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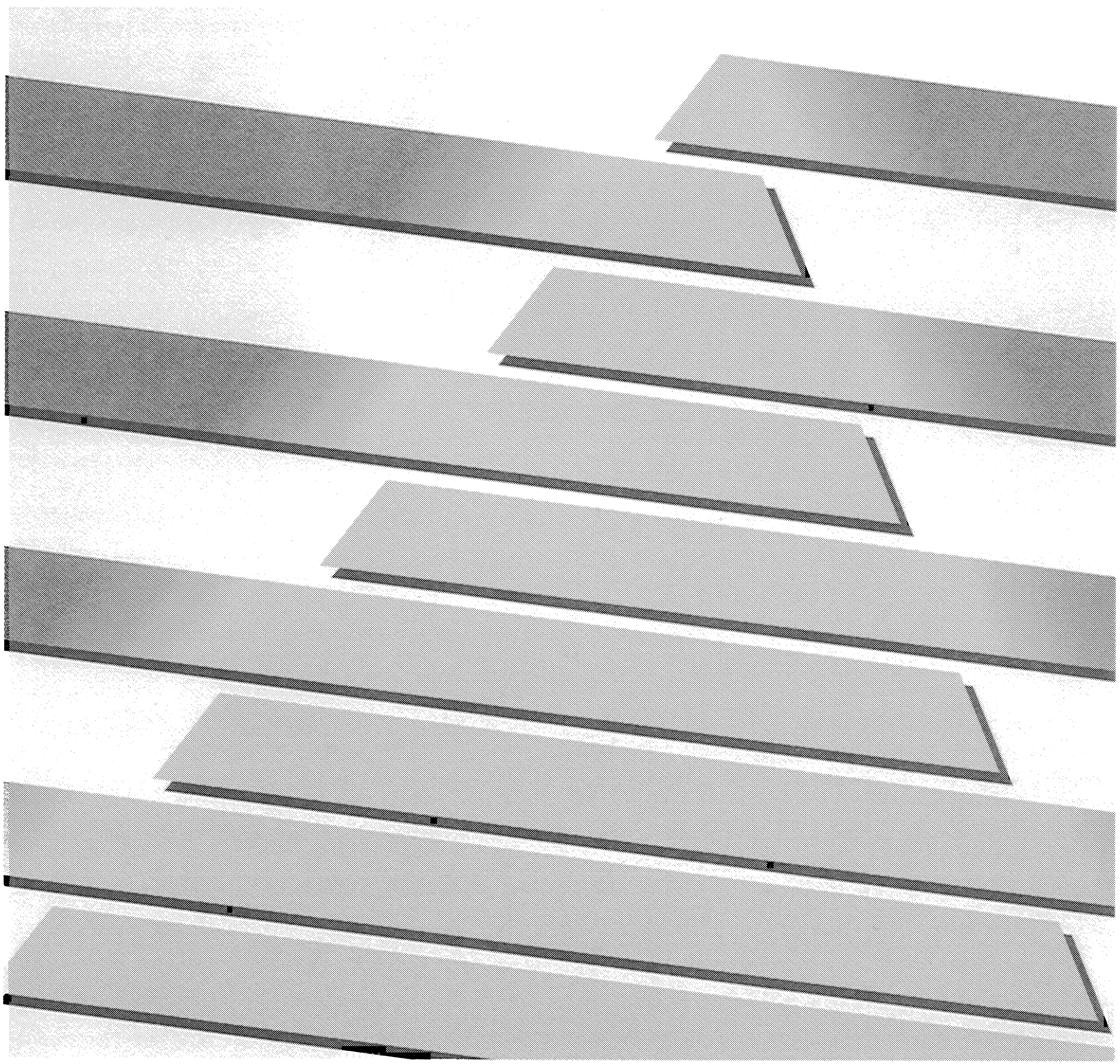
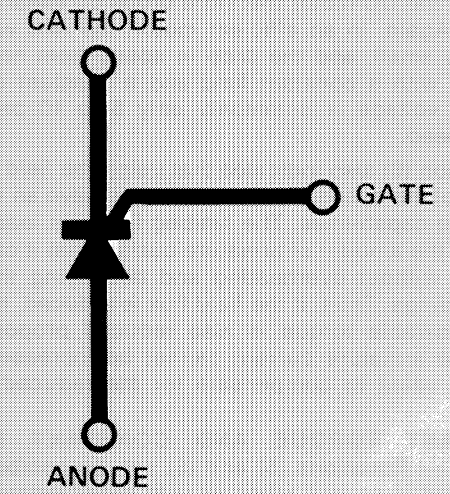
Thyristor Regulated DC Motor Control Theory



The theory, illustrations and diagrams expressed and presented in this manual are intended solely to aid in the understanding of the Thyristor Regulated Speed Drive. ALLEN-BRADLEY (DRIVES DIVISION) cannot assume responsibility or liability for any design or application based on this theory.



THYRISTOR — An efficient and relatively small solid state device, utilized in AC to DC conversion circuits, to provide control of motor output.

THYRISTOR DC MOTOR CONTROL — One of the earliest but still applicable adjustable speed DC drives uses an AC motor driving a DC generator to supply power to the DC motor. Such M-G set drives, known as Ward-Leonard systems, control the speed of the motor by varying the power supplied to the field of the generator and therefore the output voltage to the motor. Generator field power can be varied manually with rheostats or variable transformers, or automatically with regulators using vacuum tubes, thyratrons, magnetic amplifiers, or semiconductors as the controlling device. Where it is desirable to control the field of the motor as well, similar means are used. M-G set drives using automatic regulators have been used for nearly every type of application, and a high degree of sophistication has developed, making it possible to meet almost any desired level of precision or response.

One of the most advantageous characteristics of the M-G set drive is its inherent ability to regenerate. When a load tends to overdrive the motor, the motor becomes a generator and delivers power back through the M-G set and into the AC lines. This action is a requirement for such applications as unwind braking, hoists lowering a heavy load, or for controlled stopping of high inertia loads.

In spite of its many desirable characteristics, the M-G set drive has not met with complete acceptance, because of several disadvantages. Since the conversion of AC power to mechanical power involves three machines (the AC motor, the generator, and the DC motor), each of which is less than 100% efficient, the overall efficiency is rather low, even with very large drives. Maintenance is often a problem, since there are at least two sets of bearings and brushes to wear out. In addition, the M-G set is large, heavy, and often objectionably noisy.

Several methods of eliminating the M-G set have been successfully developed to take advantage of the capabilities of the DC motor, without suffering the problems of the M-G set. These drives are called "static" DC drives, since there are no moving parts to the power conversion equipment that controls and converts the AC power.

Static drives take several forms. Some of the earliest types utilized mercury pool tubes or thyratrons to provide controlled rectification of AC power. Magnetic amplifiers or saturable reactors in combination with ordinary rectifiers have also been widely used to control DC motors. Regeneration has been accomplished with gas tubes by providing two sets of controlled rectifiers, one for supplying power to the load, and the other for returning it to the line. With this approach, however, the cost is often unacceptable and a much greater degree of complexity is required. Regeneration with magnetic amplifier power supplies has never been commercially available.

More recently, silicon controlled rectifiers or thyristors have replaced the various types of gas tubes as the means of controlled conversion of line power to DC. The extremely high efficiency of these devices combined with their small physical size has resulted in enthusiastic acceptance and considerably more widespread use of DC drives.

BASIC DC SHUNT MOTOR PRINCIPLES — Since the DC shunt motor represents an electrical load to the thyristor which changes characteristics according to the nature of the mechanical load at the motor shaft, a basic knowledge of the DC motor is essential in understanding the techniques for properly controlling the thyristor.

For purposes of this discussion, a DC shunt machine can be considered to consist of two basic parts, a field which is stationary, and the armature, which rotates. The field may be either a permanent magnet or an electromagnet, and its purpose is to establish magnetic poles on the frame of the motor, which act in conjunction with magnetic poles of the armature to provide the forces that cause rotation of the armature. In contrast to an AC induction motor whose speed is dependent upon the number of poles, the speed of the DC motor is not related to the number of poles, but instead to the interaction of several mechanical and electrical variables.

The armature consists of a series of coils, which are connected externally to the motor through a commutator and brushes. The commutator serves to switch the power in successive coils as the armature rotates, so that the magnetic armature poles remain in the same location relative to the field poles.

As the armature turns in the magnetic field, the motion of its conductors generates a voltage. This is true whether the machine is delivering power to a mechanical load or if it is being driven by some external means. When operating as a motor, this generated voltage is commonly referred to as "counter EMF" since its polarity is in a direction that is counter to or opposing the applied voltage. When the machine is being driven by mechanical means, it acts as a DC generator, and in fact, a DC machine can be used as a generator equally as well as a motor.

The magnitude of the DC voltage generated in a DC machine is proportional to the speed of rotation, the amount of magnetic field flux, and a constant of proportionality. This can be shown mathematically as:

$$E_g = K_1 \phi S \quad (1)$$

where E_g is the generated voltage, K_1 is the constant of proportionality, ϕ is the field flux, and S is the speed.

