A STEPPING MOTOR DIRVE CIRCUIT FOR SPACE APPLICATIONS

by

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ABSTRACT

This paper describes a new magnetic core circuit that is used to supply power in the proper phase and time sequence to a bi-directional stepping motor. This circuit will power a standard voltage stepping motor from a non-standard voltage power supply and includes a means for maintaining a constant energy pulse excitation over a wide range of d-c power supply input voltage, a means for supplying power to the winding of the motor on pairs of isolated conductors and a means for conductively isolating the low level logic circuits from the high level power circuits.

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INTRODUCTION

This paper describes an electronic circuit that generates the correct voltage polarities and amplitudes in the proper sequence for operating a bi-directional stepping motor from a d-c power source. The basic design can be used to drive a wide range of stepping motors simply by choosing the proper turns ratio in the output transformers and providing adequate base current drive to a set of switching transistors. The particular circuit described here operates from a d-c power source of 16 to 22 volts to drive a 28 volt size 8, four-phase motor, requiring a power of 1.76 watts at a maximum stepping rate of 100 steps per second. Three signal inputs are required to control the stepping rate and the direction of rotation.

DESIGN GOALS

Below is a list of the general design requirements that had to be met in this device:

(1) Stand-by power should be less than 10 milliwatts.

(2) In order to obtain the maximum efficiency, all motor windings must be powered simultaneously.

(3) The motor must immediately make one step in the opposite direction upon the application of the first stepping pulse following a change in direction input.

(4) The unit must be capable of powering a standard 28-volt motor from a 16 to 22 volt power source.

(5) The unit must not spuriously respond to 5-volt peak-to-peak noise pulses on the 19-volt (nominal voltage) input line and 1 volt peak-to-peak noise pulses on the 5-volt input line.

(6) Any high frequency noise current pulses fed back on the d-c power lines must be less than 1 milliampere peak-to-peak.

ISOLATION REQUIREMENTS:

Considerable emphasis has been placed on the need to have good noise immunity from noise on the power lines connected to this device. This requirement is necessary because the motor driven by this circuit will be used in an earth-orbiting satellite experiment in which many devices are to be operated from the same power bus and there is no assurance that there will not be large noise pulses on this bus. Also, there will be some modes of operation in which the motor will be stepped to a particular position and be required to remain in this position for many orbits of the satellite, without responding to noise pulses. The emphasis on noise immunity is also a result of experience with past circuit designs in which all the tests conducted before satellite launch indicated proper operation, only to find that in orbit the equipment occasionally responded to noise pulses. Because of these considerations, it was decided to conductively isolate the low-level logic circuits from the high-level power circuits in this unit; that is, eliminate the common power connection between the high-and low-level circuits. This was accomplished by deriving a 50 KHz low level square wave on an isolated-common power supply and then, by transformer coupling, amplifying this signal to a level suitable for driving the motor.

PULSE REQUIREMENTS FOR MOTOR

In order to excite all of the motor windings at each step, a bi-directional current must be provided to each winding in the proper sequence. If one winding is labelled A and the other winding B, and if a current pulse in one direction is labelled I_A or I_B, and a current pulse in the other direction is labelled $\overline{I_A}$ or $\overline{I_B}$, then the motor will rotate in one direction with the following repeated sequence of pulses: $I_A\overline{I_B}$, I_AI_B, $\overline{I_A}I_B$, $\overline{I_A}\,\overline{I_B}$. The direction of rotation is reversed by driving the windings with the current direction that had just been applied to place the motor in the present position. In other words, if the motor has just moved to the rest position after the application of I_AI_B, it will return to the previous position if currents I_AI_B are applied or it will step to the next position in the same direction if currents $\overline{I_A}\,\overline{I_B}$ are applied.

PHASE RECOGNITION AND CONTROL CIRCUIT

Figure 1 is a diagram of a core array with four non-linear and four linear cores that are used to sense and store the direction of current applied to the windings of the motor in a first cycle of operation, and provide the signals necessary to control the direction of currents required to step the motor in a second cycle of operation. The non-linear cores are labelled AB, $\bar{A}B$, $\overline{AB}$, and $A\bar{B}$, where a letter without a bar over it represents one current direction and a letter with a bar over it represents the other current direction. The linear cores are labelled A, $\bar{A}$, B and $\bar{B}$, where the bar and non-bar represents the set and reset flip-flop inputs respectively.

