CHAPTER 1

Motor Speed Controls

1.1 Motor Speed Control

AC or DC?

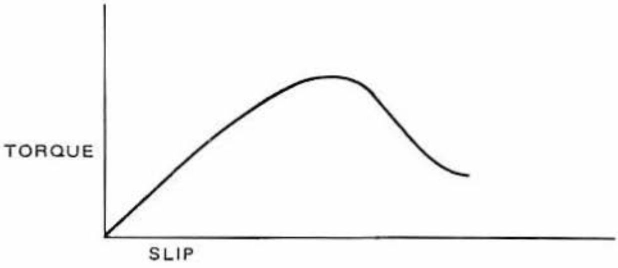
Variable-speed motor drive circuits are used to provide easy and versatile control of powered drive systems. There are two basic types of speed-control systems, one for dc or universal motors and the other for ac induction motors. A dc-motor control system requires a minimum of power and control circuitry, but controls a motor that is expensive to purchase and expensive to maintain. The electronic control system for an ac motor is more complex and therefore more expensive, but the additional cost is offset by the economies of using an ac motor. An ac motor is much less expensive than an equivalent dc motor, its cost ranging from one-half the price for fractional-horsepower motors to one-fifth the price for large integral-horsepower motors. Moreover, since an ac motor has no brushes or commutators, it requires less maintenance, is more rugged and reliable, and can operate in explosive, dusty or highly humid atmospheres, and at high altitudes. In addition, ac motors can have higher maximum speeds than dc motors, and they can be liquid cooled. These advantages, when coupled with the availability of standard-rated motors from stock, make ac motors more attractive for most industrial applications than dc motors.

Speed Control for AC Motors

DESIGN CONSIDERATIONS

The speed of an ac induction motor can be controlled by varying either the amplitude or the frequency of its supply voltage, or both. The variable-voltage, fixed-frequency technique has the disadvantage that the maximum torque of the motor is porportional to the square of the applied voltage; therefore, this control is effective only over small torque ranges.

Better speed control is obtained through the use of a variable-frequency drive system, but the motor characteristics discussed below may



$$\text{Slip}_{\text{max torque}} = \frac{R2'}{\left[(R1)^2 + (X1 + X2')^2\right]^{1/2}}$$

See Figure 1-2 For Definitions of Terms

Figure 1-1 – Slip-Torque Characteristics of Induction Motor

apply restraints that will limit the effectiveness of this approach. Generally, the best speed control is obtained through a system which varies both frequency and voltage.

No matter what type of speed control is used, a motor must be operated within its nameplate ratings. This rating gives the safe torque and speed limit for the motor as determined by the temperature limit, maximum safe rotational speed, and the saturation limit of the iron used in the motor. To keep from saturating the iron, the rms stator voltage must be proportional to the frequency of this voltage. Under this condition the maximum torque producible is independent of the frequency of the applied voltage. However, maximum torque occurs at a particular value of slip* at a particular supply frequency. The torque-versus-slip curve is shown in Figure 1-1. Peak efficiency occurs at the point of maximum torque.

It is possible to control the slip by varying the rotor resistance. The maximum torque that a motor can develop is independent of the rotor

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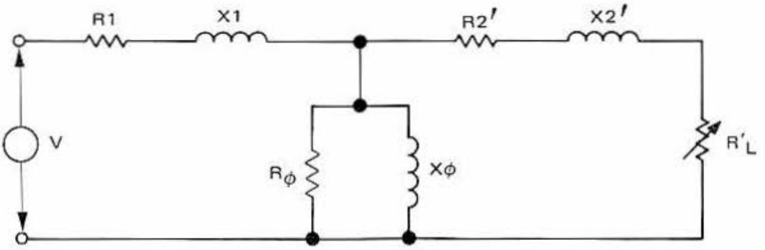
*Slip is defined as

$$s = \frac{S_{sync} - S_{rotor}}{S_{sync}}$$

where S_{rotor} is the rotor speed, and S_{sync} is the synchronous speed. Synchronous speed is equal to $\frac{120\,f}{P}$, where f is the supply frequency in hertz and P is the number of poles.

resistance, as shown by the equation in Figure 1-2; however, the slip at which maximum torque is developed is a function of this resistance as shown by the equation in Figure 1-1. The effects of the rotor resistance are shown in Figures 1-3, 1-4 and 1-5. If the rotor resistance is controlled over the speed-control range of the motor, then the operating characteristics can be optimized and power requirements for a given load minimized.

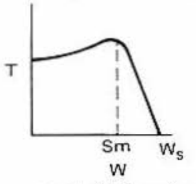


$$\text{Torque}_{\text{max}} = \frac{7.04}{S_{\text{sync}}} \cdot \frac{V^2}{2\left[R1 + \sqrt{R1^2 + (X1 + X2')^2} \right]}$$

R1 = Resistance of stator
X1 = Reactance of stator
R2' = Resistance of rotor reflected into stator
X2' = Reactance of rotor reflected into stator
RL' = Resistance of load reflected into stator
Rφ = Leakage resistance
Xφ = Leakage reactance
S_{sync} = Synchronous speed
V = Input voltage

Figure 1-2 — Equivalent Circuit of Induction Motor

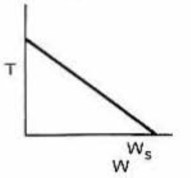
K,K1,K2 = Constants
W = Speed
W_s = Speed for zero torque
Sm = Speed of maximum slip
V = Applied voltage



$$T = \frac{K\ V^{2}(1-w/w_s)}{Sm^2 + (1-w/w_s)^2}$$

Figure 1-3

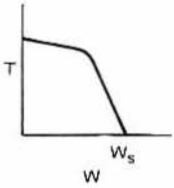
Speed-Torque Characteristics of Conventional Rotor



$$T = \frac{K_1\ V^{2}\ (w_s - w)}{w_s}$$

Figure 1-4

Speed-Torque Characteristics of High-Resistance Rotor



$$T = K_2\ V^{2}$$

Figure 1-5

Speed Torque Characteristics of Constant-Torque Rotor

It is also possible to achieve the high torque-to-current ratio typical of a dc motor by controlling the slip. Thus some of the characteristics of a dc and an ac motor can be combined. Generally, this type of control is not used as it involves the use of slip rings.

If the rotor resistance is constant, then the slip at maximum torque is inversely proportional to the applied frequency. For supply frequencies below the design value a series of speed-torque curves, as shown in Figure 1-6, can be obtained. Note that the maximum torque is constant, as it is limited by the saturation level of the iron. This level depends on the voltage magnitude at any particular frequency.

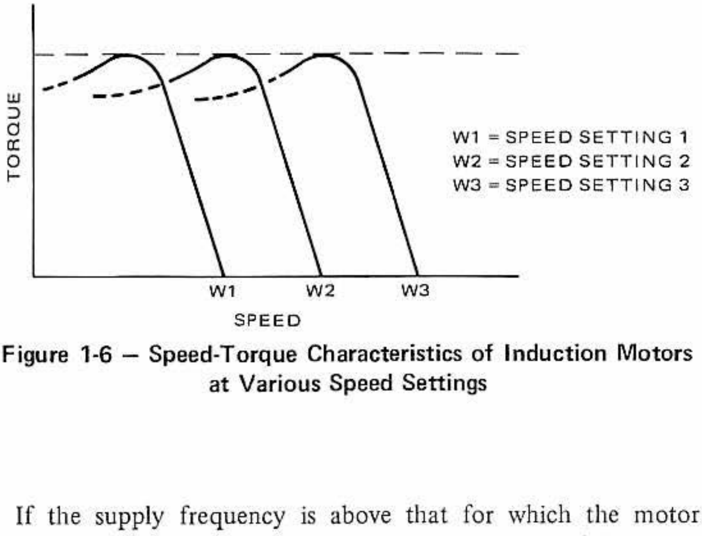


Figure 1-6 – Speed-Torque Characteristics of Induction Motors at Various Speed Settings

If the supply frequency is above that for which the motor was designed, then the horsepower rating must not be exceeded. This means the maximum torque will be reduced. Usable torque is even less at the higher speeds since friction and windage losses are increased.