The terminal voltage of the machine, however, will differ from the generated voltage if current is flowing in the armature circuit. This is because of the IR drop in the armature coils, and in the brushes. The equation of the terminal voltage in a DC machine acting as a motor becomes:

(2) $$E_t = E_g + I_aR_a$$

or

(3) $$E_t = K_1 \phi S + I_aR_a$$

where E_t is the terminal voltage, I_a is the armature current, and R_a is the armature circuit resistance, including lead and brush resistances.

If the machine is acting as a generator, the equation is the same except for the sign of the I_aR_a term.

(4) $$E_t = K_1 \phi S - I_aR_a$$

DC MOTOR SPEED — When equation (3) is rearranged to indicate the speed of a DC motor, it becomes:

(5) $$S = \frac{E_t}{K_1\phi} - \frac{I_aR_a}{K_1\phi}$$

An examination of this relationship is useful in understanding the effects of the several variables on the speed of the DC motor. If all other variables are held constant, it can be seen that the speed increases with an increase in terminal voltage, and decreases with a decrease in terminal voltage. In an efficiently designed machine, the I_aR_a voltage is only a small fraction of the rated terminal voltage, and it is reasonably correct to say that with a constant field strength (ϕ), the speed of a DC motor is directly proportional to the applied armature voltage.

By the same token, if the terminal voltage is held to a constant value, the speed of the motor is approximately inversely proportional to the strength of the field. It is apparent, therefore, that the speed of a DC motor can be readily controlled over a considerable range by varying the applied armature voltage, the strength of the field or both.

LOADING OF THE DC MOTOR — Mechanically loading the DC motor has an effect on its speed through the second term $\frac{I_aR_a}{K_1\phi}$ of equation (5). The torque delivered by the armature of a DC motor is proportional to the strength of the magnetic field poles and also the armature poles. Since the strength of the armature poles is dependent upon the amount of armature current, the expression for torque is:

(6) $$T = K_2 \phi I_a$$

where T is the torque, and K_2 is another proportionality constant. If equation (6) is rearranged to show the effects of loading on armature current, it becomes:

(7) $$I_a = \frac{T}{K_2\phi}$$

This means that with a constant field strength, the armature current is directly proportional to the torque loading of the motor shaft. If this information is interpreted along with equation (5) to indicate the effects of load on speed, it can be seen that the $\frac{I_aR_a}{K_1\phi}$ term increases in magnitude directly with load torque, and the speed of the DC motor therefore drops off linearly as it is loaded. Again, in an efficient motor, the I_aR_a voltage is relatively small, and the drop in speed from no load to full load with a constant field and a constant armature terminal voltage is commonly only 5 to 10 percent of rated speed.

Equation (6) also indicates that using the field strength to control the speed of a DC motor will have an effect on its torque capabilities. The limiting factor in loading of a motor is the amount of armature current that it can safely conduct without overheating and destroying the armature windings. Thus, if the field flux is reduced, the maximum allowable torque is also reduced proportionally, since the armature current cannot be increased above the safe value to compensate for the reduced flux.

CONSTANT TORQUE AND CONSTANT HORSEPOWER — Equations (5) and (6) can be combined and rearranged in several other ways to show various effects of changing conditions, but the complete range of operation of a DC motor can be summarized by referring to two basic regions of operation known as "constant torque" and "constant horsepower."

The terms constant torque and constant horsepower are often misinterpreted to mean that the load exhibits these characteristics, and that, for example, a motor operating in its constant torque mode will necessarily deliver to the load a fixed value of torque. The correct interpretation is related to the **maximum ability** of the motor to deliver torque or horsepower to its load, as governed by the current ratings of the armature and field windings. In a given mode of operation, the load may actually vary from zero to this maximum value. The torque produced by the motor, within its rating, is dictated by the load requirement.

It was stated earlier that the speed of a DC motor can be varied by controlling either the applied armature voltage, the field strength, or both. The method used determines whether the motor is capable of constant torque or constant horsepower output.

For maximum torque, equation (6) indicates that maximum field flux (ϕ) is required. If the field windings are operated at full rated current, this condition is met. The speed of the motor can then be controlled by varying the applied armature voltage from zero to its rated value. At rated armature voltage and rated field current, the motor operates at a speed known as "base speed." At base speed and below, the maximum operating torque is a constant value, since it is limited only by the maximum safe armature and field currents. This area of operation is thus known as the constant torque range of speed control. In a permanent magnet field motor, this is the only range of operation available. Since horsepower is a function of both speed and torque, the available horsepower in this range is proportional to speed.

If it is desired to operate the motor above base speed, it becomes necessary to weaken the field, since further increases in armature voltage are not permitted by the maximum ratings of the motor. Equation (5) shows that speed can indeed be increased by reducing field flux, but equation (6) indicates that the torque capabilities will suffer by the amount of field flux reduction.

Thus, an increase in speed by control of field strength is accompanied by a proportionate reduction in the maximum torque, resulting in a range of constant horsepower operation. There are a number of types of loads that require reduced torque at higher speeds, and this method of control is useful in these cases.

THYRISTOR POWER CIRCUITS — Thyristor power circuits for supplying controlled DC to a motor can take several forms. For purposes of illustration, Figure 1 shows a single phase half-wave circuit which is often used for controlling small DC motors.

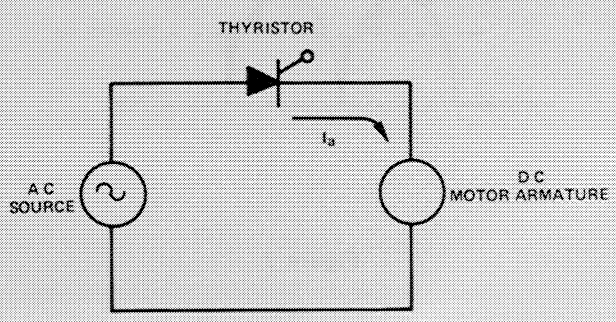


Figure 1

The waveform in Figure 2 illustrates the operation of the circuit of Figure 1 when the DC machine is acting as a motor. The thyristor can be gated on, only if its anode is positive with respect to its cathode. This occurs between point T_1 and T_2, and the shaded area represents the conduction time if the thyristor is gated at point A. Note that conduction continues past the point where the supply voltage becomes negative with respect to the counter EMF. This is a result of the inductive nature of the armature, which forces current to flow for a short additional time.

Since the conduction period is short compared to a complete electrical cycle, the ratio of peak to average current is very high, the form factor poor, and the motor utilization inefficient. For this reason, this circuit is normally used only with small motors, where derating to accommodate higher losses is not too costly.

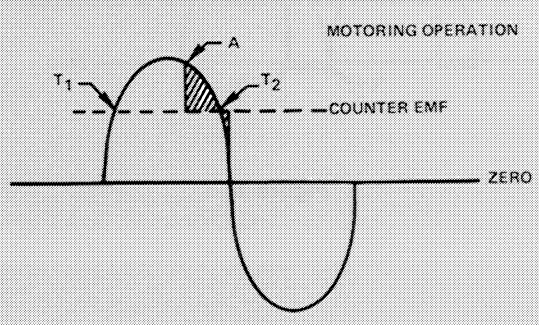


Figure 2

Figure 3 shows the waveform for the circuit of Figure 1 when the motor is regenerating. For regenerative operation, the motor counter EMF must be reversed in polarity, either by reversing the armature connections, reversing the direction of rotation, or reversing the direction of field current. As in Figure 2, the thyristor can be gated on anytime its anode is positive with respect to its cathode, from Time T_1 to T_2. In this case, however, this time interval represents a considerably larger part of the

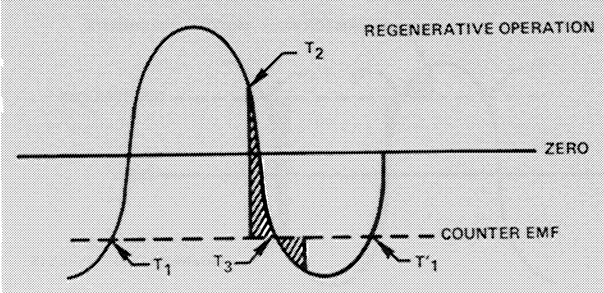


Figure 3

cycle and care must be taken to prevent excessive or destructive armature currents by gating too early in the cycle. Point T_2 (Figure 3), represents a realistic gating point, and the conduction period is shown shaded. Note again that conduction extends beyond T_3 because of the inductive nature of the armature circuit. If the armature current or inductance is sufficient to cause conduction to continue to time T'_1, the line voltage again becomes more positive than the counter EMF, and the thyristor never stops conducting. During the ensuing period, the large difference between line voltage and counter EMF causes extreme current to flow, and the condition is known as an "inversion fault." With large DC machines, this condition can be destructive to thyristors or even the motor, and means must be provided to prevent such faults or to protect the equipment if they occur.