The non-linear cores are wound with two sets of series-connected four-turn windings (one set for each motor winding); a series-connected set of five-turn windings, for reading out the cores; and two sets of 30-turn output windings on each core, for producing a signal for switching two linear cores. Each linear core has two sets of four-turn input windings and a 42-turn output winding. A set of diodes is connected in series with each set of four output lines from the non-linear cores and a capacitor is connected in series with each of these sets. The 30-turn windings return through an inductor back to the two capacitors. One of each of two bias resistors is connected to the common cathode connection of each set of four diodes and the other end of each resistor is connected to each side of a direction control flip-flop, not shown on this diagram.

The number of turns on the phase A and phase B windings were chosen to just switch all of the flux in one core with the sum of the two motor winding currents. In this instance, each winding requires 30 milliamperes for a total of 240 milliampere-turns on the selected core. This is enough excitation to switch the core in about five microseconds.

The circuit shown in Figure 1 operates in the following way: First assume that the motor had been driven on a preceding step and one of the four current combinations was applied to the A and B windings. Assume that both currents were from left to right in the diagram of Figure 1. Under these conditions there will be a net excitation of 240 milliampere-turns into the non-dot ends of the windings on core AB, a net excitation of zero on cores $\overline{A}B$ and $A\overline{B}$, and a net excitation of 240 milliampere-turns into the dot ends of the windings on core $\overline{A}\overline{B}$. This particular current combination will only switch core AB to the proper remanent state to produce an output signal when a read out pulse is applied to the five-turn windings. The flux in the other cores will remain in the same remanent state as that produced by the five-turn read out winding. If the same reasoning is applied to the other three possible current combinations, it can be seen that the flux in only one core will switch for each current combination, effectively storing the motor current polarity information in this core. The selected core will remain in this state of information storage indefinitely, ready to be switched when the next read out pulse occurs. When a read out pulse appears on the series connected 5-turn windings, the previously selected core will switch and a pulse will be produced on the 30-turn output windings of this core. This pulse will cause current to flow on one of the two output lines. The particular line that is selected will depend on the state of the direction flip flop at the time of read out. If the core AB switched, there will be a choice of producing pulse outputs on linear cores $\overline{A}$ and B or A and $\overline{B}$, depending on the desired direction of motor rotation. A similar inspection of the outputs of each non-linear core will show that a signal will be produced on the proper pair of linear cores to place the voltage control flip-flops A and B in the proper states to rotate the motor one more step in either direction.

The choke L_1 serves the purpose of limiting the current that flows when the noise flux switches in the three unselected non-linear cores during the readout interval. The value of this inductor was chosen to be just large enough to present a high impedance load to all of the unselected cores during the noise flux switching interval but small enough not to affect the switching of the total flux in the selected core. This results in a greatly reduced amplitude of noise voltage produced on the output of the linear cores. The signal and noise pulse outputs from a linear core measured 6 volts, 1.0 microsecond and 0.5 volt, 0.4 microsecond respectively with the choke. The noise voltage was 2 volts, 0.5 microseconds without the choke.

The four non-linear cores are commercially available .000125 inch thick mo-permalloy tape-wound stainless steel bobbin toroid cores measuring .2 inches O.D and .094 inches I.D. and .105 inches high, exhibiting a total flux ($-B_r$ to $+B_m$) of 22 Maxwells with a noise flux of less than 4% of this value. All of the flux in this core will switch in 10 microseconds with an excitation of 150 milliampere turns. The four linear cores are commercially available

.0005 inch thick mo-permalloy tape-wound stainless-steel bobbin toroid cores measuring o.2 inches O.D., .094 inches I.D. and .105 inches high, exhibiting a total noise flux (B_r to B_m) of 20 Maxwells. All of the flux in this core will switch in 1.0 microsecond with an excitation of 240 milliampere turns.

DESCRIPTION OF BLOCK DIAGRAM

Figure 2 is a block diagram of the complete circuit. There are two voltage-polarity-control flip flops A and B, one for each motor winding; a motor-direction flip flop C; a motor-drive pulse-width control flip flop D; a 50 kHz oscillator, controlled by gate number 1 on flip flop D; four "and" gates with inputs from the voltage polarity control flip flops and flip flop D (through gate number 1); four amplifiers and rectifiers, two providing a positive voltage and two providing a negative voltage; a feedback voltage E_{fb}, applied to an RC time constant; a non-linear core array connected to the two motor windings and to amplifier number 1 and having outputs to a linear core array; a linear core array with outputs to flip flops A and B controlled by flip flop C; a five microsecond blocking oscillator.

