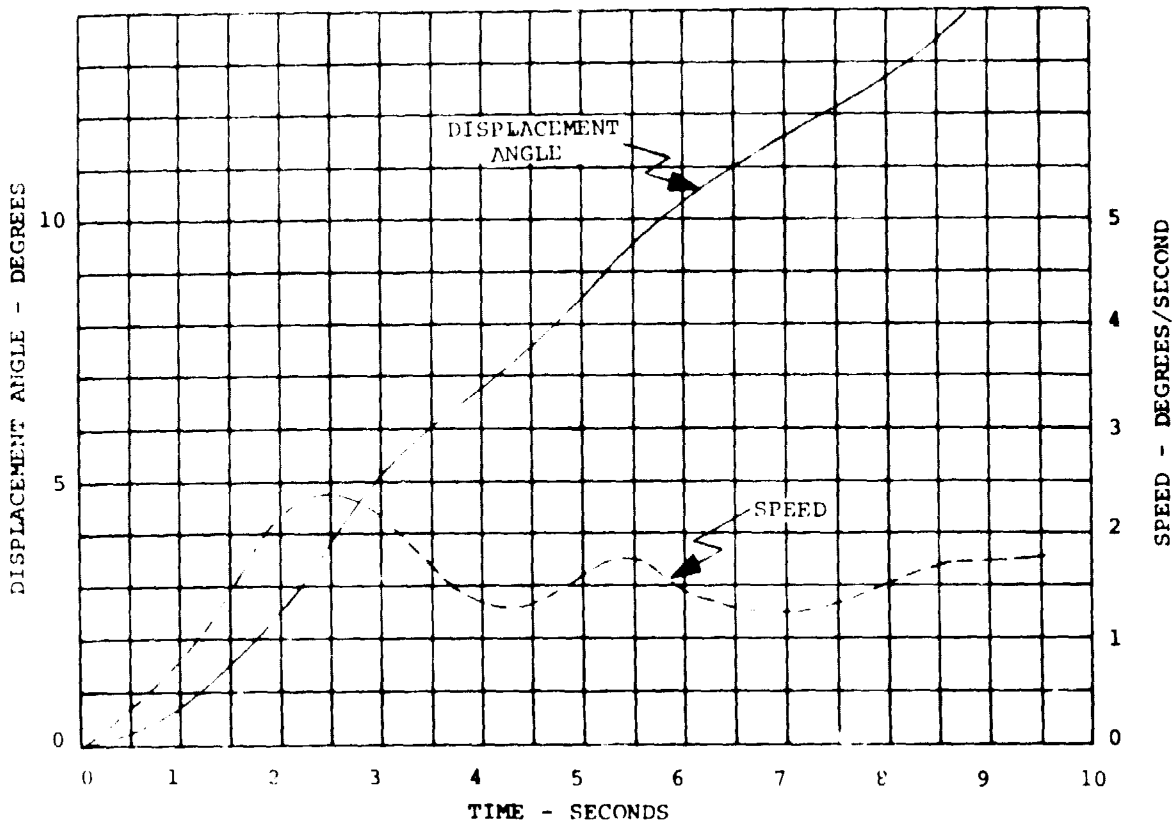


Figure 25. - Typical Start-Up Characteristics. Displacement Angle and Speed Vs. Time. Start-Up From Rest at 30° Error. [5 Slug-ft^2 Array]

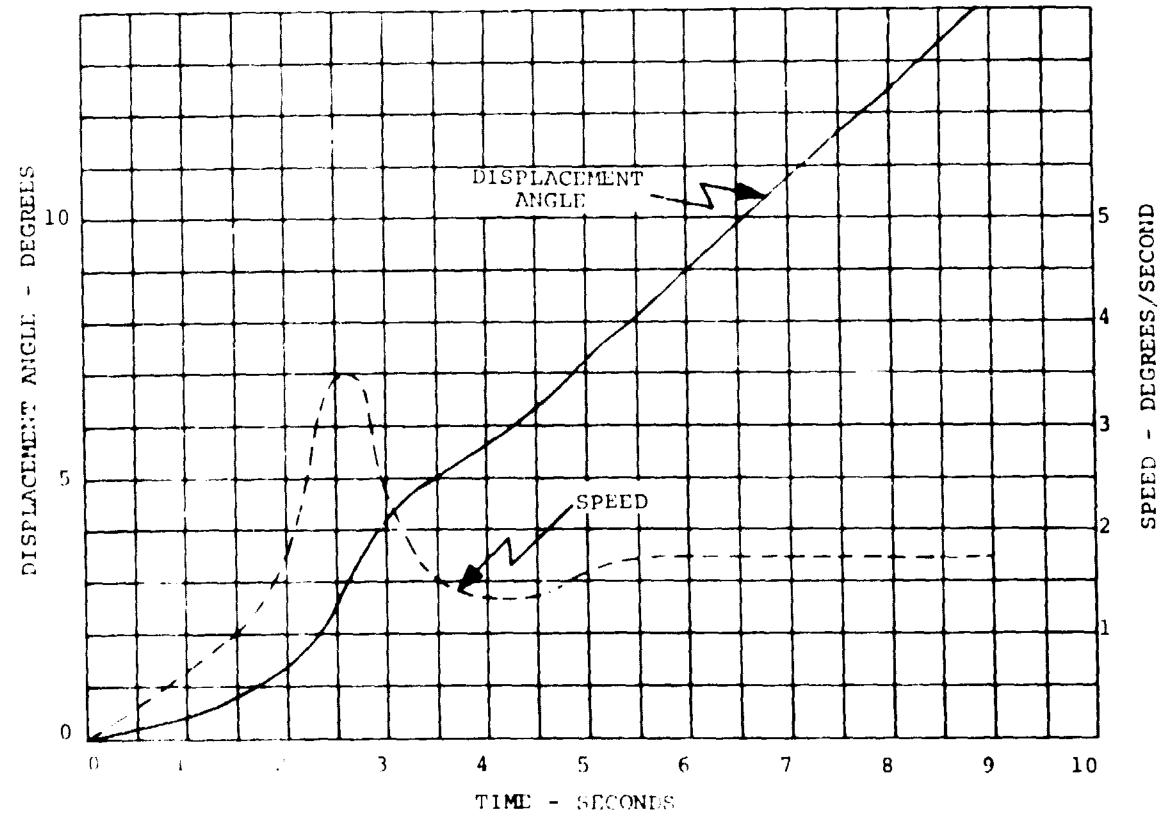


Figure 26. - Typical Start-Up Characteristics. Displacement Angle and Speed Vs. Time. Start-Up From Rest at 30° Error. [10 Slug-ft^2 Array]