A motor is capable of providing more power than listed on the name plate, but this increases the heat dissipated in the motor. The ratings which can not be exceeded without degrading the reliability are the maximum temperature limit of the winding insulation, and the maximum rotational speed of the armature.

The combination of all of these factors points to the fact that to achieve optimum performance in controlling the speed of an induction motor, a supply voltage which varies directly with the supply frequency should be used.

The equations shown in Figures 1-3, 1-4 and 1-5 hold when an induction motor is excited by a steady-state sinusoidal stator voltage.

Generally, the circuits used to control the frequency of the supply for the motor do not supply a steady-state sine-wave voltage. Therefore, the equations shown are only approximate. If it is necessary to maintain precise speed and torque control, then a speed-sensing circuit which feeds back to a variable-frequency and variable-voltage control circuit should be employed.

CIRCUIT CONFIGURATION

Either transistors or thyristors can be used as the main speed-control element for a motor. Transistors require continuous drive to remain in the "on" state and must be able to withstand high voltages and currents. When saturated, they dissipate less power than thyristors. Thyristors require a power pulse to turn on and will remain on until their anode current is reduced below the hold value. This reduction of current may occur from the natural commutation during the cycle of a sine wave, or by special circuits which bypass the current or insert high series impedance.

Two types of circuits are used to provide variable-frequency alternating voltages for motors, inverters and cycloconverters.

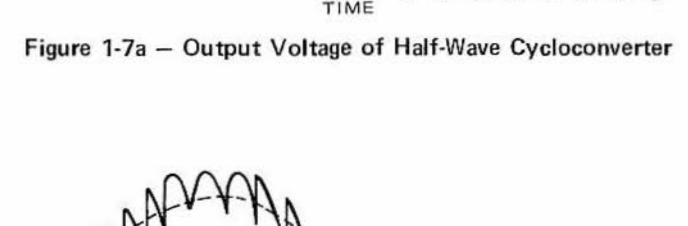


Figure 1-7a – Output Voltage of Half-Wave Cycloconverter

Figure 1-7b – Output Voltage of Full-Wave Cycloconverter

A cycloconverter changes the frequency of a three-phase alternating power source without the necessity of an intermediate ac-to-dc conversion stage. Cycloconverters require multiple control devices with three-phase excitation, and are limited to low output frequencies. The output of a cycloconverter has a relatively large ripple voltage, but comparatively small ripple current, which is what contributes to motor heating. The higher the output frequency, the greater is the ripple current since there are fewer supply pulses per output cycle. This limits the practical upper frequency for a cycloconverter to one sixth the supply frequency if a half-wave converter is used (i.e., three thyristors and three diodes), and one third the supply frequency if full-wave control is used (i.e., twelve thyristors) as can be seen by the output waveform for both types as shown in Figure 1-7.

An inverter is a dc-to-ac converter; it can be designed for variable-frequency output. If an inverter is to be used on alternating current, the ac must first be rectified and filtered to obtain direct current. If thyristors are used as the main controlled element in the inverter, then they must be forcibly commutated. Forced-commutation circuits can be either regenerative or nonregenerative: The regenerative inverter requires a power supply that can absorb as well as deliver power; an example is a dual phase-controlled rectifier operating off the public supply lines. Inverter circuits can supply frequencies much higher than power line frequencies and do not require as many main control devices nor control circuitry as complex as do cycloconverters. Inverters can also operate from either rectified alternating current or from a dc supply.

If operated from an ac supply, the inverter presents a higher power factor to the line than a cycloconverter and is better isolated from the line for switching spikes, due to the filtering. For these reasons, only inverter circuits are described here for variable-frequency motor speed controls.

In certain applications, cycloconverters can provide optimum characteristics for speed control. For excellent discussions on cycloconverters see references four and five in the bibliography for this chapter.

Speed Control for DC Motors

DESIGN CONSIDERATIONS

The speed of a dc motor is dependent on the applied voltage. For a series motor, the speed is directly proportional to the applied voltage. For a shunt motor, a constant voltage should be applied to the shunt field to maintain constant field flux so that the armature reaction has negligible effect. When constant voltage is applied to the shunt field, the speed is a direct function of the armature voltage and, consequently, the armature current. If the field is weak, then the armature reaction may counterbalance the voltage drop due to the brushes, windings and armature resistances with the net result of a rising speed load characteristic. The performance of a dc motor operated from a rectified ac supply can be significantly different from one operated from a dc supply, as explained below.

The maximum working torque of a dc motor is governed by the design maximum temperature rise of the motor. This torque is proportional to the average armature current, whereas the copper loss is proportional to the rms value of the armature current. Therefore, for any given motor the maximum working torque is less for an ac supply than for a dc supply. The form factor (F_f), which is equal to Irms/Iavg, can be used as a measure of motor performance. It can be shown that the ratio of the dc armature copper loss to the ac armature copper loss is equal to $1/(F_f)^2$. The speed torque curves for several dc motors are shown in Figure 1-8 and 1-9.

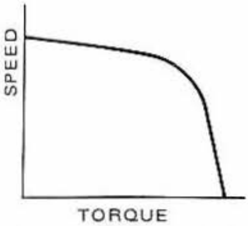


Figure 1-8 – Speed-Torque Characteristics of Shunt-Wound or Permanent-Magnet Motor

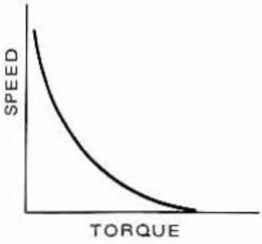


Figure 1-9 – Speed-Torque Characteristics of Series-Wound or Universal Motor

CIRCUIT CONFIGURATIONS

The speed of a shunt-wound motor can be controlled with a variable resistance in series with the field or the armature. Varying the field current for small motors provides a wide range of speeds with good speed regulation. However, if the field becomes extremely weak, a rising speed-load characteristic results. This method cannot provide control below the design motor speed. Varying the resistance in series with the armature results in speeds less than the designed motor speed; however, this method yields poor speed regulation, especially at low speed settings. This method of control also increases power dissipation and reduces efficiency and the torque since the maximum armature current is reduced. Neither type of resistive speed control is very satisfactory.

Thyristor drive controls, on the other hand, provide continuous control through the range of speeds desired, do not have the power losses inherent in resistive circuits, and do not destroy the torque characteristics of motors.

A permanent-magnet motor has operating characteristics similar to those of a shunt-wound motor. Separate field and armature circuits are not required as in a shunt-wound motor since the field is provided by the permanent magnet.

Although a series-wound motor can be used with either dc or ac excitation, dc operation provides superior performance. A universal motor is a small series-wound motor designed to operate from either a dc or an ac supply of the same voltage. In the small motors used as universal motors, the winding inductance is not large enough to produce sufficient current through transformer action to create excessive commutation problems. Also, high resistance brushes are used to aid commutation.