The circuit operates in the following way: When power is applied flip flops A, B, and C will come up in either state. Direction flip flop C must be pulsed to obtain a given rotation direction. The first pulse applied to the motor stepping rate input will trigger the blocking oscillator and drive amplifier number 1 for five microseconds. The output of amplifier number 1 switches one of the cores in the non-linear core array that was previously switched by the pulse currents through the motor windings during the preceding step of the motor. Switching this core produces an output on two of the four linear cores. (The pair selected depends on the state of flip flop C) and places flip flops A and B into the required states to produce the proper voltage polarities to the motor windings to obtain the desired rotation direction. At the end of five microseconds motor drive pulse width control flip flop D is set. This causes gate number 1 to close which starts the 50 kHz oscillator and applies an input signal to amplifiers 2, 3, 4, and 5, and furnishes a d-c bias to the four "and" gates connected to these amplifiers. Two of the four amplifiers are gated on by the combined gate number 1 and flip flop A and B inputs. The output of these active amplifiers is amplified and then rectified in the power amplifier-rectifier stages. The power amplifier-rectifier drives a transistor switch that applies the voltage of a given polarity to the motor. These two simultaneous excitations to the motor causes it to rotate and at the same time, the current through the two windings switches one of the four non-linear cores in the core array which stores the information that identifies which one of the four possible pulse combinations that has just been applied to the motor. This information is used to switch two of the four linear cores in another core array to set up flip flops A and B when the cycle is repeated on the next motor step. The particular pair of linear cores that switch on the next step depends on the state of motor direction flip flop C at that time.

The duration of the motor excitation pulse depends primarily on the time constant of the RC time constant circuit, the magnitude of the reference voltage (E ref.) and the magnitude of the 16 to 22 volt input. The rectifiers connected to the four amplifier-rectifiers in Figure 2 are connected to windings on transformers in these amplifiers. As the 16 to 22 volt input increases, voltage E_{fb} also increases. This increase causes the capacitor in the RC time constant circuit to charge to the comparison voltage more quickly and results in a shortening of the duration of the motor excitation pulse. The circuit is initially set up so that the motor steps properly with the input voltage at 16 volts. Then, as this voltage increases, the motor drive pulse width decreases linearly to provide a means of maintaining a constant energy input to the motor. The clamp connected to the RC time constant returns the voltage across the capacitor to zero at the end of the drive pulse. This clamp is necessary in order to establish the same reference voltage at the beginning of each time interval, regardless of the stepping rate.

DESCRIPTION OF SCHEMATIC DIAGRAM

Figure 3 is a schematic diagram of the complete circuit and Figure 4 is a diagram of complimentary-symmetry flip flop marked WM 555Q in Figure 3. The logic and flip-flop circuits are intended to be operated from a 5-volt isolated power supply and the power amplifiers from a noisy 16 to 22 volt satellite power supply. In order to maintain the isolation of the 5 volt supply, it would be desirable to trigger the blocking oscillator and the set and reset inputs to the motor direction control flip flop through isolation transformers, especially if these signals must be conducted over a long distance. This circuit will be used in a spectrometer in the OSO-H satellite and the three input signals will be supplied on isolated shielded twisted pair lines from non-linear-core ground command logic circuits located in another part of the experiment.

The "and" gates, controlling amplifiers 2, 3, 4, and 5, are made up of transisotrs Q10, Q13, Q16, and Q19 with emitters connected together and returned in common through gate number 1 transistor Q3. This connection places the common emitter return of the amplifier transistors, such as transistors Q8 and Q9, through the collector-to-emitter resistance of two transistors in series. The 50 kHz signal applied to the bases of the amplifier transistors will not appear across the transformer primary unless both of the series-connected gate transistors are turned on.

The 50 kHz oscillator common return is also connected to the collector of gate transistor Q3. This connection allows power required by the oscillator gates and amplifiers to be consumed only when it is needed during the duration of the motor pulse.

Amplifier transformers T10, T11, T12, and T13 serve to conductively isolate the 5-volt power supply common from the 19 volt common and to impedance match the 50 kHz signal from the first amplifier stage to the power amplifier.

The secondary winding is segment-wound from the primary winding in order to minimize the capacitive coupling between the two windings. This method of construction eliminated most of the stray coupling, but there was still a very small differentiated signal present on the secondary even with the gate transistor off. This signal was caused by the fast rise and fall time of the 50 kHz square wave appearing across the primary and coupling through the small remaining primary-to-secondary capacitance. This signal was eliminated by lengthening the rise and fall time of the 50 kHz square wave with capacitors C15, C16, C17, and C18 across the primary windings.