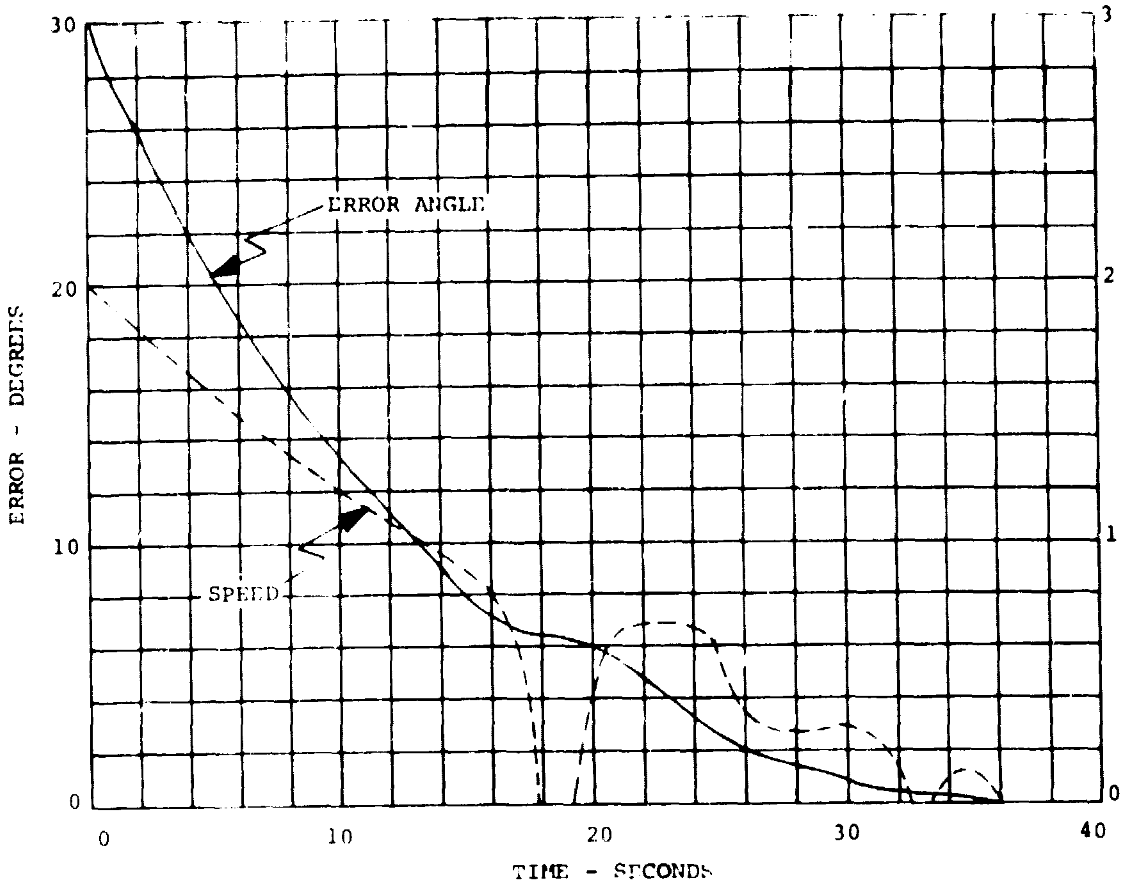


Figure 27. - Array Error and Speed Vs. Time During Final 30° of Reorientation From Large Forward Error [5 Slug-ft^2 Array]