The characteristics of a universal motor operated from alternating current closely approximate those obtained from a dc power source up to full load; however, above full load the ac and dc characteristics differ as

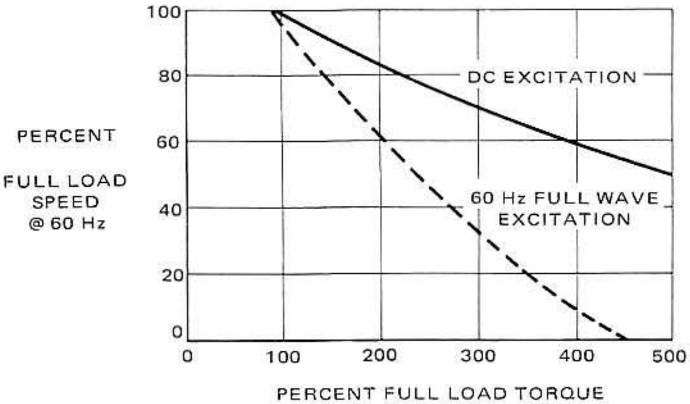


Figure 1-10 – Typical Speed-Torque Curve for Universal Motor

shown in Figure 1-10. For a series motor that was not designed as a universal motor, the speed-torque characteristic with ac rather than dc is not as good as that shown for the universal motor. At light loads, the speed for ac operation may be greater than for dc, since the effective ac field strength is smaller than that obtained on direct current. At any rate, a series motor should not be operated in a no-load condition unless precautions are taken to limit the maximum speed.

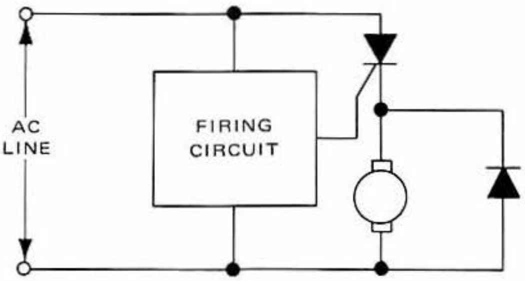


Figure 1-11 – Typical Speed-Control Circuit Showing Free-Wheeling Diode

Since torque is proportional to armature current and motor voltage, a current- or voltage-sensitive circuit can be used to regulate the voltage applied to the motor. A variable-voltage power supply can consist of a circuit which provides a repetitive power pulse from either an ac or a dc source. If an LC filter is used for smoothing, a free-wheeling diode is generally included across the input of the filter to reduce commutator sparking by using the filter inductor to help maintain dc in the motor. The diode is used across the motor if such a filter is not used; this is shown in Figure 1-11. The supply thyristor shown in the figure is turned on at some phase angle to deliver the proper voltage. It will shut off at nearly 180°, if 0° is taken to be the time the voltage goes positive through zero, at high rotor speeds with low torque loads, since a large back emf is generated and the armature current is low. The free-wheeling diode will not conduct under this condition. At moderate speeds and loads, the thyristor will turn off at some angle greater than 180° when compared to the voltage angle. Here the free-wheeling diode will conduct from the time the thyristor turns off until the energy in the motor is less than that required to forward-bias the diode. At low motor speeds and high torque loads the free-wheeling diode will still be conducting when the thyristor is turned on again. The increasing current when the thyristor is on, and decaying current when the diode is conducting, can affect motor commutation to a degree such that sparking can occur. A slight amount of sparking is not detrimental to motor performance, but should be avoided if possible since environmental conditions may not tolerate sparking.

As a rough guide, the free-wheeling diode conducts continuously when the form factor is less than 1.11, and conducts for part of the cycle when the form factor is greater than this value.

For fractional and small integral-horsepower dc motors operating from alternating voltage, a single-phase supply is generally used. For larger motors (over 3 hp), three-phase supplies are generally used. The control of a three-phase supply is more complex, but the ripple frequency is much higher, and consequently, less ripple voltage is presented to the motor. An important point to remember is that there is a maximum voltage that can be placed on the armature. This is especially important to note when phase control of the power lines is used to vary the voltage, because the peak line voltage may be placed on the armature even though the average voltage is much less.

Braking a Motor

The braking of a motor provides a method of controlling the coasting of the rotor and its load. Several methods may be used to brake a motor: mechanical, dynamic, plugging or regenerative. Mechanical braking requires the least complicated control; it also causes power to be dissipated in elements external to the motor. The disadvantages of mechanical braking are its higher initial cost and greater maintenance costs.

Dynamic braking is accomplished by placing an electrical load (generally a short) across the armature while maintaining a dc field. This may be done in an ac induction motor by replacing the ac supply with a dc supply which is removed when the machine is stopped. The motor then becomes a generator with a shorted armature, and the energy of the load is converted to electrical energy in the armature circuit and dissipated as heat.

Plugging requires that the windings be connected for reverse rotation. The large reverse-surge current resulting creates a large reverse torque. The motor must be disconnected from the power source when it has stopped or it will run in the opposite direction.

In regenerative braking, the motor must be connected to the power source during the times the back emf is greater than the source voltage, so that current is forced back into the source against the source voltage. The energy of the load is dissipated in the source and not in the motor for this method. Regenerative control may be achieved on an ac supply by using a bridge of four thyristors which are triggered in diagonal pairs at a time when the supply voltage opposes the return of current.

The method used for braking depends on the characteristics of the motor, the available power source, allowable coasting of the rotor and whether or not control is required after stopping. If the rotor is to be kept from turning after stopping then a mechanical brake must be used.

When braking power is applied to a motor, care must be taken not to exert too large a force on any element of the system. The motor itself will not be harmed as long as it does not dissipate excessive power, but elements connected to the rotor may be damaged if it is stopped too quickly. For example, gears may be stripped if a high inertial load is stopped too rapidly. Thus each part of the power train must be examined when establishing stopping requirements. If a motor's direction is to be reversed these same criteria apply and must be considered.