One step of the motor will be described by tracing the sequence of events from the application of a motor stepping rate input pulse to the termination of the motor pulse width. A pulse applied to the blocking oscillator trigger input will cause transistor Q1 (Figure 3) to conduct for a period of five microseconds until the core of transformer T1 saturates. This applies a positive 5-volt signal to the base of transistor Q2 which causes it to turn on and connect terminal 16 of the core array module to the common return of the 5-volt supply. If we assume that the motor had just been pulsed on the preceding step with currents of the direction shown by the arrows on the series-connected four-turn windings, the flux in the core of transformer T 7 ($A\overline{B}$) will have been reset. When terminal 16 of the core array module is connected to the 5-volt common through transistor Q2, a current will flow from the positive side of capacitor C10, through the 5-turn windings and back to the common return. The flux in the core of transformer T7 will switch and a voltage will appear across the two 30-turn secondary windings of T7. One of the two series-connected four-turn windings on linear cores A, $\overline{A}$, B or $\overline{B}$, will be pulsed by this voltage, depending on the desired motor direction. If we assume flip flop C is in such a state to reverse-bias diode D26, then diode D25 will be zero biased and a pulse current will flow in the four-turn winding of linear cores $\overline{A}$ and $\overline{B}$ (T4 and T2). This current will cause a voltage to be produced on the 42-turn windings of T2 and T4 and flip flops A and B will be reset. This causes $\overline{A}$ and $\overline{B}$ of flip flops A and B to become positive and gate transistors Q13 and Q19 turn on. All of this occurs during the first one microsecond of the five microsecond blocking oscillator pulse. At the end of five microseconds the overshoot of the blocking oscillator causes flip flop D to be reset and $\overline{D}$ becomes positive. Gate transistor Q3 conducts and connects the common return (pin 1) of the 50 kHz oscillator module and the emitters of gate transistors Q10, Q13, Q16, and Q19 to the power supply common. This applies a 50 kHz signal to the inputs of amplifiers 2, 3, 4 and 5 since only amplifiers 3 and 5 will respond, because transistors Q11, Q12, Q17 and Q18 are the only ones returned to the power supply common. Amplifiers 3 and 5 drive amplifier-rectifier circuits 2 and 4, and a 50 kHz square wave voltage will appear on the secondaries of transformers T15 and T17. This voltage is rectified by diodes D9, D10, D17 and D18 to provide a negative d-c voltage to terminals 1 and 4 of motor windings A and B respectively. Diodes D11, D12, and D19 and D20 supply a negative voltage between the emitter and base of switches, Q29 and Q31 which turns these transistors on and connects the positive polarity from the center-tapped secondaries back to terminals 3 and 6 of motor windings A and B through the two sets of four-turn windings in the core array. This results in the application of the desired voltage polarity $\overline{AB}$ to both motor windings.

The 21-turn windings on transformers T15 and T17 (in this example) provide a nominal 10-volt square wave that is rectified, by diodes D21 and D22, and applied as a 10-volt d-c voltage across the RC circuit R23 and C11. The absolute value of this voltage will depend upon the value of the 16 and 22 volt d-c input voltage applied to the primary of transformers T15 and T17. Capacitor C11 charges through resistor R23 until the voltage across it rises to a value slightly larger than the base voltage (Eref) of transistor Q5. Transistor Q6 will begin to conduct when the voltage across C11 exceeds Eref, and transistor Q4 will turn on. This causes motor pulse width control flip flop D to be set which turns off gate transistor Q3 to stop the 50 kHz oscillator and terminate the motor excitation. A positive voltage is applied to the base of clamp transistor Q7, when flip flop D is set, discharging capacitor C11 in preparation for the next motor pulse. It can be seen that the time required for the voltage across capacitor C11 to reach the reference voltage will be a function of the voltage Efb, i.e., the higher this voltage, the shorter the time. This results in the application of a relatively constant energy per step to the motor even though the power supply voltage is varied. It is also obvious that the length of the pulse at a given power supply voltage may be adjusted by changing the value of the reference voltage applied to the base of transistor Q5. Diode

D1 is used for temperature compensation. This diode changes the reference voltage in the same direction and amount as rectifier diodes D21 and D22 change the feed back voltage with ambient temperature variations.

A frequency of 50 kHz was chosen for the oscillator in order to be able to use small size transformers and keep the weight and volume of the unit to a minimum. The core in transformers T10, T11, T12, and T13 is a ferrite toroid measuring .375 inches O.D., .188 inches I.D. and .125 inches thick. The core in transformers T14, T15, T16 and T17 is a 1/2 mil thick mo-permalloy tape on a stainless steel bobbin toroid measuring .320 inches O.D., .134 inches I.D. and .160 inches thick. A check of the efficiency of all of the circuits operating on the 16 to 22 volt power supply was performed by placing 910 ohm one watt resistors in place of the motor windings and simultaneously measuring the power dissipated in the resistors and the power furnished by the 16 to 22 volt power supply at a rate of 100 pulses per second. The ratio of peak power output to peak power input at a voltage of 19 volts was $\frac{3 \text{ watts}}{3.28 \text{ watts}}$ or an efficiency of 92%. The same measurement made at 16 and 22 volts showed an efficiency of better than 90% at each voltage.