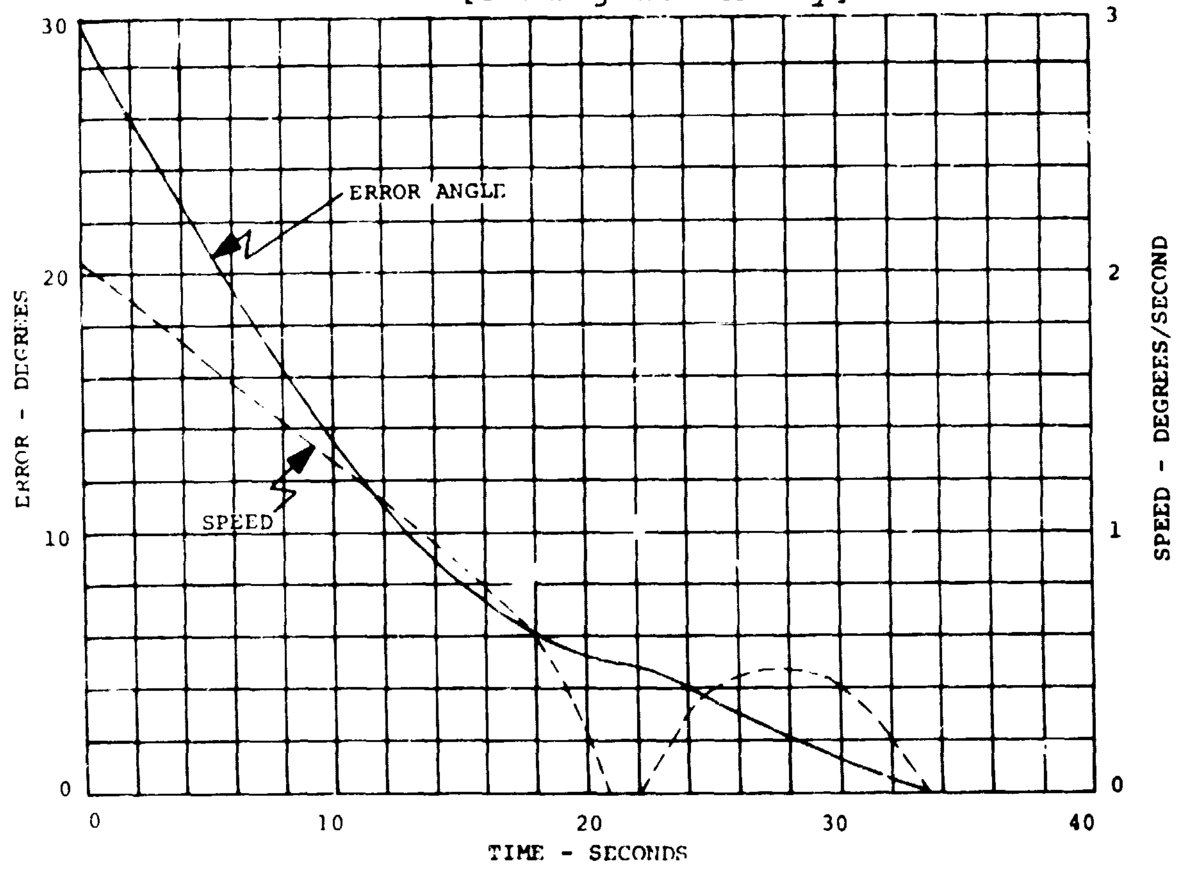


Figure 28. - Array Error and Speed Vs. Time During Final 30° of Reorientation From Large Forward Error [10 Slug-ft^2 Array]

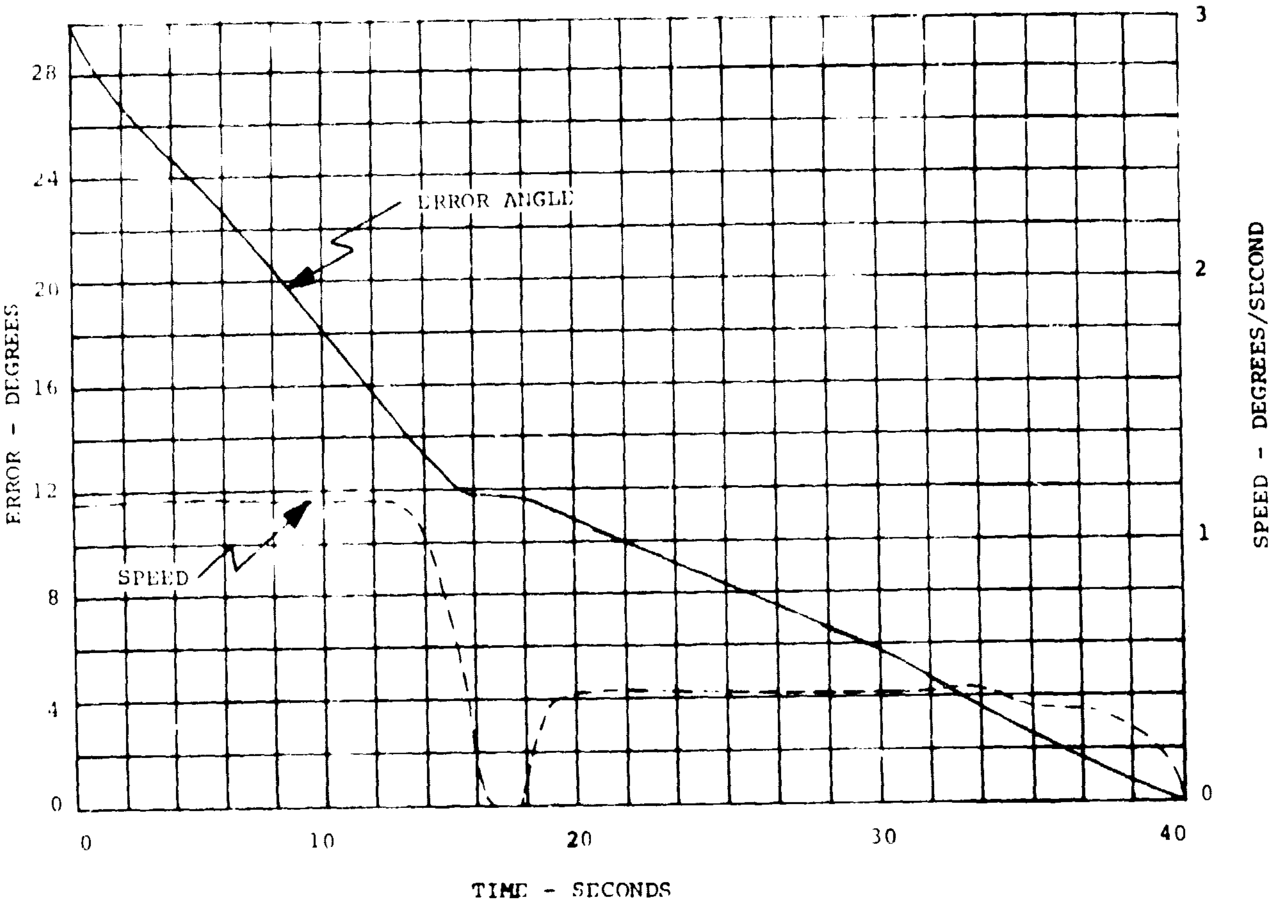


Figure 29. - Array Error and Speed Vs. Time During Final 30° of Reorientation From Large Reverse Error [5 Slug-ft^2 Array]