Regeneration occurs between times T_2 and T_3 because, during this time the direction of the armature current opposes the instantaneous polarity of the AC line voltage.

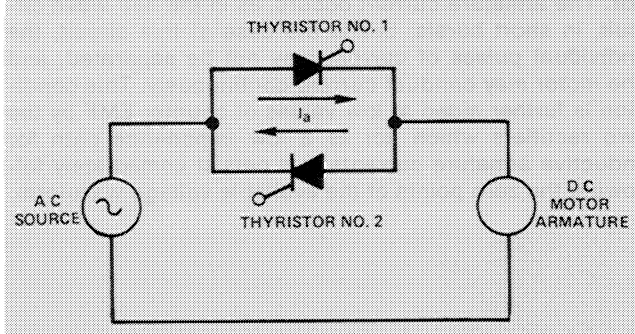


Figure 4

Figure 4 is a single phase, half-wave circuit in which two thyristors are used to accomplish motoring and regeneration without the need to reverse the armature voltage. An examination of the waveform in Figure 5 (on page 4) will indicate that it is merely a combination of the results of Figure 2 and Figure 3. For motoring, Thyristor No. 1 is gated on anytime between T_1 and T_2. For regenerating, Thyristor No. 2 is gated on anytime between T_2 and T'_1. Thyristor No. 2 is susceptible to inversion faults and must be protected accordingly.

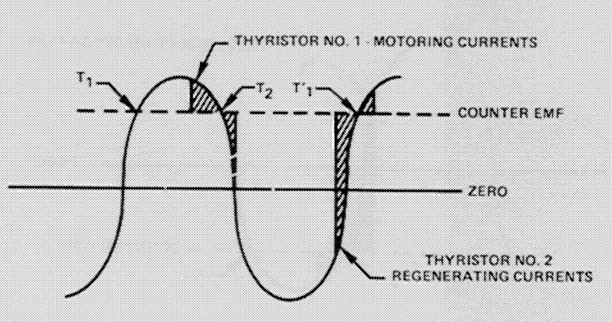


Figure 5

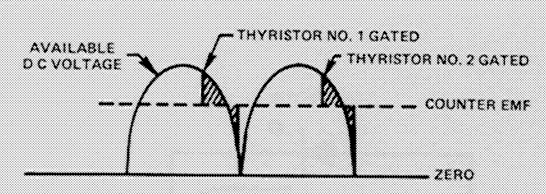


Figure 7

The maximum output voltage that can be obtained with any of these half-wave circuits depends to a great extent upon the armature circuit inductance, since at high voltages, the conduction time for motoring operation is very short, and a high inductance will prevent buildup of significant current. For regenerative operation, voltage must be limited to avoid inversion faults. With most standard DC motors up to 1/2 or 3/4 HP, the maximum practical DC output voltage is approximately 65 to 70 percent of the RMS line voltage. The reverse voltage rating of the thyristor should be peak AC voltage plus highest counter EMF.

To avoid the poor current form factor obtained with the half-wave circuit, three types of full-wave single phase power circuits may be used. Figure 6 is a bridge circuit consisting of 2 thyristors and 2 rectifiers that are commonly used for drives which do not require regenerative capabilities. Figure 7 shows the voltage relationships existing in this circuit.

Thyristors conduct on alternate half cycles, so the conditions of Figure 2 occur at twice line frequency, resulting in a more favorable armature current form factor. The armature current occurs, as in the half-wave circuit, in short bursts, but in the case of this circuit, the individual pulses of current may not be separated, and the motor may conduct current continuously. This condition is further aided at low values of counter EMF by the two rectifiers which act as a low impedance path for inductive armature currents that persist immediately following the zero points of the available voltage waveform.

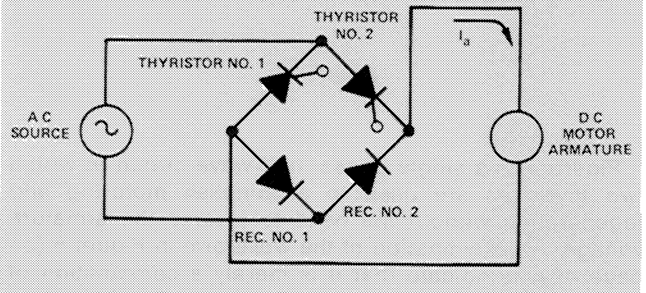


Figure 6

Figure 8 and Figure 9 illustrate the actual waveforms of armature voltage that are commonly seen both in discontinuous conduction and continuous conduction. Figure 8 shows discontinuous conduction.

At time T_1, the motor counter EMF is seen. When the thyristor gates on at T_2, the voltage at the armature follows the line voltage to T_3, at which time the rectifiers prevent reversal of the voltage beyond the value corresponding to their forward drop. At T_4, when armature current has dropped to zero, the armature voltage again becomes the counter EMF.

As armature current is increased, continuous conduction produces the waveform shown in Figure 9. No counter EMF is seen now, because the instantaneous voltage is either line voltage or the forward conductive voltage of the two rectifiers.

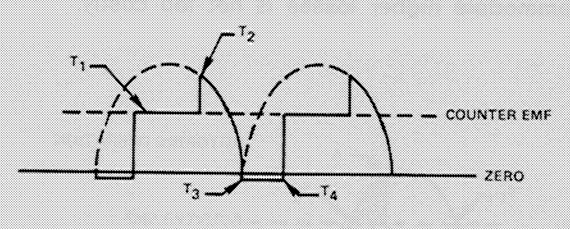


Figure 8

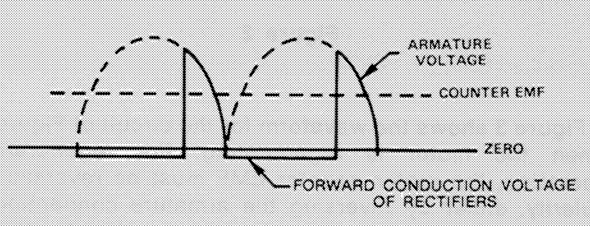


Figure 9

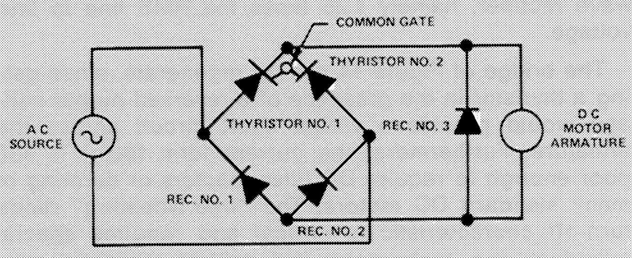


Figure 10

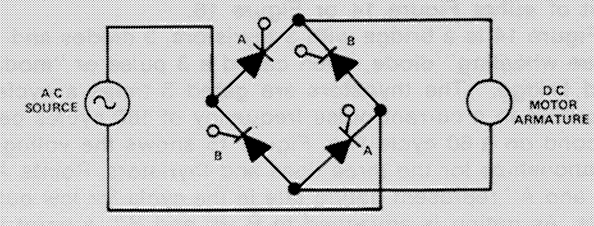


Figure 12

Figure 10 shows a modification of the same circuit with the thyristors in adjacent legs of the bridge on the DC side rather than the AC side. This connection is often used to take advantage of a common gate terminal to simplify the gating circuit. However, a third "free wheeling" rectifier must be added to prevent loss of control during continuous conduction, since once it is conducting, a thyristor acts as an ordinary rectifier unless its current is interrupted.

If control is lost, the circuit effectively becomes a half-wave uncontrolled supply with a "free wheeling" rectifier, as shown in Figure 11, and the output becomes ordinary half-wave rectified power. Rectifier No. 3 prevents this by providing an alternate path that allows the thyristor to regain blocking ability.

For applications requiring the ability to regenerate, the circuits shown in Figure 12 and Figure 13 may be used. Figure 12 is a four thyristor bridge in which opposite pairs of thyristors conduct on alternate half cycles. The operation is the same as with the half-wave circuit of Figure 11, only the conduction occurs on each half cycle. Inversion faults may be prevented very simply in this circuit by gating all thyristors just before the end of each half cycle of AC line voltage, so that conduction will switch to the pair of thyristors which is approaching its negative half cycle.

Figure 13 utilizes a center-tapped transformer to eliminate two of the thyristors of Figure 12. Output voltages are identical but voltage ratings of the thyristors must be twice as great.