ELECTRICAL AND MECHANICAL SPECIFICATIONS

The complete unit has the following specifications:

(1) Stand-by power requirements:

(a) 5 volt input: 7 milliwatts

(b) 19 volt input: 0 milliwatts

(2) Power input at a motor stepping rate of 100 steps per second:

(a) 5 volt input with 19 volts on the other power input: 50 milliwatts.

(b) 19 volt input: 1.273 watts

(3) Noise input tolerance: 50 volt in series with 19 volt common will not cause a false trigger.

(The noise immunity of the 5 volt input will depend on the isolation of the power supply and signal input).

(4) High frequency conducted noise on any power line from the unit: 1 ma

(5) Minimum amplitude input signals at $-20^{\circ}C$:

(a) Stepping rate input: -2.5 volts, 1 microsecond.

(b) Motor direction input: +2.0 volt, 1 microsecond.

(6) Input impedance:

(a) Stepping rate input: 10K ohms.

(b) Motor direction input: 10K ohms.

(7) The motor pulse width will change no more than 10% over the temperature range of minus 20 degrees C. to $+60^{\circ}$ C. when driving a motor at the same ambient temperature.

(8) Size: approximately 2 3/8" x 2 3/8" x 7/8"

(9) Weight: approximately 55 grams

(10) Vibration: 15 G, 5 to 2000 cps.

(11) Temperature: minus 20 degrees to plus 60 degrees Centigrade.

CONCLUSIONS:

The circuit described in this paper could be designed to control almost any stepping motor requiring an average power of the order of two watts; higher powers than this would require additional amplification of the 50 kHz square wave. The circuit could be changed to accommodate a wide range of d-c input or motor voltages; in our case it was convenient to be able to use a 28-volt motor. Motors with additional phases could be driven by changing the number of cores in the core array to include one non-linear core for each current combination. An eight-phase motor could be driven by adding two more power-amplifier-rectifier outputs, one additional flip flop, two more linear and four more non-linear cores. This would provide the necessary 8 combinations of currents to 3 motor windings.

Core circuits, similar to the ones used in this motor control, have proved quite reliable in space environments. If they are properly fabricated they are rugged and reliable. All of the multiple-core logic circuits that we fabricate are wound as a unit in such a way so as to eliminate all joints in the wire. As an example, transformer T6 (Figure 3) has two 30 turn secondary windings. The finish end of each of these windings is left long enough to wind four turns on two of the linear cores. In this way there are no joints in the wire except at the anode of diodes D23 and D24 at one end and the header terminal at the other end. All of the series-connected windings on cores T6, T7, T8 and T9 are also wound this way.