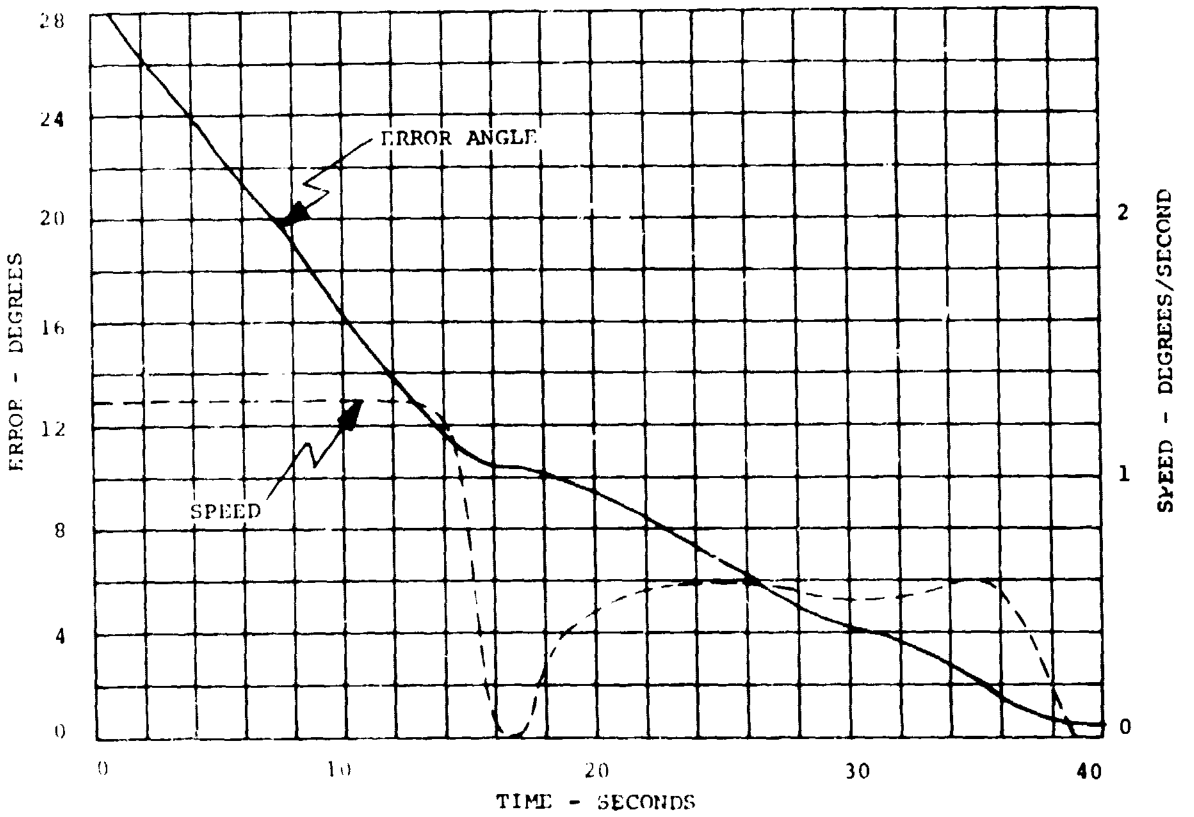


Figure 30. - Array Error and Speed Vs. Time During Final 30° of Reorientation From Large Reverse Error [10 Slug-ft^2 Array]

Dark-period mode. - To test the dark-period tracking control, the reference-pulse source was set at approximately three pulses per second and the system was allowed to track the light source normally during a 45-degree calibration period. The signal A' was monitored to determine the start and finish of the period. (A' goes high at the beginning of each period.) After a full 45-degree calibration period was completed, the light was turned off. The position of the array was observed for the next 70 minutes. During this period, the total variation was approximately 1.2 degrees. The error at the beginning of the dark period was 0.7 degree. The maximum error during the period was 1.7 degrees. The accumulated error at the end of the 70-minute period was negligible. During the period, the motor rotated approximately 250 degrees. With each control pulse, the array was moved counter to the rotation of the motor stator, an average of 0.47 degree. The observed variation in increments of movement was approximately one-third to one degree. There are several factors which contribute to this variation: (1) variation in motor "ripple torque" when not energized, (2) non-linearities in the magnetic sensors, (3) non-linearities in the signal, RAMP, (4) mismatch in the magnitudes of RAMP and BUS signals, and (5) possible variation in the reference-pulse frequency.

External control. - External controls incorporated into the system are (1) Track, the normal command for automatic control, (2) Standby, which removes control signals from the motor allowing an idle condition, (3) Forward, which allows forward movement of array on command, (4) Reverse, which allows reverse movement of array on command, and (5) Speed control, a pulse source which determines the average slew rate during manual control.

Tests show that all external control functions operate properly. The standby command overrides all other control functions. When an external pulse is applied, the array is moved an average of 0.47 degree in the commanded direction (Forward or Reverse).

Tests show that best results are obtained if a standby command precedes any other external command. This assures proper initializing of control signals before the specific command takes control. It is recommended that the external control be designed to automatically give a standby command any time the command is changed.

As the system is presently designed, the external speed control is simply a series of pulses. This is satisfactory so long as the pulse rate is low (in the order of one pulse per second or lower). Higher rates may be used if acceleration is considered, i.e. if the pulse rate is increased from zero at a controlled rate so that the array may accelerate and keep up with the external pulses.

An alternative to the external speed control would involve a design change to incorporate the automatic speed control on external command. The acceleration characteristic would then be controlled by the feedback circuit in the same way as in automatic reorientation from a large error. The external speed control signal would be a voltage of adjustable level rather than a pulse train.

Functional Tests

Functional tests were made on all circuit functions to determine their operational ability. Most of the circuit functions are logic functions and must operate according to the design intent. Once it was determined that logic circuits were functioning properly, no further functional tests were made.

A few circuits, however, required some adjustment and deserve further comment. These circuits have to operate at particular voltage levels and form interfaces with other circuits external to the controller.

Solar sensor output. - The circuit was designed to operate from a maximum solar sensor output current of 60 to 80 microamperes. This level was chosen to be compatible with the light source available. This current range was confirmed by test.

Figure 31 shows the response of the amplifiers of figure 4, used to process the solar sensor signals. The curves show the response to a signal applied from sensors No. 3 and No. 4, operating in parallel while the signal from the other pair of sensors (No. 1 and No. 2) is zero. The output of the first-stage amplifier, E_{CW}, is a linear function of the solar sensor current, and has an output of 48 millivolts per microampere. (A similar amplifier is used to obtain E_{CC}.) The output of the second-stage amplifier is the difference signal, $E_{CW}-E_{CC}$, amplified by a factor of two. Amplifier saturation limits the maximum output to approximately 8.5 volts.

The response to a signal from sensors No. 1 and No. 2 is the same as shown in figure 31 except that the second stage output, $2(E_{CW}-E_{CC})$, is negative. When both pairs of solar sensors produce an output, similar characteristics are obtained, where in figure 31 the input current is the difference of currents in the two pairs of sensors and the lower curve represents $E_{CW}-E_{CC}$.