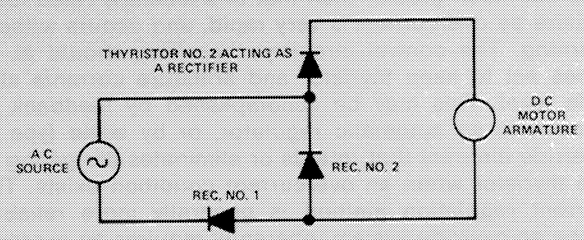


Figure 11

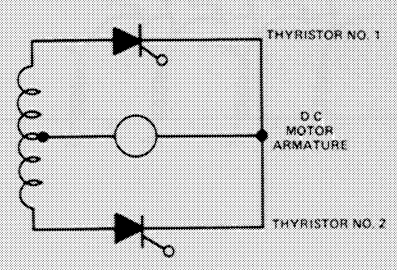


Figure 13

THREE PHASE POWER CIRCUITS — Three phase power circuits provide a better current form factor than single phase circuits, since they operate with pulse frequencies either 3 or 6 times the line frequency. Many variations are possible, but most equipment uses the circuit of either Figure 14 or Figure 16.

Figure 14 is a bridge with 3 thyristors, 3 diodes and a "free wheeling" diode, often called a 3 pulse or "modified bridge." The thyristors are gated 3 times a cycle, resulting in a current pulse frequency of 180 cycles per second on a 60 cycle line. Figure 15 shows the voltage relationships for the three lines and thyristors. Points A, A', and A" represent gating late in the cycle for low outputs. As gating is advanced to B, B' and B", a point is reached where current will naturally transfer from one diode to another, and gating before this point, at C, C' and C", for example, results in an output that is essentially full-wave. The maximum DC output voltage of this bridge is identical to that of an ordinary 3 phase full-wave rectifier, namely 1.35 times the RMS line to line voltage.

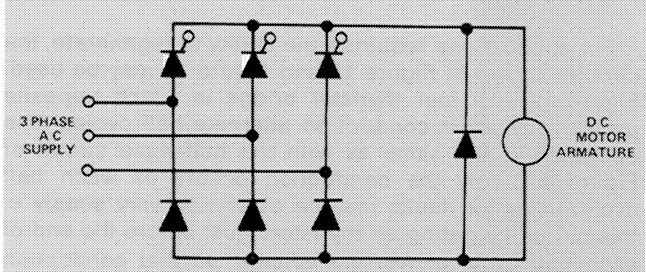


Figure 14

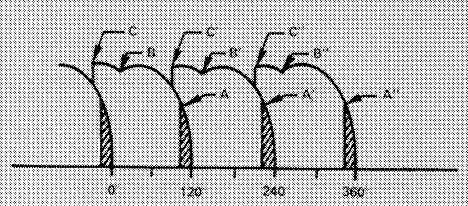


Figure 15

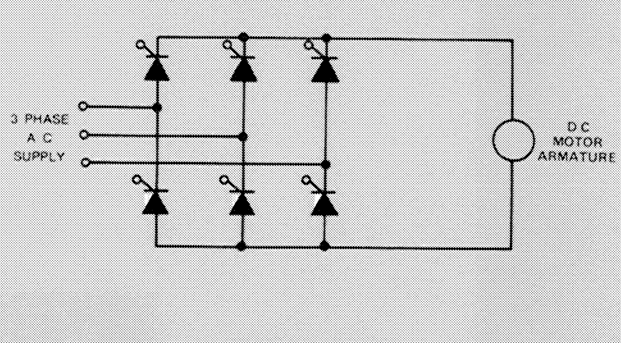


Figure 16

The bridge of Figure 14 cannot regenerate, since gating a thyristor in the presence of a reversed output voltage would provide a virtual short circuit across the armature. Furthermore, the current form factor is still poor enough to require DC filter reactors or derating of many standard DC motors. The "free wheeling" diode turn-off characteristic is critical and requires special manufacturing techniques and critical transient suppression circuitry. Therefore, the circuit of Figure 16 offers distinct reliability and performance advantages.

This circuit uses 6 thyristors and can be controlled either 3 or 6 times per cycle. Its operation is identical to that of Figure 1, Figure 12 and Figure 13 except on a three phase basis. The gating circuit must provide for gating two thyristors at a time, since each path for current contains 2 thyristors. Maximum output voltage, either for motoring or regenerating is 1.35 times the RMS line voltage. With this arrangement of thyristors and gating 6 times per cycle, standard DC motors may be utilized without derating.

THYRISTOR CONTROL CIRCUITRY — For safe and reliable operation of a DC drive powered by thyristors several factors must be considered. Probably the most significant of these is the control of peak armature currents by gating the thyristors at a safe part of the positive half of the AC cycle. Since the impedance of an armature is very low, particularly on large machines, gating a thyristor too early in the half cycle can produce extremely large currents. For example, with a motor rated at 100 amperes, it is not at all unusual to attain peak currents in excess of 1500 amperes if the thyristor is gated at the wrong time. These large currents may destroy or damage the thyristor, since its mass and thermal capacity is small and not much greater than that of a similarly rated fuse. Failure by overcurrent is very rapid, and occurs without warning. The control circuitry, therefore, should at all times act to keep thyristor and armature currents at a safe level. This may be accomplished by feedback of current to an automatic regulator, or by some type of override circuitry that retards or eliminates the gating of the thyristor when an overcurrent condition exists. The current regulation method is generally more reliable, since an override system inherently requires an overcurrent situation to exist before it acts to limit armature current.

Excessive voltages can also destroy the thyristors. Two types of excessive voltages are common. Short-duration transient voltages often are generated on the AC power lines by the switching of inductive loads. Because of the short duration, and therefore a rather limited energy content, these transients can be easily suppressed by RC filters or by selenium devices which act to absorb voltages above a predetermined magnitude. Some form of protection against these line transients is required, since even a relatively low energy voltage spike can burn out a thyristor.

When field weakening is used to operate the motor above base speed, and the field is suddenly strengthened, the counter EMF may rise to a value several times its rated voltage. This condition can cause the commutator to flash over and it can also apply too much voltage to the thyristors. Protective circuitry must be included in drive systems employing field weakening to prevent this type of overvoltage.

A third consideration for reliable thyristor performance is the method of gating the thyristor. It is desirable to "turn-on" the thyristor as rapidly and positively as possible, since during the transition between off and on, considerable instantaneous power is being dissipated by the thyristor. If the "turn-on" time is too long, a slow degradation of the thyristor may result, and it will ultimately fail. For this reason, the gating signal should be several times as large as the minimum required, and it should have a rise time of less than a microsecond. In general, pulse gating is preferred, since a pulse can have a substantial instantaneous power level, without a significant average power which might overheat the thyristor gate. The duration of the pulse must be sufficient to allow current to buildup to a value which will keep the thyristor conducting.

AUTOMATIC REGULATION OF MOTOR SPEED AND OUTPUT TORQUE — In a given drive system, the operator sets a reference voltage or current which corresponds to the operation he desires. The familiar speed potentiometer on speed regulated drives, or the tension adjustment on winder drives are examples of adjustable reference signals.

In response to the reference signal, the amplifier controls power to the machine, causing it to function in a manner that tends to produce the desired result. When the proper operating point has been reached, the feedback signal acts to prevent further changes.

The source of the feedback signal depends upon the type of regulator. In a Bulletin 1372 or Bulletin 1373 Regulated Speed Drive, a tachometer generator provides a voltage that is proportional to the actual speed of the output shaft. In a DC center winder, where armature current is regulated, a resistor in series with the armature produces a voltage proportional to armature current. In any case, the feedback signal must be proportional to the quantity being regulated. The term "transducer" is used to describe any device that converts the mechanical output of the drive to an electrical signal for feedback. Tach generators, strain gages, current transformers, and many other transducers have been successfully used for feedback signals with various drives.

The amplifier, the reference and the feedback are connected in such a way that the amplifier can compare the reference and feedback signals to determine the difference, if any, which exists between them. If a difference is present, the amplifier uses it as the input signal to cause the drive to respond in the direction that tends to reduce the error. This idea is vital to an understanding of regulator action, and can be stated simply as follows: **The complete regulator always attempts to make the reference and feedback signals equal.**

The use of feedback from the motor or external sensing devices makes it possible to obtain almost any desired degree of accuracy in controlling the speed, torque, or horsepower of the motor.

The simplest form of feedback for motor speed control utilizes the terminal voltage of the motor as feedback. Figure 17 shows such a system in block diagram form.

In this system, a reference signal is compared to two feedback signals to provide an electrical and physical analog of equation (5) Page 2. The left hand term of the equation, S, is set by the reference voltage adjustment. The two right hand terms are provided by feedback signals. The field flux is held at a constant value so that the terminal voltage and armature current will provide a speed feedback signal.

As in any regulator, the amplifier acts to keep its input as close to zero as possible. Feedback signal polarities are arranged so that if the speed reference level is greater than the feedback values, which are proportional to the sum of E_t and I_aR_a, thyristors will increase their output to increase motor speed. If the speed reference level is less than the feedback level, thyristors will decrease their output to allow the motor to slow down in an attempt to equalize reference and feedback signals. With a reasonably good amplifier, speed regulation with this system can be 2% to 5% of motor base speed.