1.2 Inverter Driven Single Phase Induction Motor Speed Control

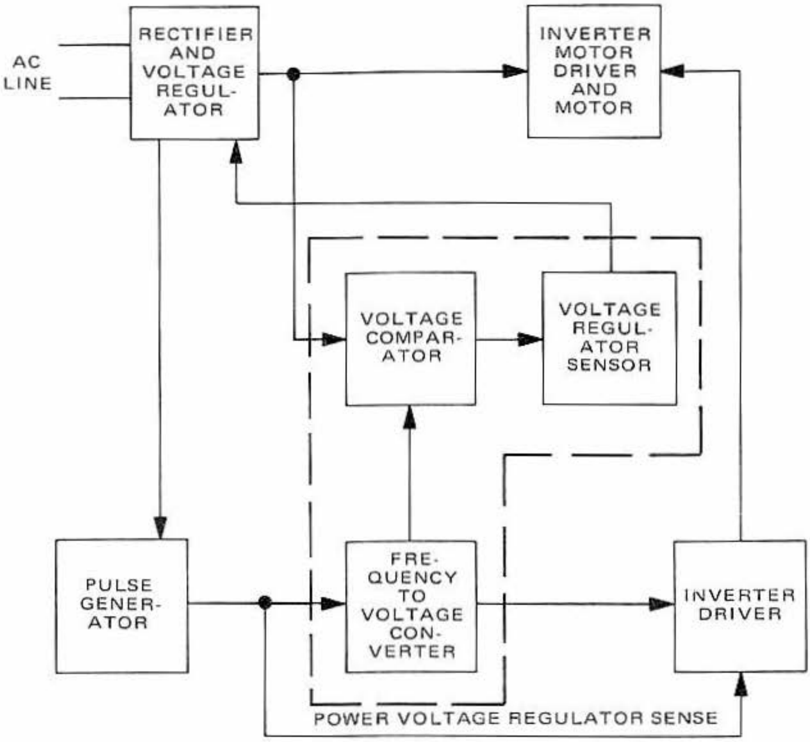


Figure 1-12 – Block Diagram of AC-Induction-Motor Speed Control

The block diagram of a single-phase, forced-self-commutated inverter which provides a variable-frequency, variable-voltage supply to a motor is shown in Figure 1-12. The circuit exhibits excellent speed control. The motor losses, due to the high frequency components of the square-wave voltage, though higher than with a sine-wave voltage, were not large enough to overheat the motor. Several speed-torque curves obtained from a 1/6 horsepower, 115 volt, 1200 r/min, 60 Hz induction motor are shown in Figure 1-14. This circuit can be used to control the speed of a single-phase induction motor with no modifications to the motor.

Inverter

The typical inverter circuit uses a transformer whose center-tapped primary windings are connected to the power supply alternately through the switching devices. This alternating voltage is transformed into the secondary which supplies the ac power to the load. A circuit such as this require a large transformer to drive a large motor. The circuit, which is shown in Figure 1-13 uses the same principle of operation but uses a center-tapped choke (L1) as an auto-transformer to supply the load. The inductance of the choke is not critical, but the windings must be able to handle the required motor current. To demonstrate that the inductance value was not critical, the choke was replaced by two resistors. The only difference in operation was that the peak-to-peak motor voltage was twice rather than four times the supply voltage, as obtained through auto-transformer operation of the choke.

An attempt was made to use the windings in the motor in place of the auto-transformer in the commutating circuit, but the only result was an overheated motor. This technique requires that the motor be modified to bring out the center point of the windings. Torque should be developed when the current is switched from one winding to the other. However, as the motor was not designed for this use, the torque developed when current increases in one winding was opposed by the torque developed in the other winding due to its current decreasing. The overheating was a result of the stator iron being saturated and allowing excessive current to pass through the windings.

The commutating capacitor (C1) must be small enough that a full charge can be placed on it at the highest frequency of operation required. The capacitor charges through the choke (L1), so the capacitor value depends on the choke inductance. Diode D1 and inductor L2 provide a reverse bias to SCR Q3 when it is being commutated off due to the firing of SCR Q4. This reverse bias must be held across the SCR long enough to ensure that it will turn off. The same operation occurs when SCR Q4 is to be commutated off except that diode D2 now conducts.

This circuit presents a square-wave voltage to the motor. This results in about 15% lower motor efficiency than that obtained with a sine-wave source, due to the high-frequency components of the waveform.

Inverter Driver and Oscillator

The inverter SCRs Q3 and Q4 are driven by the inverter driver and oscillator (See Figure 1-13). The driver is basically a flip-flop. Pulse transformers are used to couple the inverter SCRs to the driver.

The frequency of the multivibrator is controlled by a unijunction oscillator which provides pulses at a frequency set by the RC network attached to the emitter. These pulses trigger a one-shot multivibrator, which in turn triggers the inverter-driver multivibrator. The frequency of the voltage applied to the motor is one half that provided by the unijunction oscillator because of the divide-by-two action of the flip-flops.

Power Voltage Regulator

As discussed previously, for best results, the amplitude and frequency of the voltage applied to the motor must be varied proportionally; this is a function accomplished by the power voltage-regulator circuit. The basic circuit is a one-shot multivibrator whose output is filtered to obtain a dc level. This multivibrator output also provides a negative pulse necessary for triggering the multivibrator of the inverter driver. The magnitude of the filtered output voltage is a direct function of the frequency of the one-shot multivibrator since the pulse duration is fixed and the frequency variable. The filtered voltage is applied to a voltage comparator consisting of transistors Q5 and Q11. The voltage to which the comparison is made is the voltage applied to the inverter circuit. The voltage comparator does two things: It is used to set the supply voltage, and once set, it regulates this voltage. Transistor Q11 sets the reference voltage and transistor Q5 senses the supply voltage. The charging rate of capacitor C2 is controlled by the degree of conduction of Q5. The faster C2 charges, the sooner unijunction transistor Q6 fires, and thus SCR Q1 and SCR Q2 turn on sooner. This increases the supply voltage obtained from the filter composed of L3 and C3. SCR Q1 and SCR Q2 and diodes D3 and D4 form a full-wave bridge providing power to the inverter circuit. The range over which the supply voltage can be varied for a given inverter frequency range is controlled by the width of the one-shot multivibrator's pulse.

This power voltage regulator and power supply can be used as the supply for the other ac induction motor speed control circuits shown in this chapter.

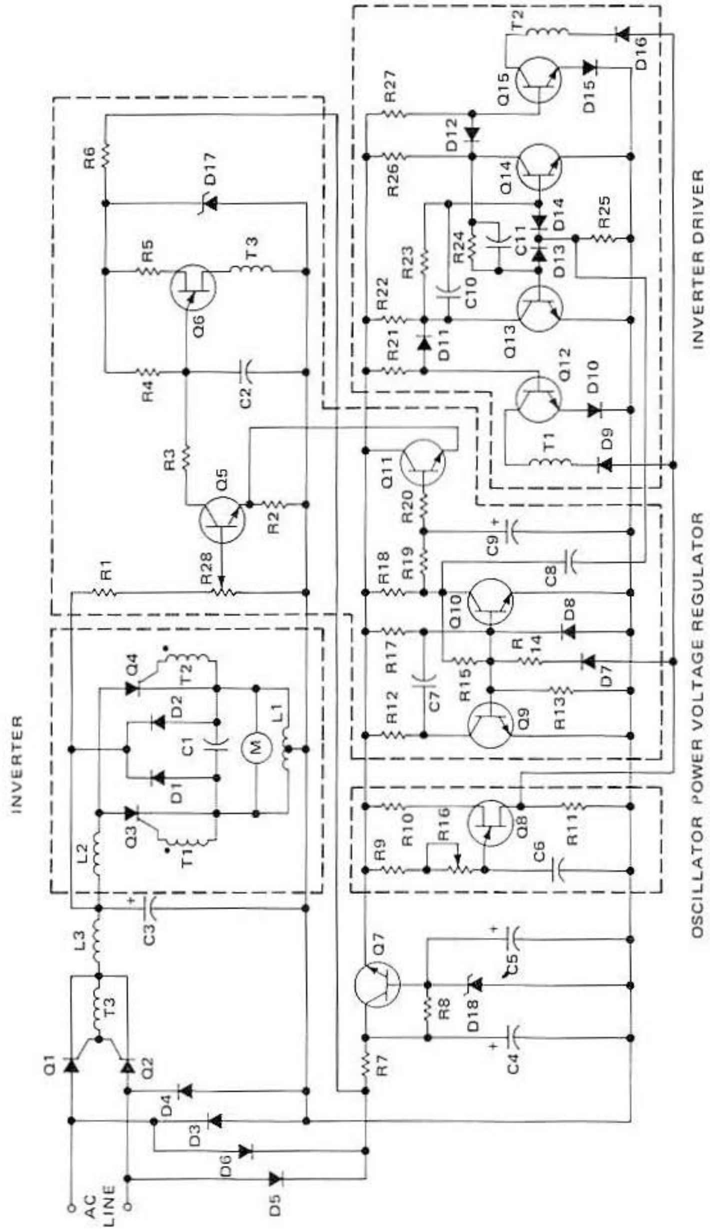


Figure 1-13 – Speed-Control Circuit for Inverter-Driven, Single-Phase, Induction Motor