If the same solar sensors were to be used in direct sunlight it would be necessary to modify the control circuit by changing the feedback resistor in the first stage amplifiers, figures 4(A) and 4(B), to give the proper output voltage to the circuit.

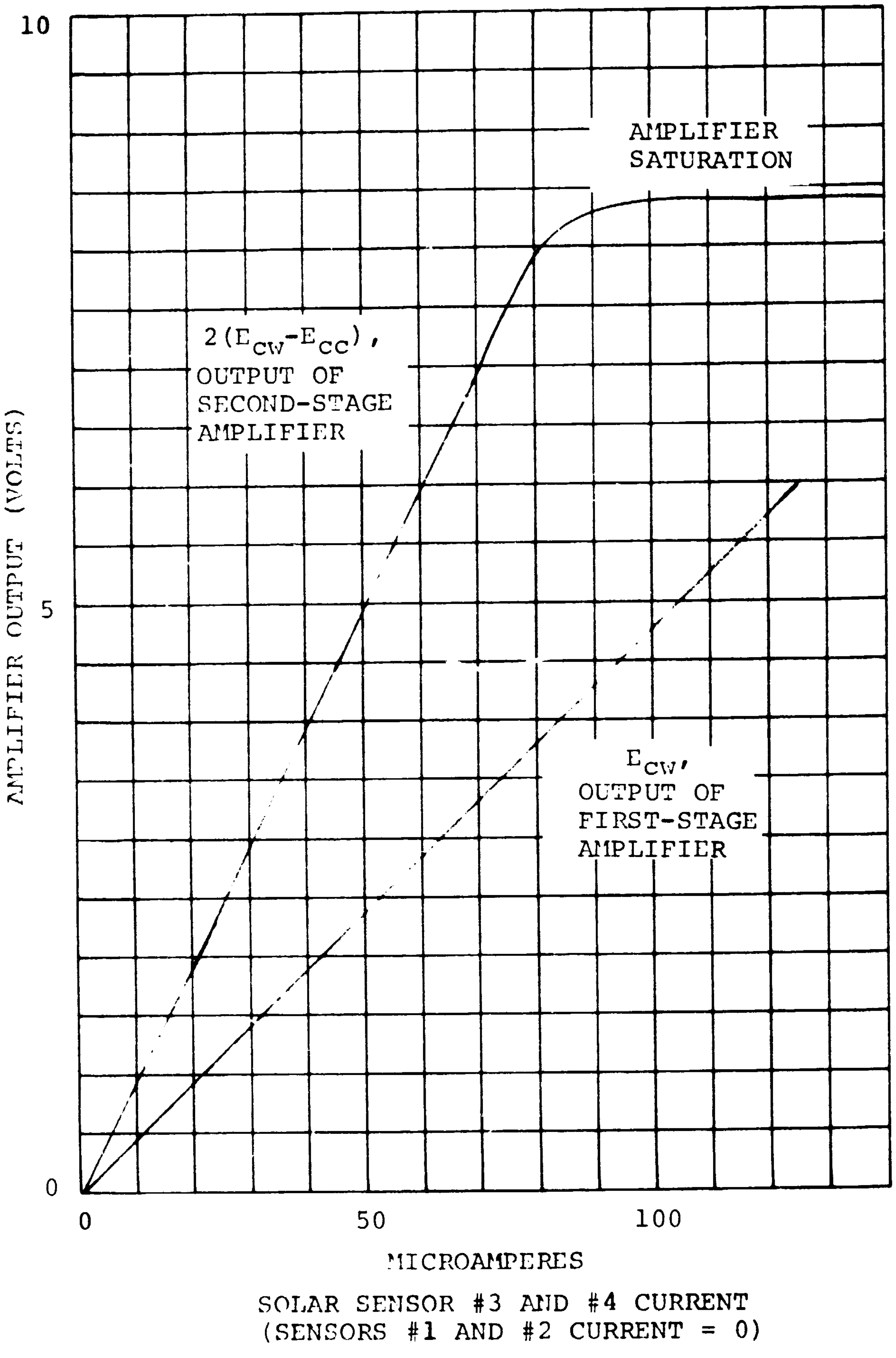


Figure 31. - Solar Sensor Amplifier Output Characteristics

Magnetic sensor output. - A test was made to determine the output characteristics of the magnetic sensor which is part of the motor assembly. Figure 32 shows a plot of the rectified output voltages from the magnetic sensor. The variation in amplitude from phase to phase was considered excessive so that adjusting potentiometers were installed in the breadboard circuit (figure 12). Adjustment was made so that the output of all the signals had approximately equal maximum values. Test results are shown in figure 33, where the maximum output voltages are approximately 8.5 volts. It will be noted also that the variation in slopes and angular position of the curves is slight.

It is important to note that if a different motor were used with the controller, the controller would require adjustment for proper operation. It is, therefore, recommended that in further development a reliable interface be provided by providing the adjustment within the motor commutator circuit.

NEW TECHNOLOGY

Two patent disclosures were issued during the final quarter of the contract covering the reorientation methods and dark-period control. All disclosure information is contained in this report.