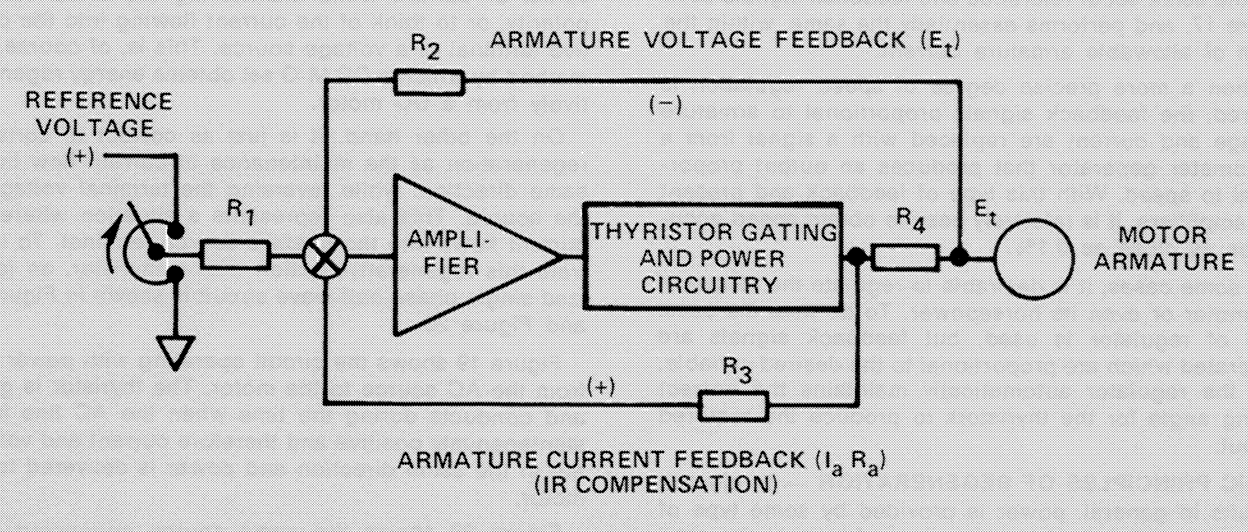


Figure 17

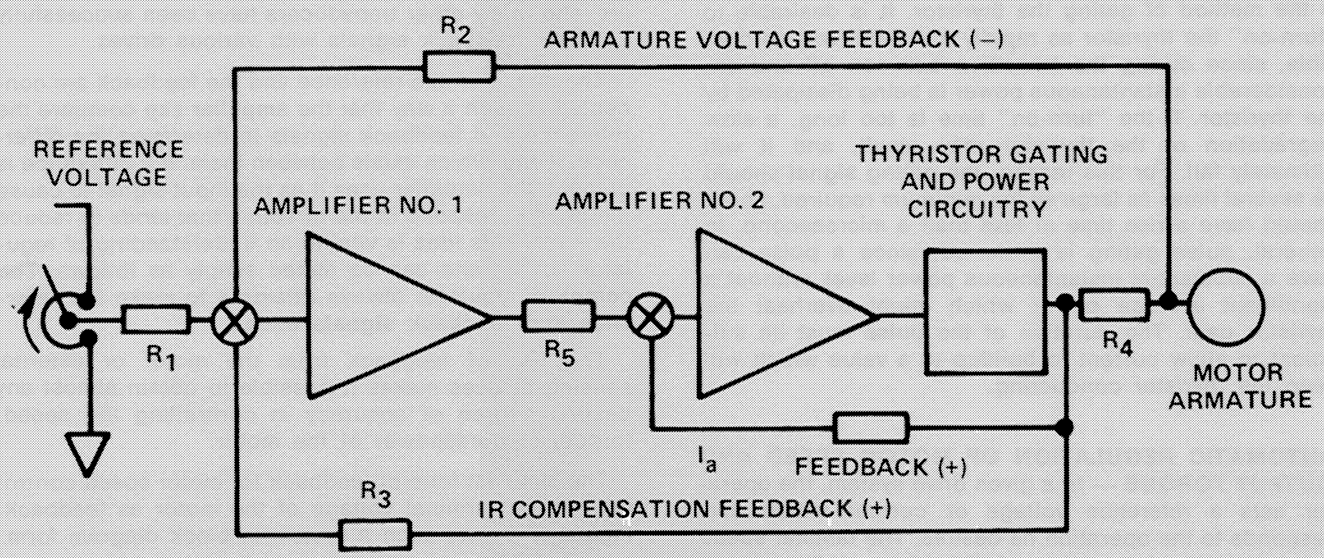


Figure 18

The circuitry of Figure 17 offers no protection against excessive current from the thyristors to the motor. Figure 18 shows a similar system which has what is known as an "inner loop" current regulator to overcome this deficiency in the system of Figure 17.

The "inner loop" consists of Amplifier No. 2, the thyristor gating and power circuit, and the feedback proportional to armature current. This inner loop acts as an accurate armature current regulator, and regulates the armature current to a value proportional to the output of Amplifier No. 1. Since the output of Amplifier No. 1 will saturate at some value, armature current is necessarily limited to the amount corresponding to this saturated output. If the response characteristics of the current regulator are adjusted so that a step-function input results in a current response without overshoot, then the armature current will not even transiently exceed the desired amount. This type of regulator has been successful in preventing failures of thyristors due to overcurrent.

The "outer loop" regulator includes Amplifier No. 1 and the same set of reference and feedback signals as in Figure 17, and performs essentially the same, within the limits of allowable armature current.

When a more precise degree of speed regulation is desired, the feedback signals proportional to armature voltage and current are replaced with a signal from a tachometer generator that produces an output proportional to speed. With this type of feedback and present day amplifiers, it is relatively easy to obtain speed accuracies as close as 0.1%.

In some cases, it is desirable to regulate the torque of the motor or even its horsepower. To do this, the same type of regulator is used, but feedback signals are generated which are proportional to the desired variable, and the regulator automatically maintains the correct gating angle for the thyristors to produce the required output.

BASIC PRINCIPLES OF REGENERATION — In electric circuits in general, power is provided by some type of source, and absorbed by some type of load. In the case of static DC drives, the AC lines are the source of power, and the DC motor the electrical load, which in turn supplies power to a mechanical load.

Certain types of mechanical loads, however, are capable of transiently or continuously becoming sources of power. For this type of load, it is desirable that the DC motor, and the control devices that connect it to the AC lines, become the load for this source of mechanical energy. The process by which the mechanical energy is converted into electrical energy as DC power and then returned to the line as AC power is known as regeneration or inversion.

Mathematically, the power flow in a DC electrical circuit can be represented by: $P = E_t \times I_a$; where P is the power, and E and I are the terminal voltage and current at the source. If P is positive, the power flow is from the source to the load; if P is negative, the power flow is from the load to the source, and is therefore regenerative.

For regeneration to occur, the polarity of either the voltage E_t or the current I_a can be reversed, providing the negative sign to P. There has been a tendency for the average person to consider regeneration as the reversal of current while maintaining the same voltage polarity, or to think of the current flowing into the positive terminal of a voltage source. This is, of course, the method by which a DC M-G set obtains energy regeneratively from a DC motor.

On the other hand, it is just as correct to consider regeneration as the maintenance of current flow in the same direction, while reversing the terminal voltage at the source. This also represents a situation where the current flows into the positive source terminal. To illustrate this regenerative action with a thyristor, an idealized single phase half-wave circuit is shown in Figure 19 and Figure 20.

Figure 19 shows the circuit operating with power flow from the AC source to the motor. The thyristor is gated and conducts during the time when the AC line is instantaneously positive and therefore current and voltage are in the same direction and power is delivered to the motor.

Figure 20 shows the same source connected to a generator with the polarity reversed. If the thyristor is gated so that it conducts during the negative cycle of the

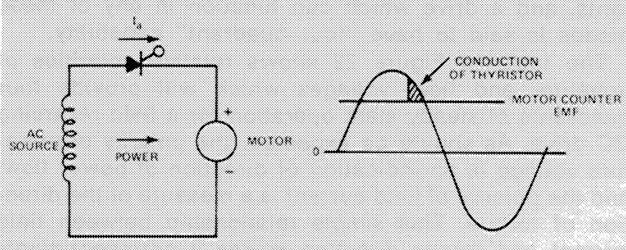


Figure 19

AC voltage wave, current and voltage will be in opposing directions, and power will flow from the generator to the AC source. Note that the thyristor is gated at a time when the AC line voltage is instantaneously more positive than the generated EMF, since a thyristor will conduct only when its anode is positive with respect to its cathode. With the generator voltage as shown, however, this action can occur in the negative half of the AC cycle, and the terminal voltage is therefore also negative. In Figure 20 it is important not to gate the thyristor early in the positive half cycle of the AC voltage, as extremely large currents may result, with power flow from the source to the generator for part of the AC cycle. With large DC machines as a load, this condition may be destructive.