Parts List for Figure 1-13

CAPACITORS
C1 – 10 µF, N.P., 300 V
C2 – 0.05 µF, 25 V
C3 – 6,000 µF, 300 V
C4 – 50 µF, 50 V
C5 – 50 µF, 25 V
C6 – 0.25 µF, 25 V
C7 – 0.25 µF, 25 V
C8 – 0.001 µF, 25 V
C9 – 50 µF, 25 V
C10 – 0.001 µF, 25 V
C11 – 0.001 µF, 25 V

DIODES
D1 – MR1125
D2 – MR1125
D3 – MR1125
D4 – MR1125
D5 – 1N4004
D6 – 1N4004
D7 – 1N4001
D8 – 1N4001
D9 – 1N4001
D10 – 1N4001
D11 – 1N4001
D12 – 1N4001
D13 – 1N4001
D14 – 1N4001
D15 – 1N4001
D16 – 1N4001
D17 – 1N4744
D18 – 1N4744

INDUCTORS
L1 – 32 mH, CT, 10 A
L2 – 1 mH, 10 A
L3 – 20 mH, 10 A

TRANSFORMERS
T1 – SPRAGUE 11 Z 13
T2 – SPRAGUE 11 Z 13
T3 – SPRAGUE 11 Z 13

RESISTORS
R1 – 30 kΩ, 1 W
R2 – 620 Ω, 1 W
R3 – 560 Ω
R4 – 43 kΩ
R5 – 330 Ω
R6 – 22 kΩ, 1 W
R7 – 3.5 kΩ, 5 W
R8 – 1 kΩ, 1 W
R9 – 20 kΩ
R10 – 2.7 kΩ
R11 – 390 Ω
R12 – 10 kΩ
R13 – 6.8 kΩ
R14 – 22 kΩ
R15 – 56 kΩ
R16 – 60 kΩ, 1 W Potentiometer
R17 – 150 kΩ
R18 – 2 kΩ
R19 – 33 kΩ
R20 – 10 kΩ
R21 – 6.8 kΩ
R22 – 10 kΩ
R23 – 36 kΩ
R24 – 36 kΩ
R25 – 51 kΩ
R26 – 10 kΩ
R27 – 6.8 kΩ
R28 – 2.5 kΩ, 2 W Potentiometer

TRANSISTORS AND SCRs
Q1 – 2N5170
Q2 – 2N5170
Q3 – 2N5170
Q4 – 2N5170
Q5 – 2N4124
Q6 – 2N4871
Q7 – 2N3019
Q8 – 2N4871
Q9 – MPS6531
Q10 – MPS6531
Q11 – 2N4124
Q12 – 2N3904
Q13 – 2N3904
Q14 – 2N3904
Q15 – 2N3904

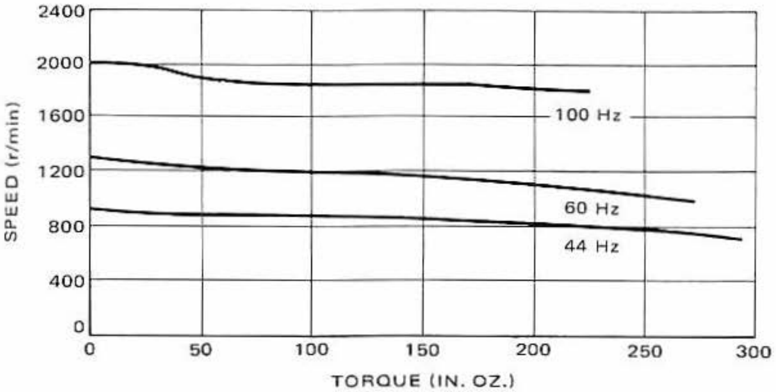


Figure 1-14 – Speed-Torque Characteristics of Induction Motor Controlled by Inverter-Driven Speed Control

1.3 Ring-Counter-Driven 3-Phase Motor Speed Control

The three-phase, forced-self-commutated inverter in Figure 1-15 is actually a ring counter which has a motor winding as the load for each stage. The successive firings of the SCRs create a moving flux field around the stator, which develops a torque on the rotor. The commutating circuit requires a dc supply. It is important to remember that the excitation current must be held constant, so the supply voltage has to be varied with the applied frequency. If the ac power lines are used as the primary source, then a voltage regulator similar to that shown for the inverter-driven, single-phase motor control of Section 1.2 can be used to provide the variable direct current for this circuit. The value of commutating capacitors C1, C2 and C3 depends upon the parameters of the particular motor used. The capacitors must be small enough to ensure that an adequate charge for commutation be stored in them at the highest frequency of interest. The charging rate depends on the motor winding inductance and the capacitance.

The time constant of the SCR firing circuit (such as R3, R4, and C4) must allow gate current to exist long enough for the anode current to exceed the holding current in this period of time. This again depends on the inductance of the motor winding. If the inductance is too large, a resistor to provide holding current can be placed in parallel with the winding.

An advantage of this circuit over other inverters is the ease with which the motor's rotation can be reversed. Interchanging any two of the three windings will reverse the rotation.

The motor's neutral connection is tied to the positive side of the supply voltage. The other end of each winding is returned to the supply through an SCR. When an SCR is on, the 1.5 kΩ resistor connected to its anode is grounded, allowing the diode connected to the other side to be forward-biased, but when the SCR is off the 1.5 kΩ resistor is at the supply potential, reverse-biasing the trigger input diode. What this does is to steer the next pulse arriving at the trigger input to the SCR at the right of the one that is on. To obtain the same speed as with an ac supply, the driving frequency must be increased by the factor equal to the number of windings used in the ring counter. In this case three windings were used so the driving frequency had to be 180 Hz to attain the same speed as normal motor operation on 60 Hz. The particular motor used in this test had two-pole, three-phase, wye-connected 220 volt windings. This meant that each winding was a 110 volt winding. Therefore, at 3600 r/min the supply voltage had to be 110 volts to deliver design torque per winding. However, the rated torque can not be achieved since only one winding is energized at