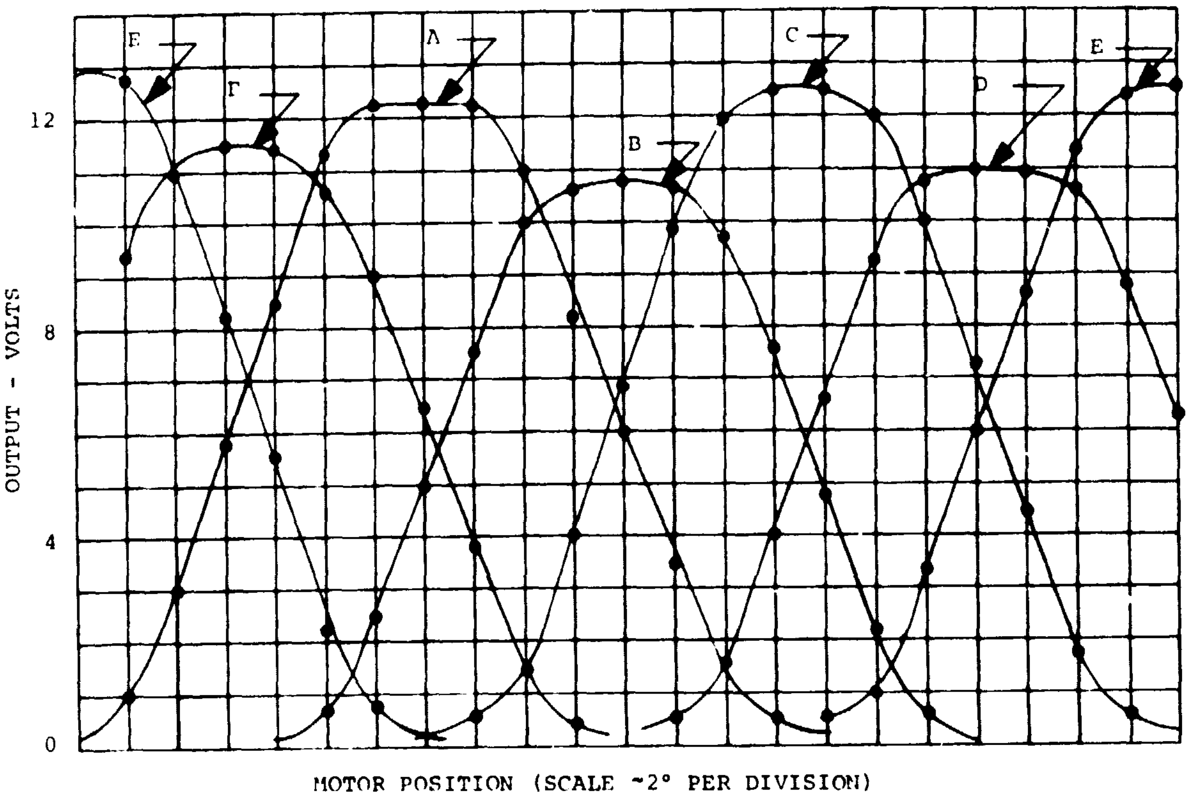


Figure 32. - Rectified Output From Magnetic Sensors

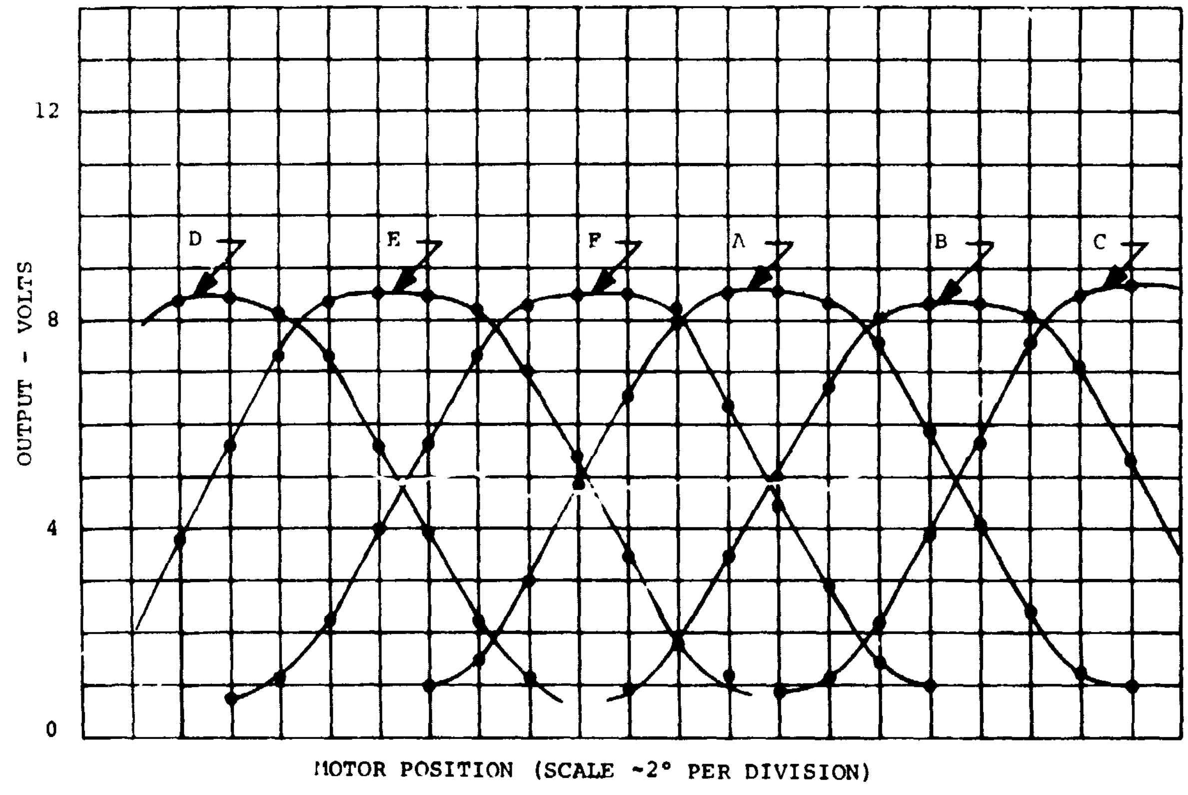


Figure 33. - Modified Output From Magnetic Sensors

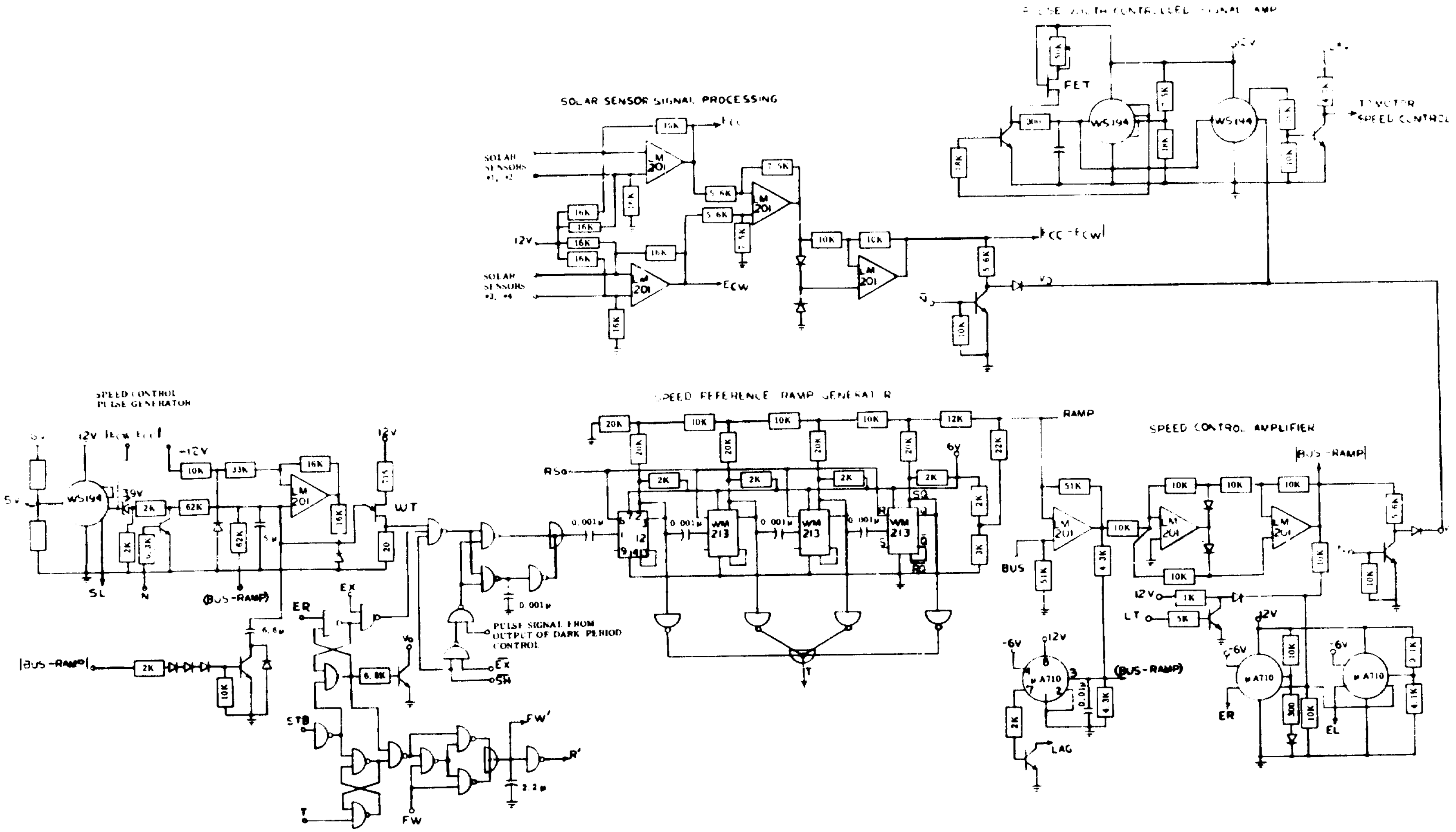


Figure 34. - Solar Array Reorientation System Control Diagram

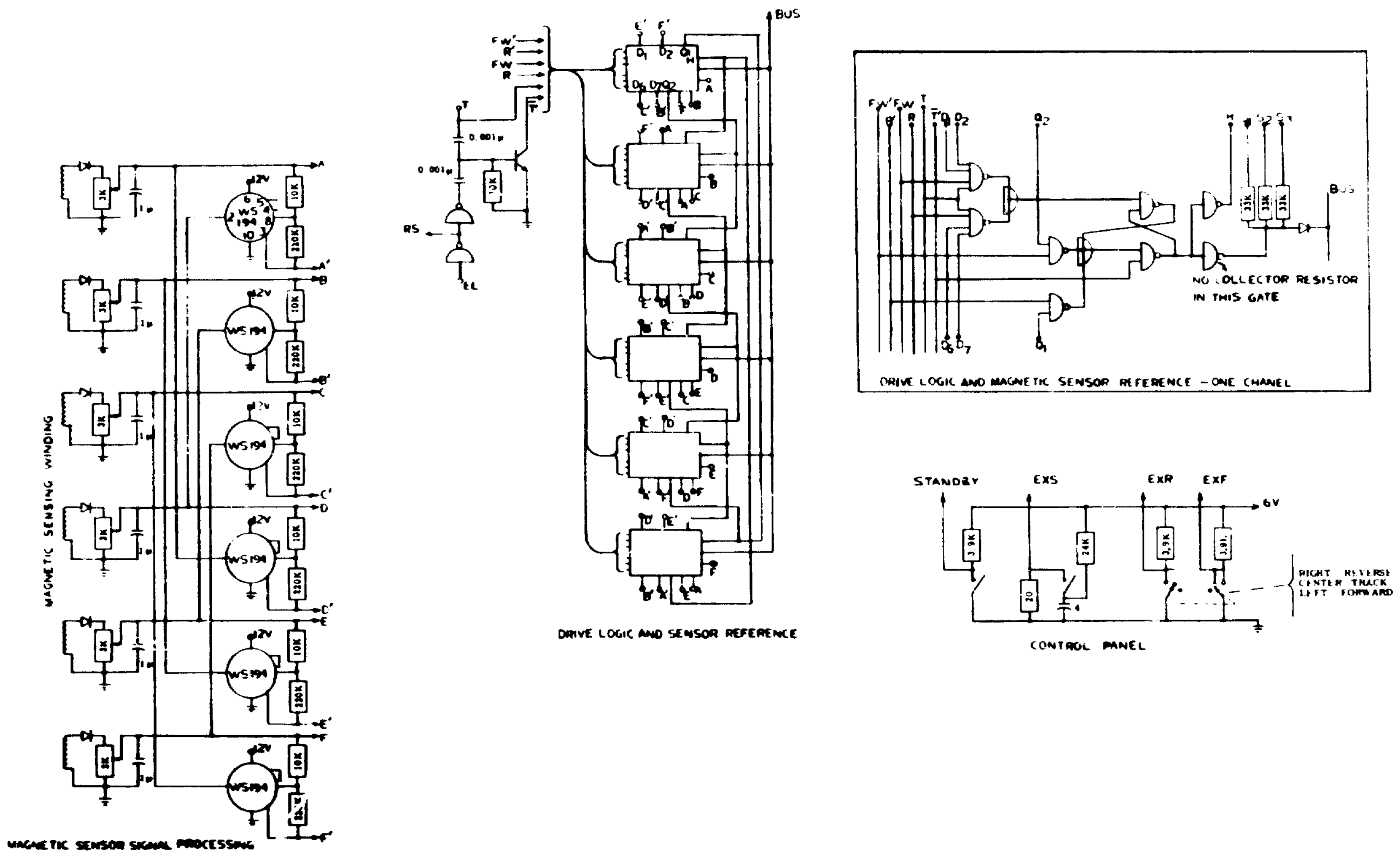
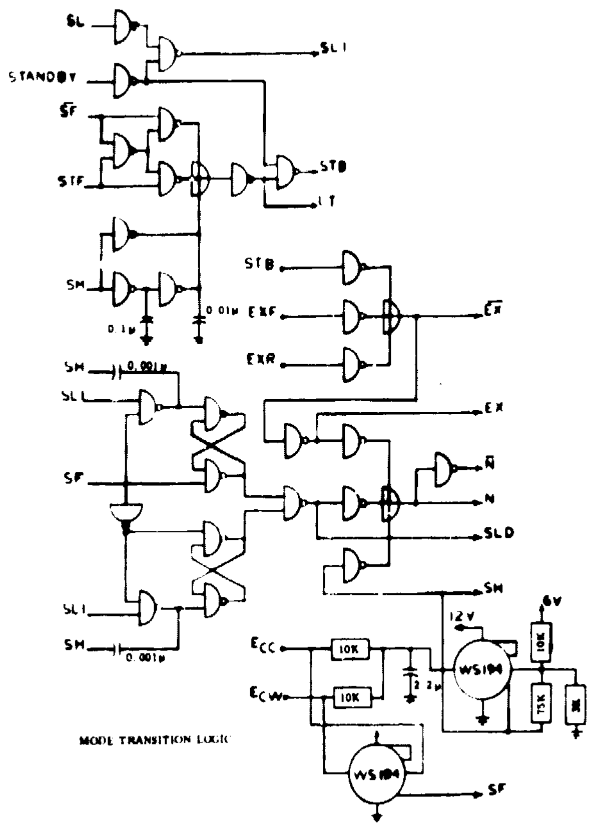
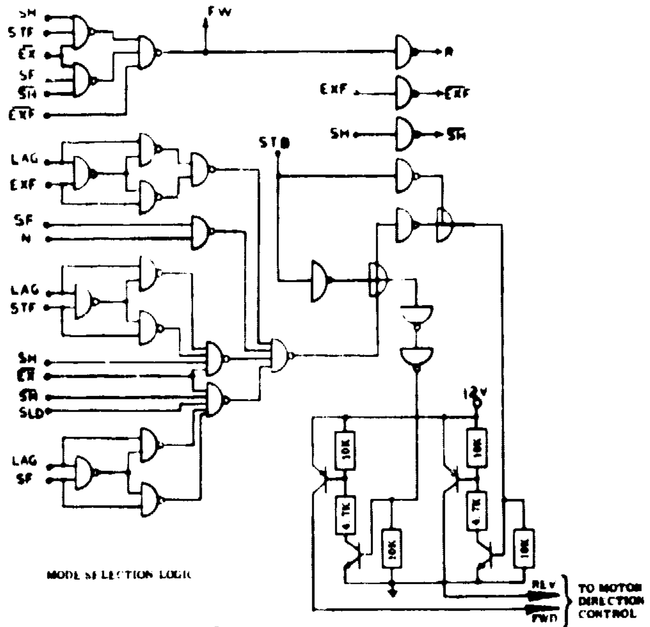


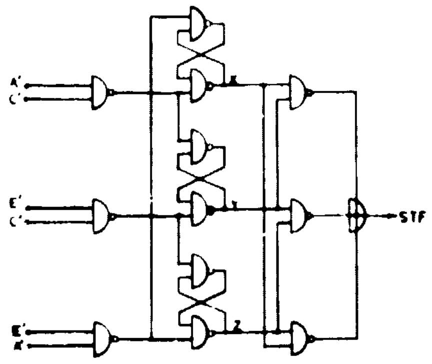
Figure 34. - Continued



MODE TRANSITION LOGIC



MODE SELECTION LOGIC



DIRECTION LOGIC

Figure 34. - Continued

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2. Yates, W. W. et al, Second Quarterly Report for *An Advanced Brushless D-C Torque Motor*, NASA contract report NAS 5-10263, Report No. 66.69E.

GLOSSARY OF LOGIC SIGNAL SYMBOLS