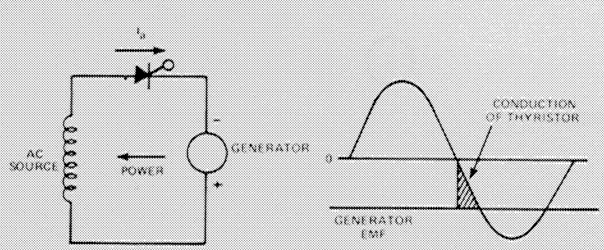


Figure 20

Figure 21 shows a conventional method of connecting the two circuits of Figure 19 and Figure 20 to a motor so that either motoring or regeneration can be obtained. Again, this circuit is shown simplified for ease of understanding. If motoring is desired, Thyristor No. 1 is gated for conduction of armature current during the positive half cycle of AC Source No. 1. If regeneration is desired, Thyristor No. 2 is gated so that it conducts during the negative half of AC Source No. 2. In this case, the motor terminal voltage does not change polarity, but direction of current flow through the motor reverses.

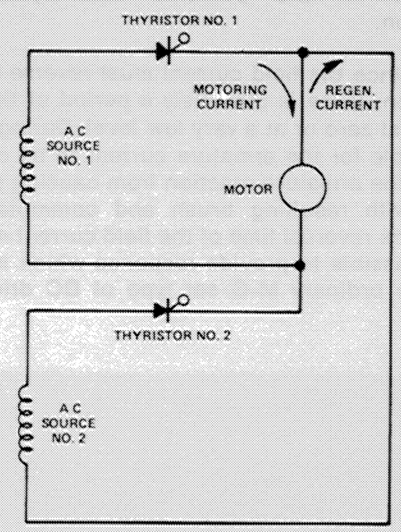


Figure 21

With the type of circuit shown in Figure 21, single or three phase bridges of thyristors are used for each of the controlled sources. Two problems may arise with this approach. First, twice as many thyristors are required to provide both motoring and regeneration as are required to allow one type of operation only. This inherently increases the cost of a drive which must operate in both modes. Secondly, if both thyristor sources conduct simultaneously, a line-to-line fault exists where power flows from one source to the other and the current may reach dangerous levels. Additional logic circuitry is required to prevent this condition or to protect circuit components in the event it happens. This additional circuitry adds further to the cost and also the complexity of the system.

The duplication of sources can be avoided if a single set of thyristors is used and the motor terminal voltage is reversed when regeneration is required. This could be accomplished, of course, by mechanical switching of the motor armature terminals, but a more convenient approach is to reverse the direction of current in the motor field. If this is done, the counter EMF generated by the armature reverses, and the conditions of Figure 20 exist.

FUNDAMENTAL REQUIREMENTS OF A FIELD REVERSING REGENERATIVE DC DRIVE — Certain basic requirements exist for the design of a successful thyristor drive that provides regeneration by field reversal. First, the power circuit must be of the type shown in Figure 16 since those shown in Figure 10 and Figure 14 present a virtual short circuit to a reversed voltage at the output terminals.

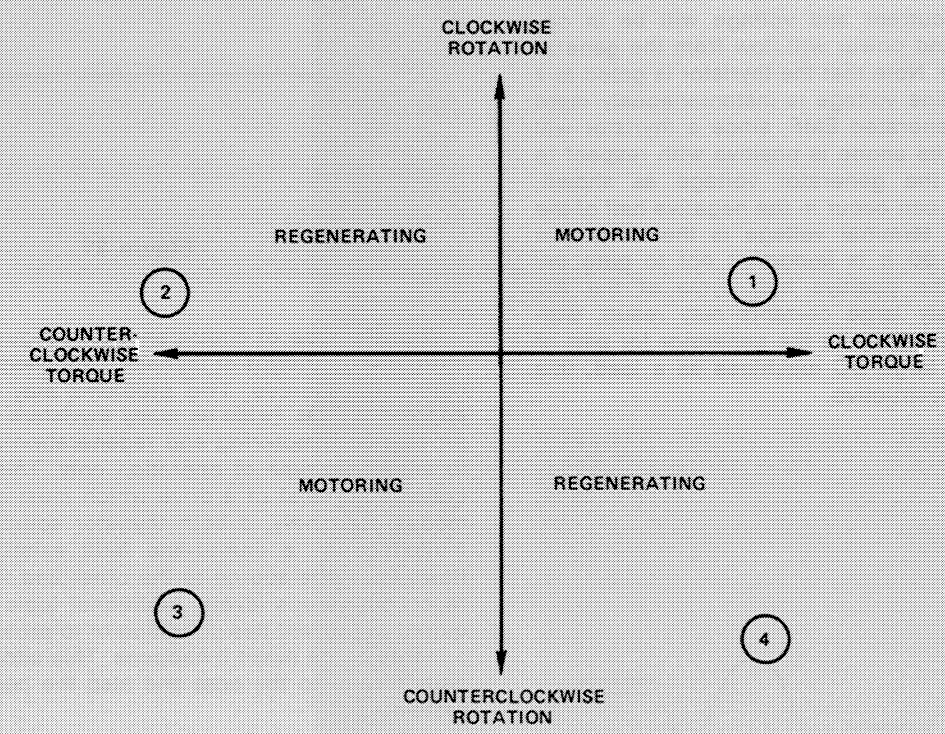
Second, the gating control of the thyristors must provide for conduction in both halves of the DC line voltage wave, since motoring occurs during the positive half cycle and regeneration in the negative half cycle.

Third, the magnitude of armature current must be dependably controlled, since extremely large fault currents can exist in a DC machine whose counter EMF is capable of swinging rapidly both positive and negative. This control of current should include protection against conduction in the positive half cycle during regeneration.

Fourth, since the field current must reverse to provide regeneration, there is obviously a period of time during which it is at zero or at a very low level. During this time, it is desirable for the armature current to be controlled, to prevent the armature reaction from causing poor commutation with resulting brush and commutator wear. Similarly, the reversal time of the field current must be as short as possible to provide response which is comparable to the ordinary M-G set type of DC drive.

FOUR QUADRANT OPERATION — The operation of a drive which is capable of rotation in either direction and independent selection of the direction of output torque can be described by a graph in which the vertical axis represents speed and the horizontal axis represents torque. This graph, shown in Figure 22 has four quadrants, and a drive which can function in any of these modes is said to have "four quadrant" capability.

The table in Figure 22 shows relative polarities of armature and field voltages which will provide four quadrants of steady state operation for a field reversing DC drive. As should be expected, the polarity of armature voltage is an indication of direction of power flow, and the polarity of field current is a measure of the direction of torque. This simple relationship between field current and torque direction makes it correspondingly easy to apply conventional DC analog regulator principles to effect 4 quadrant control on a steady state basis.



QUADRANT	ARMATURE VOLTAGE	FIELD VOLTAGE	MOTORING OR REGENERATING
1	+	+	MOTORING
2	–	–	REGENERATING
3	+	–	MOTORING
4	–	+	REGENERATING

Figure 22

SYSTEM BLOCK DIAGRAM — Figure 23 is a block diagram of a field reversing DC regenerative drive connected as a typical speed regulator with four quadrant capabilities.

The speed reference signal and a speed feedback from a tachometer generator are compared at the input to an operational amplifier. The amplified error between these two signals acts as the input to two inner feedback loops; one controlling the motor field current, and the other controlling the armature current. Since armature current is unidirectional, the steady state input signal to its inner loop regulator must also be unipolar, and a logic circuit is used to provide this correct polarity, depending upon a combination of error signal polarity and field current direction, and based upon the four quadrant chart of Figure 22.

If the inner loop regulators are examined, each requires certain characteristics. The field current regulator in the system shown regulates field current to a value related to both the polarity and magnitude of the amplified error signal. This action satisfies the conditions of four quadrant operation, since the polarity of the error between the reference and the tachometer, and the polarity of the motor field current have the same relationship for all four quadrants of operation.

The field current amplifier and power unit should be capable of continuous control of field current in either direction and through zero. The response should be as fast as possible, since substantial field time constants exist in the larger DC machines. Voltage forcing and the capability of reversing field voltage during the transition before current has reversed aid greatly in improving speed of response. Critics of this system often feel that it is not practical to reverse the field current of a large motor in a reasonable time. However, the same techniques used in rapid reversing of the fields of large DC generators for such applications as steel rolling-mill drives can also be used with motor fields to provide speed of response comparable to M-G set drives. Since the field power is only a few percent of the armature power, the cost is usually not prohibitive.

The armature current regulating inner loop must be capable of controlling the armature current through both the positive and negative portions of the AC line voltage. For three phase operation, this means that the range of gating angles of the individual thyristors require control over a theoretical maximum range of 60° to 240° of the AC line-to-line voltage sine wave. Since this represents only 180° of phase control, conventional gating circuits can be used, if the synchronizing period is retarded 60° from the normal 0-180° control range.

The maximum level of input signal to the armature current inner loop regulator is set by the current limit adjustment to a value which corresponds to the desired maximum or limited current. By designing the transient response of the regulator so that no overshoot occurs for a step function input signal, the current limiting action is also free of transient overcurrent conditions, since the most extreme output of the operational amplifier is a step function.