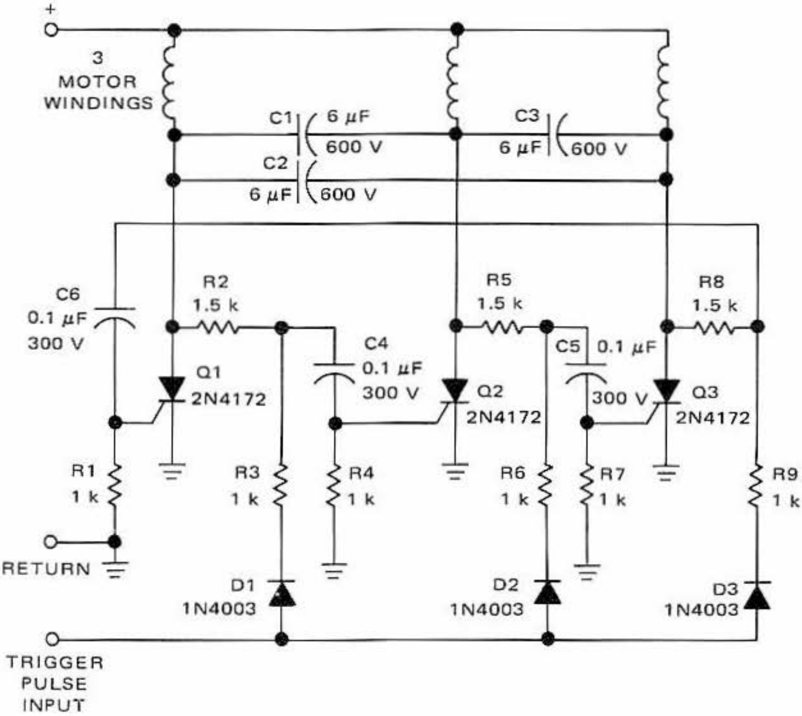


Figure 1-15 – Ring-Counter-Driven, Three-Phase Induction Motor

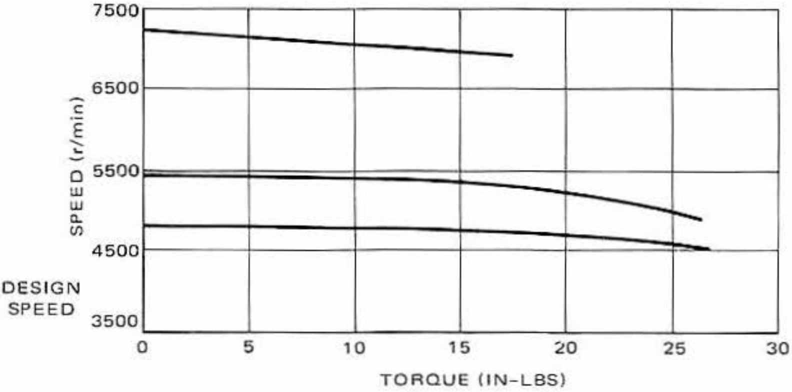


Figure 1-16 – Performance of Ring-Counter-Driven, Three-Phase Induction Motor

a time. The efficiency of the motor is about 20% less than design at rated speed due to the increased I^2R losses and core losses resulting from square wave voltage operation instead of sine wave voltage. At the higher speeds more power is required to overcome friction, windage and core losses. This particular motor was run as high as 7200 r/min; however, speeds in excess of this can be achieved. The speed-torque curve at each speed setting selected had only moderate droop. The droop increased at higher speeds as was expected, and is shown in Figure 1-16.

1.4 Series-Wound, DC-Motor Speed-Control Circuits

The speed of a series connected dc motor can be controlled by varying the average voltage applied to the motor. A variable voltage can be obtained in a number of ways, the easiest of which is phase controlling a thyristor connected in series with a motor operating from an ac supply.

The most economical circuit, in that it uses the fewest components, is the half-wave, uncompensated control shown in Figure 1-17. The control of speed is effective over a wide range, providing stable operation at low speeds with a given load. The circuit controls the average motor voltage by setting the firing point of SCR Q1. The time required for capacitor C1 to charge to the gate turn-on voltage is set by potentiometer R2. Once the SCR is on, the capacitor voltage is less than the forward voltage drop of the SCR for the rest of the half cycle. During the reverse half cycle, diode D1 blocks any current which would try to pass through the SCR gate. Capacitor C2 is then ready to begin charging when the next half cycle starts. The speed-torque curves for different speed settings of a 1/15 hp, 5,000 r/min, 115 volt motor are shown in Figure 1-18.

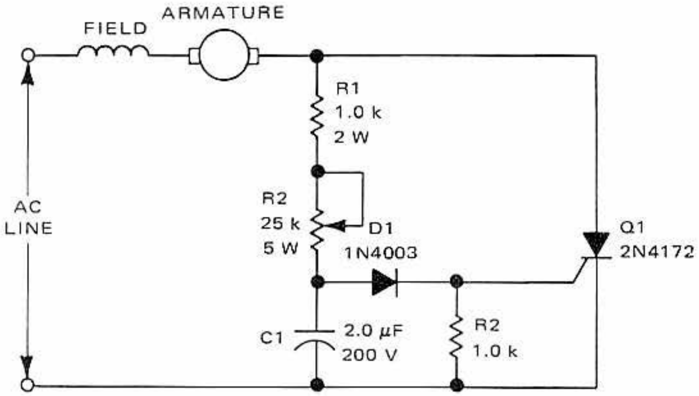


Figure 1-17 – Uncompensated Half-Wave Drive for Series-Wound DC Motors

Better speed regulation can be obtained through the use of the half-wave compensated control shown in Figure 1-19. The circuit operates similarly to the previous one but uses the back emf of the motor to provide feedback during the time when the SCR is off. This feedback compensates for load differences, as it is inversely proportional to the load. That is, as the load is increased, the motor's speed is decreased and the back emf is decreased. When this occurs, the gate voltage exceeds the cathode voltage at an earlier phase angle, and turns the SCR on sooner.

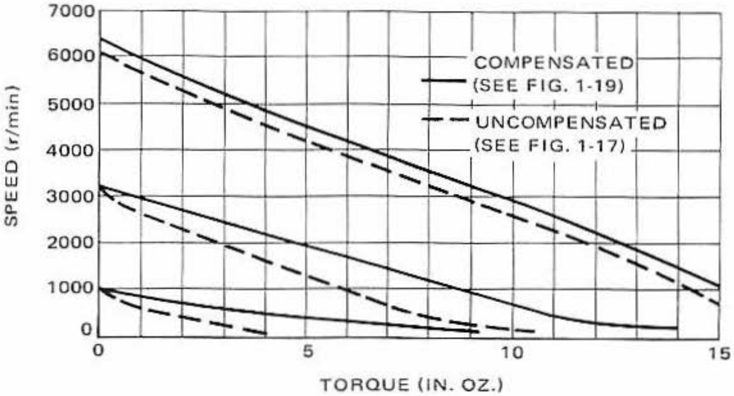


Figure 1-18 – Speed-Torque Characteristics of Series-Wound Motor with Half-Wave Control

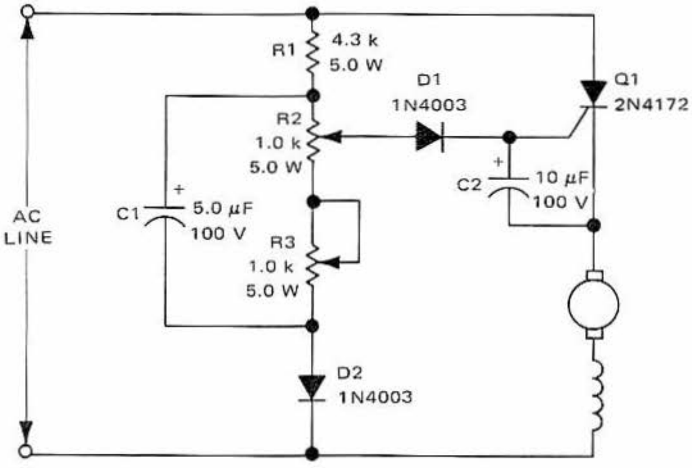


Figure 1-19 – Compensated Half-Wave Drive for Series DC Motors

This provides more drive to the motor, returning the speed to the original value. Actually, for the half-wave circuit, the speed does not remain the same, but the droop of the speed-torque curve is reduced considerably from that of the uncompensated circuit. The speed-torque curves for this circuit are shown in Figure 1-18, where they may be compared with those obtained from the uncompensated circuit. It can be seen that as the control resistance is increased, the speed is reduced, but the droop is much smaller. At slow speeds, the characteristic curves approach those of a shunt-wound motor.