A',B',C', D',E',F' -- Signals corresponding to magnetic sensor output voltages. E.g. A'=1 when A>D, B'=1 when B>E, etc.

EL -- Error limit signal. EL=1 when |BUS-RAMP| approaches the maximum value (8.5 volts).

ER -- Error signal. ER=1 when |BUS-RAMP|>2 volts.

EX -- Any external command signal.

EXF -- External command for forward drive.

EXR -- External command for reverse drive.

FW -- Forward command for all speed-limited modes of operation.

FW' -- A conditional forward command. FW' = FW except at the beginning of acceleration in the reorientation mode.

GO1, GO2 -- The signal to transfer information into memory, GO1 = GO2.

LAG -- A signal indicating that the motor position lags its command.

LT -- A signal used in the transition from dark to light operation -- used to simulate the standby condition.

N -- The normal tracking mode.

P -- The derived pulse used in dark-period control.

R -- $\overline{FW}$

R' -- $\overline{FW'}$

RS -- A direct reset signal used to set RAMP to minimum.

T -- Signal indicating that RAMP changes from maximum to minimum. T = 1 when the ramp counter is at count of zero.

T' -- A pulse which occurs when T turns on, or when EL goes high.

SF -- A forward command from the solar sensors.

SH -- The shadow signal.

SL -- A solar sensor signal indicating a larger than normal tracking error which commands speed-limited control.

SL1 -- SL or STANDBY

SLD -- A signal indicating that SL1 is on or has been on and that no change has been indicated in the direction signal SF from the solar sensors.

STB -- Standby or simulated standby.

STF -- A stored signal indicating a history of forward rotation.