Because the gating angle corresponding to normal armature currents is a continuous function from full positive to full negative output voltages, the inner armature current control loop is a conventional analog regulator.

The speed regulating system described in Figure 23 is only one of many ways that the two regulating loops can be interconnected. This specific arrangement, however, demonstrates particularly well some of the nonconventional characteristics of the drive. For example, since the magnitudes of armature and field current can be proportional, the motor behaves somewhat like a series DC motor, and full speed operation at no load can be accomplished with only a fraction of rated armature voltage. The field current regulator reference circuit can provide rated field current at speeds up to base speed of the motor.

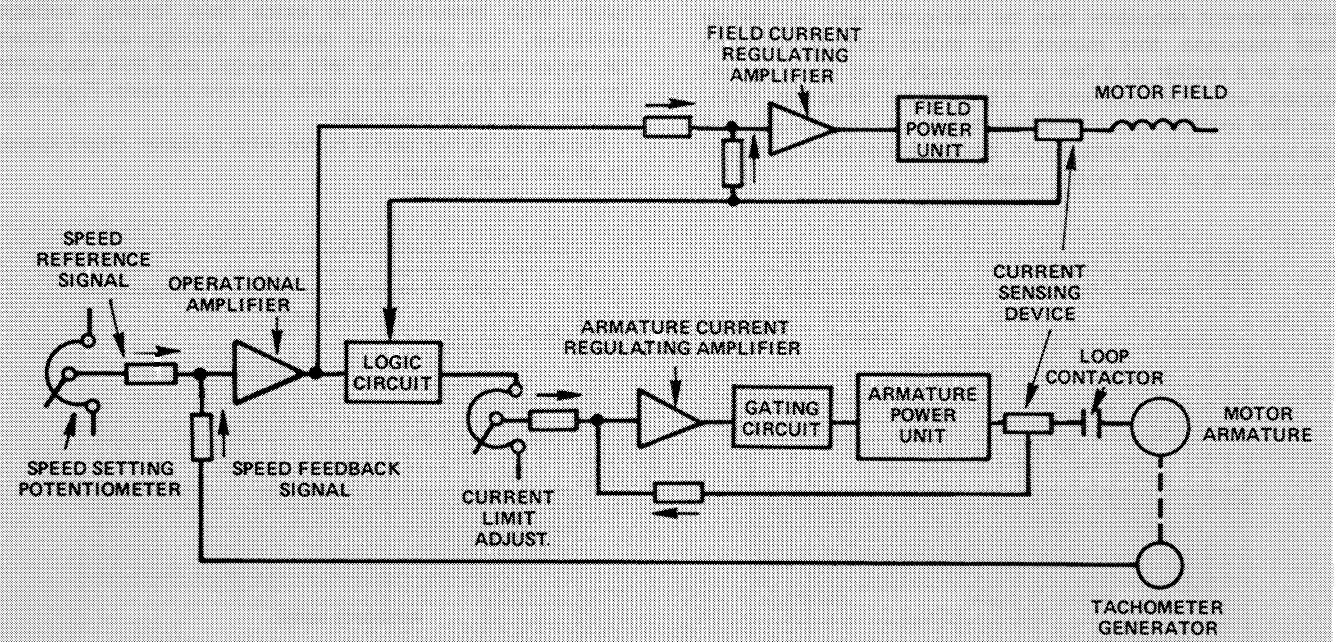


Figure 23

PERFORMANCE CHARACTERISTICS — Performance of this system during steady state conditions of operation within a single quadrant is not significantly different from other thyristor-powered DC drives which may or may not provide regeneration, and may or may not allow for controlled motor field current. The examination of transitions from one quadrant of operation to another, however, gives added insight into the understanding of this system. These transitions can be grouped into two categories: first, a reversal in the direction of rotation without a reversal of torque; and second, torque reversals with or without a reversal of the direction of rotation.

The first case might be typical of a shipboard mooring winch which exerts a steady pull on a mooring line, but takes up or pays out this line in response to changing tides, waves, and cargo within the ship. In this case, the direction of error between reference and feedback does not change, and the direction of field current remains constant. This means that the response characteristics of the drive are predominantly dependent upon the armature current regulator, and no discontinuity or dead band exists between the two quadrants of operation. It is interesting to note that conventional thyristor drives utilizing the power circuits of Figures 13, 16 and 21 are fully capable of operating in this manner, including the regenerative quadrant, if their gating circuits can provide enough range of phase control, and provisions are included to prevent inversion faults. Since there are very few loads which fit this particular case, however, most thyristor drives have not been designed to take advantage of this type of operation.

When the torque output of the drive must reverse, either with or without a reversal of the direction of rotation, the field current necessarily must also reverse, and a period of discontinuous operation exists. The logic circuit serves to make this transition as "painless" as possible. When a reversal of the polarity of the error signal indicates that a reversal of torque is necessary, the logic circuit immediately removes the signal calling for armature current and does not reapply it until the field current has succeeded in reversing its direction. Since the armature current regulator can be designed with extremely fast response, this means that motor torque drops to zero in a matter of a few milliseconds, and does not reappear until field current is in the proper direction. Without this feature, the combined action of load torque and persisting motor torque can cause excessive transient excursions of the motor speed.

From a practical standpoint, most loads which alternate the direction of torque do so at light loading conditions and field current reduction prior to a torque reversal can facilitate very rapid reversals, keeping the transient period relatively short. Where full load torque reversals are expected, the forcing techniques mentioned earlier can be used to overcome the natural sluggishness of the field.

Surprisingly enough, the more conventional 4 quadrant drive, using 2 sets of thyristors to allow armature current flow in both directions, often suffers from a similar discontinuity during torque reversals. This is a result of protective circuitry which prevents gating of one set of thyristors until the other set is no longer conducting.

TRANSIENT RESPONSE — Figure 24 through Figure 31 are oscillograph traces showing various transient conditions on a 20HP, 850RPM base speed machine.

To show the response of armature current to changing system requirements, step speed reference signal changes were used. Figure 24 shows a step input of reference signal in a direction which calls for an increase in speed, with the motor running idle. Since the motor field does not have to reverse, the armature current responds without delay. The trace shows a rise time of less than 0.02 seconds. The actual rise time is somewhat less, since the oscillograph response time is not adequate to follow the signals exactly. Note the lack of significant overshoot.

Figure 25 shows the same information, but this time the reference change is in a direction to decrease motor speed. This requires that the field reverse. The armature current drops to zero almost instantly, remains there for about 0.06 seconds, and then rises to the current limit value in another 0.02 seconds. This means that the total transient time to establish regenerative torque is about 0.08 seconds, a very acceptable figure for most applications. No field forcing was used in this case.

Figure 26, Figure 27 and Figure 28 show the response of field current following changes in reference to the inner field current regulator. These three traces were taken with essentially no extra field forcing voltage available. This particular amplifier configuration allows for regeneration of the field energy, and this accounts for the very rapid drop in field current to zero. Figure 26 shows complete reversals.

Figure 27 is the same curve with a faster chart speed to show more detail.