An inexpensive circuit which provides full-wave control, but no compensation, uses a three-layer diode and a triac. The schematic is shown in Figure 1-20. The maximum average voltage is greater for full-wave control than for half wave; therefore, the motor can provide greater maximum torque with full-wave control. The characteristic curve is the same as that obtained for the uncompensated half-wave control circuit except that it has been translated to higher torque values. This curve is shown in Figure 1-21. The triac will turn on with gate current in either direction; therefore, three-layer diode D1 is used to set the firing point. When the voltage across capacitor C2 exceeds the breakover voltage of D1, it conducts and turns on triac Q1. The time required for the voltage to reach this point is controlled by the potentiometer. When the triac is on, the capacitors discharge to the forward voltage drop of the triac. They begin to charge towards the firing voltage again when the next half cycle from the line appears after the current passes through zero.

If greater speed control is necessary, a full-wave compensated circuit such as shown in Figure 1-22 can give characteristics very similar to those of a shunt-wound motor. The operation of this circuit is the same as that

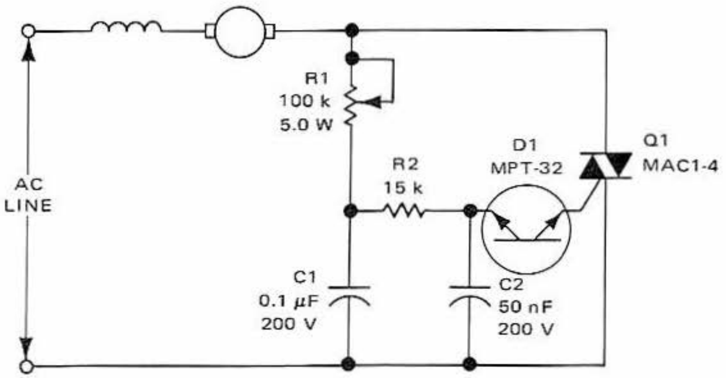


Figure 1-20 — Uncompensated Full-Wave Drive for Series-Wound DC Motors

of the half-wave circuit with compensation, with the exception that full-wave voltage is applied to the motor through the rectifier bridge, and a diode is required across the field. The function of this diode (D5) is to provide a current path for the energy stored in the inductive field, thereby enabling the SCR to turn off. An undesirable condition can occur with this circuit: At low speed settings and at no load, the SCR may not fire on every cycle due to the difference in the back emf of the motor from that at high loads and speeds. The back emf of the motor under these conditions may be greater than the gate voltage of the SCR. If this happens, the SCR does not come on and the motor slows down until the back emf is lower than the gate voltage, at which time the SCR can again be turned on.

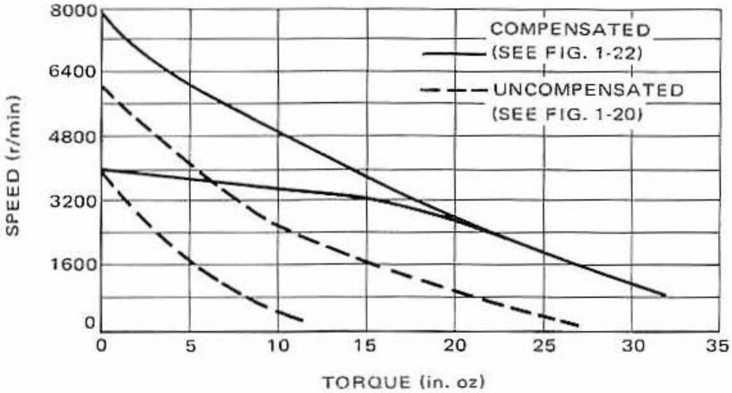


Figure 1-21 – Speed-Torque Characteristics of Series-Wound Motor with Full-Wave Control

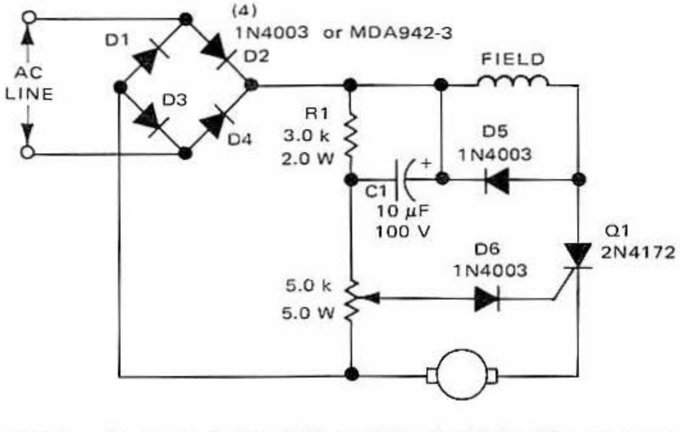


Figure 1-22 – Compensated Full-Wave Drive for Series-Wound DC Motors

This results in unstable speed control and can cause a pulsating speed. The speed-torque characteristics for this connection are shown in Figure 1-21. These curves exhibit the maximum flatness of this series. Of course, the motor characteristics as obtained when operated at rated dc voltage are the maximum that can be provided. Thus the speed-control circuit will provide effective control only up to this curve.

All of the curves shown were obtained for a 1/15 hp, 5000 r/min, 115 volt motor. This circuit is capable of controlling larger fractional

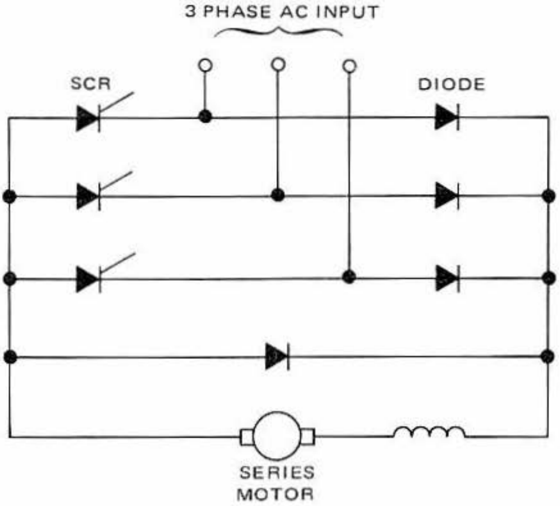


Figure 1-23 – Simplified Schematic of Half-Controlled, Full-Wave Bridge

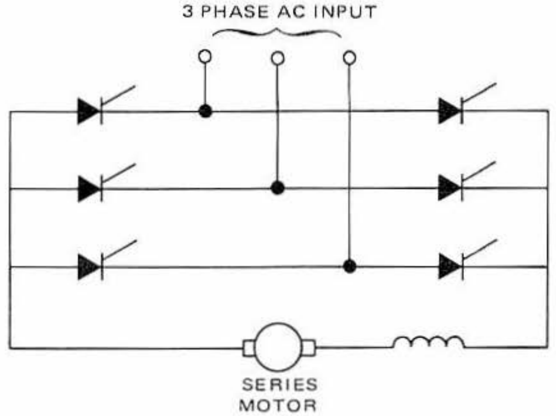


Figure 1-24 – Simplified Schematic of Fully-Controlled, Full-Wave Bridge horsepower motors. One-quarter-horsepower motors have been controlled with the devices as used in the schematics under normal conditions. The real criterion is the average steady-state current and the stalled-rotor current under the operating conditions. These two conditions must fall within the current ratings of the SCR. In most cases, higher-current SCRs will work in this circuit. Since a fractional-horsepower motor was used, a single-phase ac supply was used as the main power source. These circuits may require some adaptation for any given motor to obtain performance similar to those shown here. For large integral-horsepower motors, it may be necessary to use a three-phase supply to obtain enough driving power. This complicates the control and rectifier circuitry. Rectifier circuits as illustrated in Figures 1-23 and 1-24 can be used on a three-phase power line. The harmonic content of the output voltage with the half-wave controlled circuit is of higher amplitude and lower frequency than that of the fully controlled circuit. The fully controlled circuit has less ripple, better transient response, less susceptibility to damage from misfirings, and is readily adaptable to regenerative braking (if two circuits are connected back to back).