ACKNOWLEDGEMENTS

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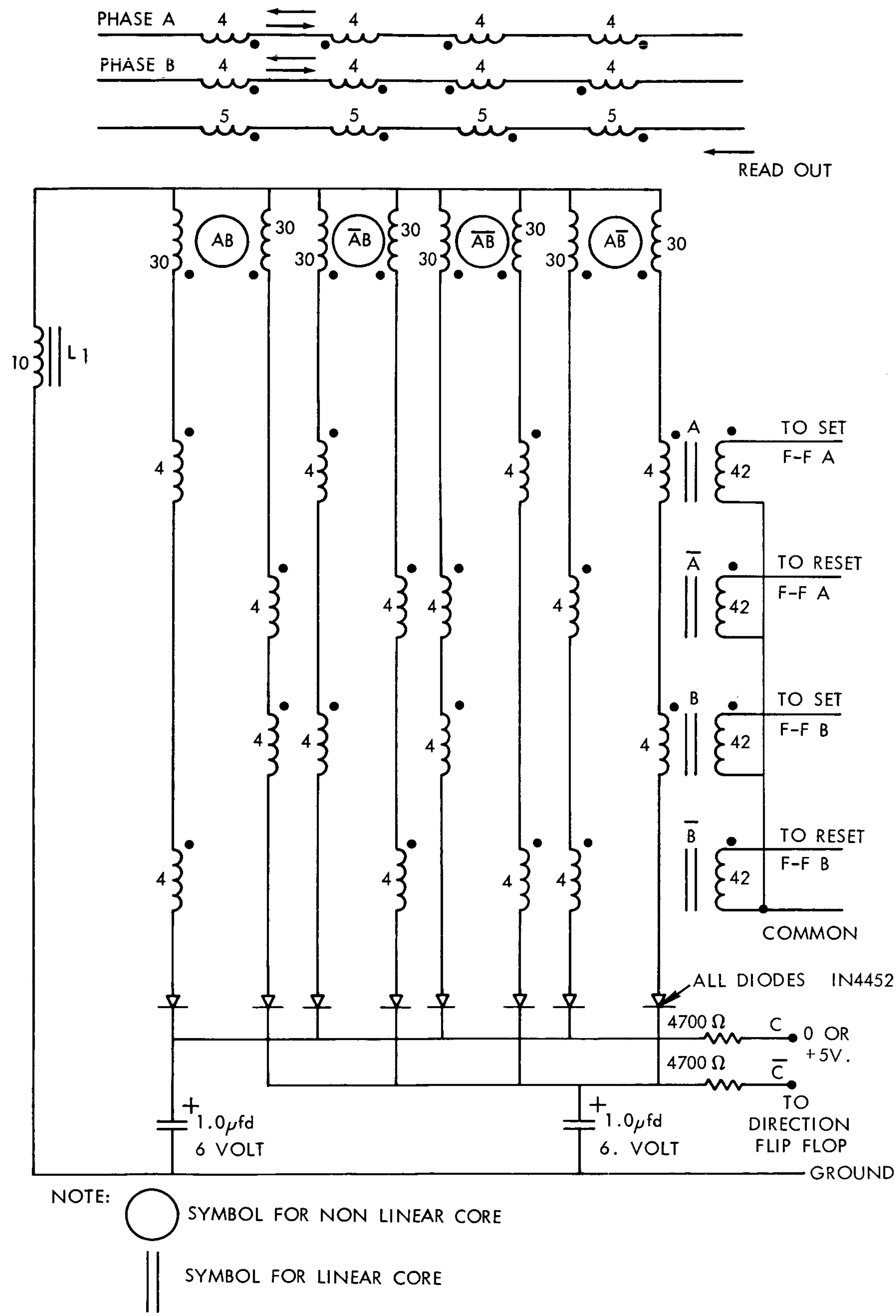
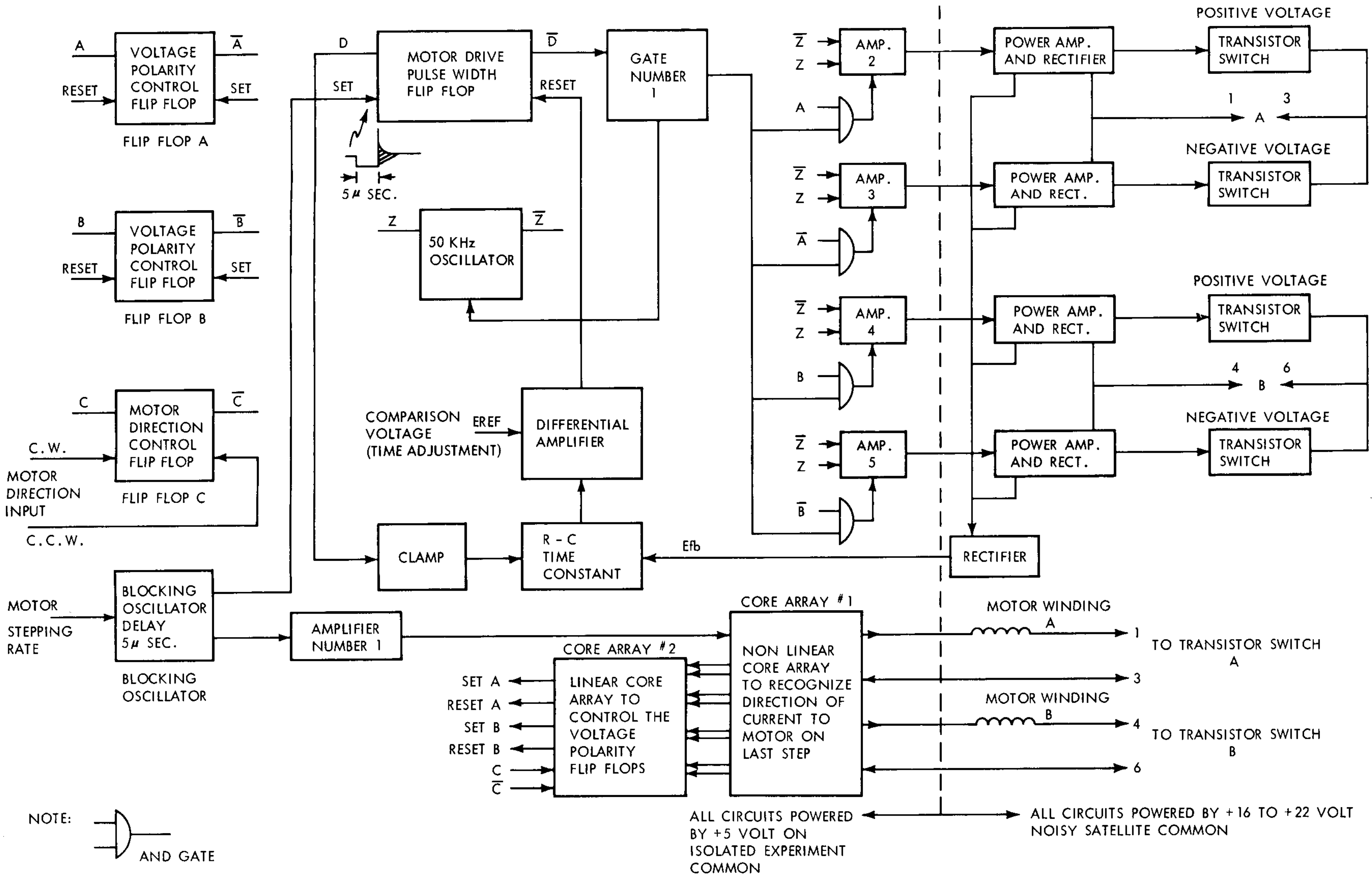