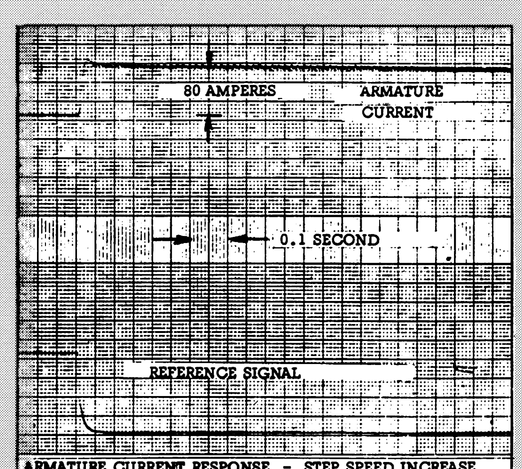


Figure 24

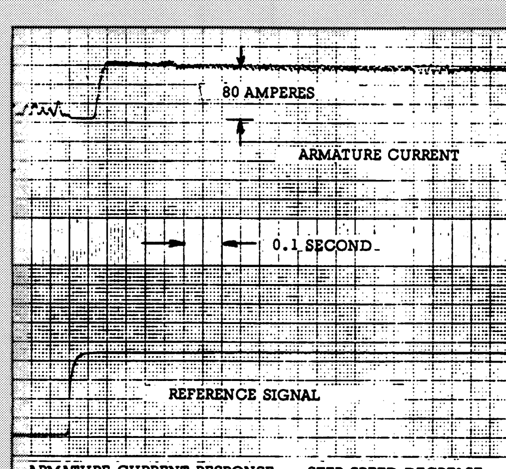


Figure 25

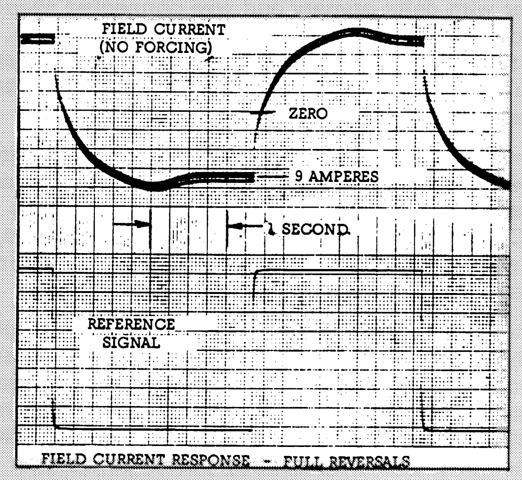


Figure 26

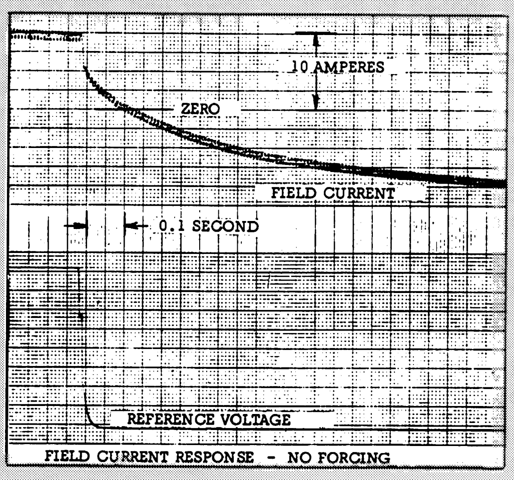


Figure 27

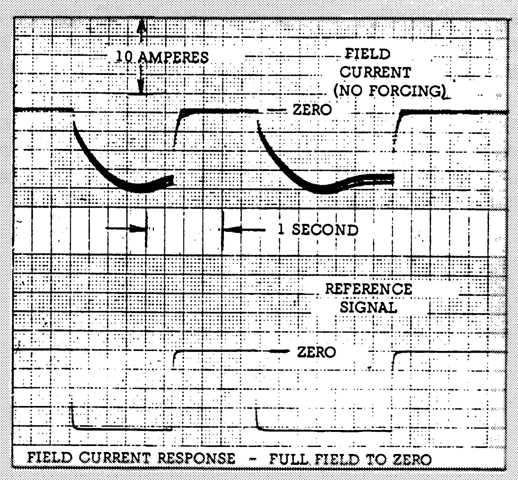


Figure 28

Figure 28 shows the regenerative collapse of the field to zero. Approximately 0.1 second is required for the field current to go from full strength to zero, and an additional 0.75 seconds to reach essentially full field in the opposite direction. 50% reverse torque is available in approximately 0.25 seconds.

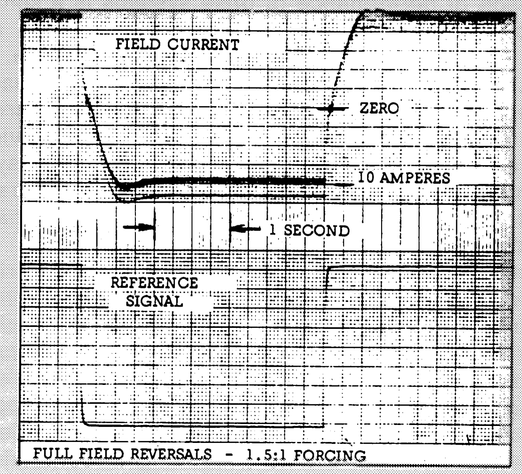


Figure 29

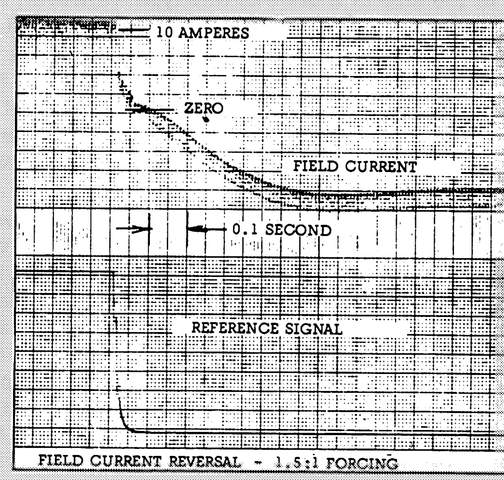


Figure 30

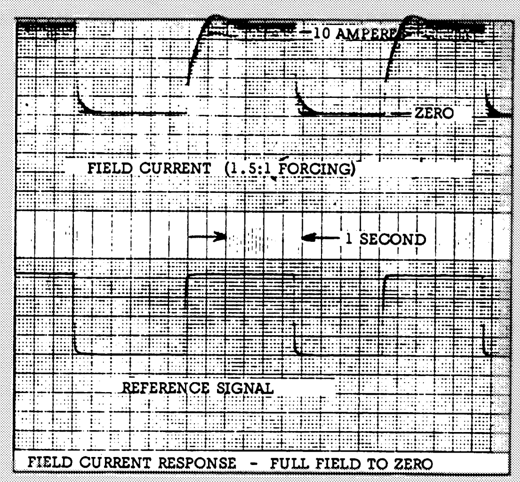


Figure 31

Figure 29, Figure 30 and Figure 31 are duplicates of Figure 26, Figure 27 and Figure 28 with extra voltage available for forcing of 1.5 to 1. Now the field current drops to zero in about 0.06 seconds, and full field is obtained in about 0.4 seconds. Additional forcing, where required, can improve response even further.

COMPARISON WITH OTHER DC DRIVES — At best, the comparison of performance of drive systems is a sensitive subject, since individual opinions are based on specific requirements and prior personal experience. In general, the drive described here can provide steady state performance equal to that of any other DC drive systems available. The regenerative capabilities provide distinct advantages over non-regenerative static DC systems, and at least for drives up to several hundred horsepower, transient performance equivalent to the ordinary M-G set drive.

In terms of cost, the field reversing regenerative drive must always be more costly than a non-regenerative static drive, but also less costly than a regenerative static drive that utilizes two sets of controlled armature power rectifiers. The simplicity of circuitry for the field reversing drive as compared to the dual armature supply regenerative drive will undoubtedly contribute to less maintenance and "down time", resulting in continuing cost savings.

PRACTICAL LIMITATIONS — There is no theoretical limitation to the size of a drive of this type. However, the long time constants of the fields of motors over 500 or 1000 horsepower require large amounts of forcing to provide reasonable response times. Fortunately, the power required for a motor field is only a few percent of the armature power, so forcing as much as 12 to one is practical from a cost and engineering standpoint and has been successfully achieved.

Multiple motor drives operating from a common power supply do not represent an outstanding example of the proper application of the field reversing DC drive. Series connections of the armatures and fields of drive motors of the same horsepower mechanically tied together are entirely practical, but considerably more work will be required before other types of single power supply, multiple motor applications are workable. Since cost is usually the reason for using a single power supply for more than one motor, each specific case must be examined to determine whether several smaller static supplies can be competitive with a larger power supply consisting of a motoring and a regenerative group of thyristors. Where the total load is not regenerative, there is, of course, no reason to provide separate supplies.

ISOLATION TRANSFORMERS — An isolation transformer with delta primary and wye connected secondary is provided, as standard, with each Bulletin 1371, 1372 and 1373 drive system. This transformer serves several useful functions and provides a significant reliability advantage to the user.

1. The transformer provides electrical isolation between the drive motor and the AC power lines. This avoids inadvertent grounding of the plant power lines if the DC motor armature circuit develops a ground. The electrical isolation also enhances safety to maintenance personnel.
2. The additional impedance provided by the isolation transformer provides enhanced semiconductor protection and reduces rate-of-rise of voltage and rate-of-rise of current as well as providing filtering action to shield transients that may come from the AC lines and otherwise destroy power conversion semiconductors.
3. Utilization of isolation transformers with regulated speed drives can facilitate the reduction of AC voltage applied to the static power unit. 208 or 415 volt isolation transformer secondary voltage is applied to the static conversion circuits as compared to 230, 440, 460 or 480 volts on direct connected drive systems. This reduced AC voltage results in a higher thyristor conduction angle to attain a 240 or 500 volt armature rating. The larger conduction angle thus provided, further reduces DC ripple and associated motor heating; AC line power factor is improved.
4. The AC supply line voltage disturbances which any static drive generates are minimized by the utilization of an isolation transformer. This reduces disturbances to other solid state control equipment such as, drives without isolation transformers, time clock systems, electronic counters, etc.
5. Voltage taps provided on the isolation transformer facilitate compensation for high or low nominal AC supply voltage.
6. Dual voltage primary windings can be provided to anticipate future changes in AC supply voltage.

Direct connection of static drives to AC power lines, avoids the cost of separately mounting a relatively heavy item and although a less expensive step, results in lower drive reliability, subjects the AC power circuit to drive-generated disturbances which can disturb other control equipment, reduces safety to maintenance personnel, and subjects the drive to variations in performance due to differences in AC line impedance levels.

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Publication DGI–2.0 — November, 1982
Supersedes January, 1974