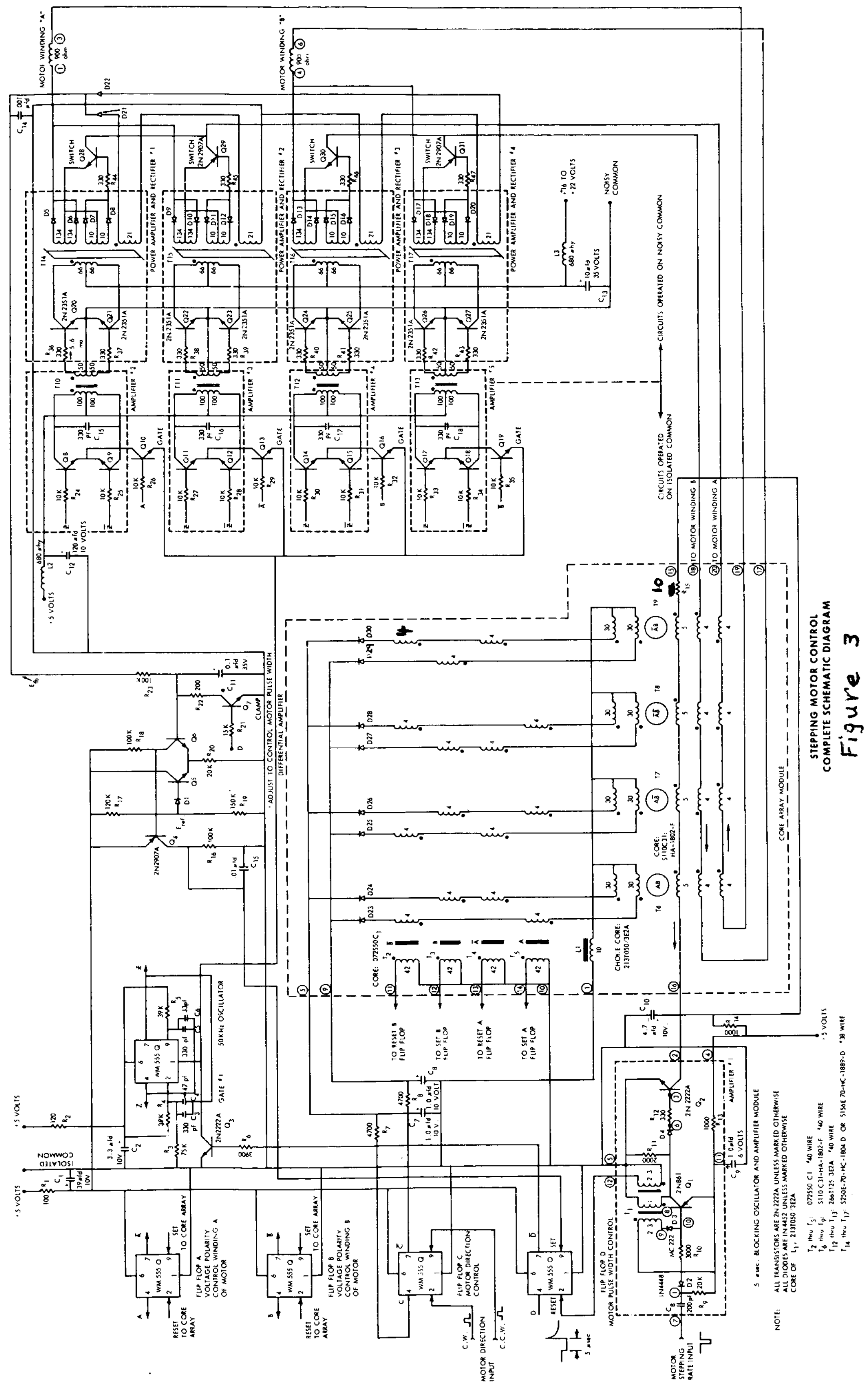
CORE ARRAY

Figure 1

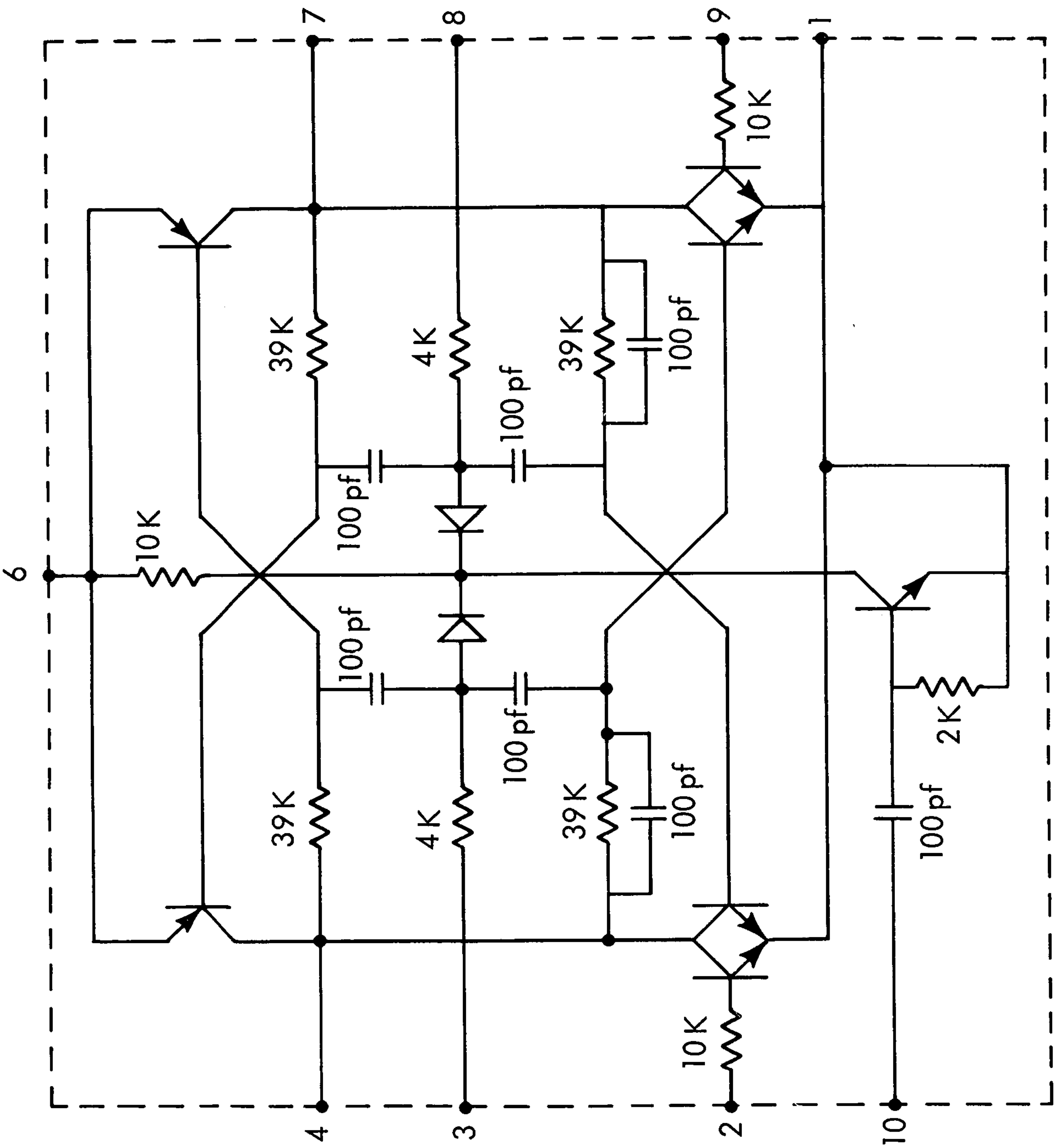


MOTOR CONTROL BLOCK DIAGRAM

Figure 2



STEPPING MOTOR CONTROL
COMPLETE SCHEMATIC DIAGRAM
Figure 3



WM555Q MODULE
Figure 4