1.5 Shunt-Wound DC-Motor Speed-Control Circuits

The circuit shown in Figure 1-25 provides half-wave control of a shunt-wound motor. The field is supplied through diode D1 during the half cycle that Q1 conducts. Diode D2 across the field winding is used as a free-wheeling diode.

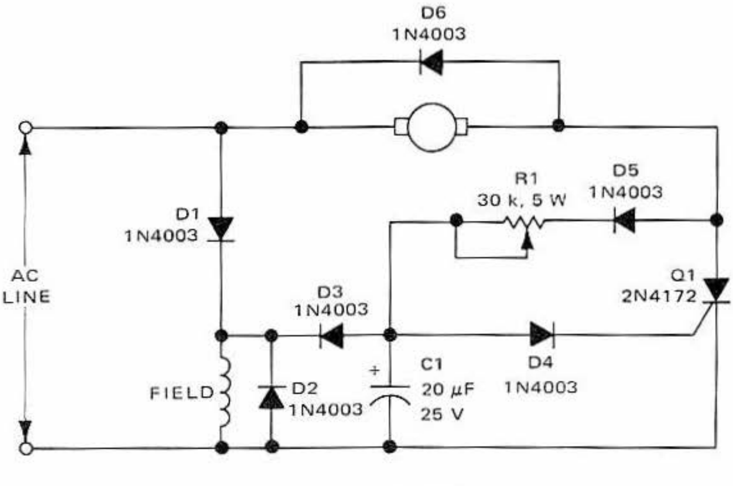


Figure 1-25 — Half-Wave Control of Shunt-Wound Motor

The average voltage applied to the armature is set by the conduction angle of SCR Q1. This angle is set by the charging rate of C1 through resistor R1. When the capacitor voltage exceeds the sum of the diode drops of D4 and the gate of SCR Q1, Q1 turns on. Q1 remains on until the current in this circuit goes to zero. Capacitor C1 is discharged through D3 every half cycle giving the same initial voltage from which the capacitor begins to charge.

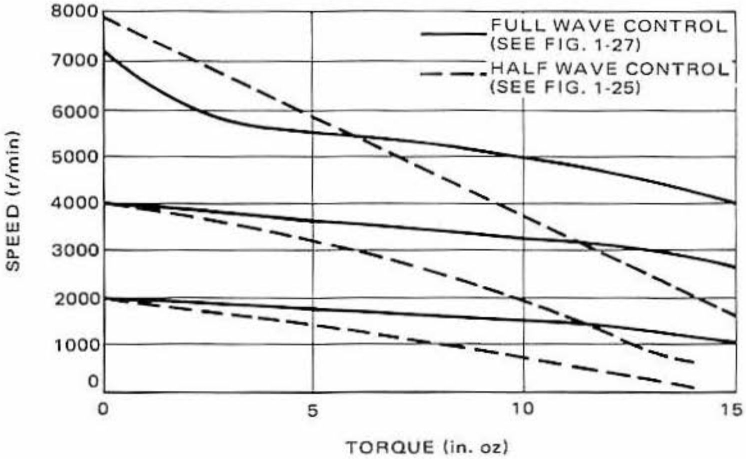


Figure 1-26 – Speed-Torque Characteristics of Controlled Shunt-Wound Motor

The speed-torque curves for a 1/15 hp, 5,000 r/min, 115 V motor used with this circuit are shown in Figure 1-26. The curve for the maximum speed setting shows the droop obtained with this circuit. When the no-load speed setting is reduced, the typical shunt-wound characteristics are obtained, but with a reduction in the droop of the curve.

Improved speed-torque characteristics can be obtained through the use of full-wave control. The circuit shown in Figure 1-27 can be used to provide full-wave control of a shunt-wound motor. The operation of this circuit is similar to that of half-wave control, except that power is supplied from a full-wave bridge. Free-wheeling diode D5 connected across the armature is necessary in this circuit; without it, current would flow through SCR Q1 and the bridge rectifier, holding Q1 on. Four-layer-diode D8 was used to provide a stable firing point for Q1. The capacitor must charge to its breakover voltage before Q1 will turn on. At low speed settings and at light loads, some degree of erratic firing of Q1 was experienced. The maximum speed at which this occurred depends on the motor and the degree of loading of that motor. Only at very low speed settings was this pulsating characteristic objectionable.

The curves obtained with this circuit and a 1/15 hp, 5,000 r/min, 115 V motor are shown in Figure 1-26. These curves show that the full-wave control provides much better speed regulation than the half-wave control circuit. These circuits may require adaptation for some motors to obtain characteristics similar to those obtained with this motor.

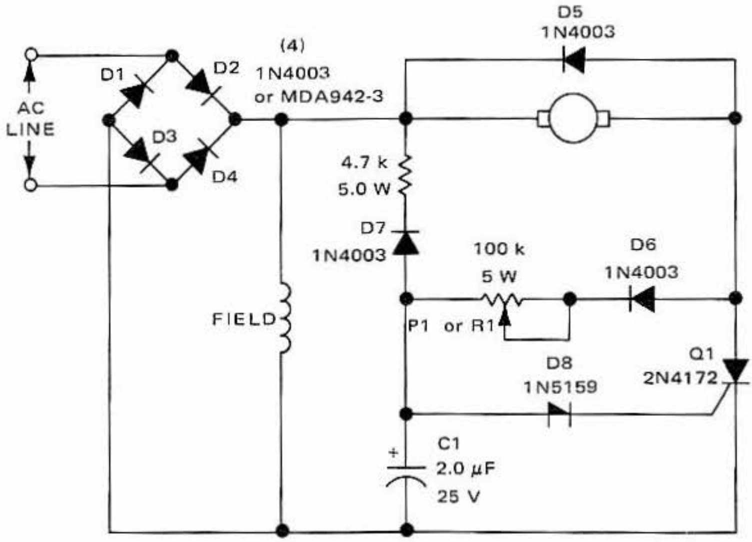


Figure 1-27 – Full-Wave Control of Shunt-Wound Motor

1.6 Direction- and Speed-Control Circuits for Series, Universal, and Shunt Motors

The circuit shown in Figure 1-28 can be used to control the speed and direction of rotation of a series-wound dc motor. Silicon controlled rectifiers Q1 through Q4 are connected in a bridge arrangement, and are triggered in diagonal pairs. Which pair is turned on is controlled by switch S1 since it connects either coupling transformer (T1 or T2) to a pulsing circuit. The current in the field can be reversed by selecting either SCRs Q2 and Q3 for conduction, or SCRs Q1 and Q4 for conduction. Since the armature current is always in the same direction, the field current reverses in relation to the armature current, thus reversing the direction of rotation of the motor.

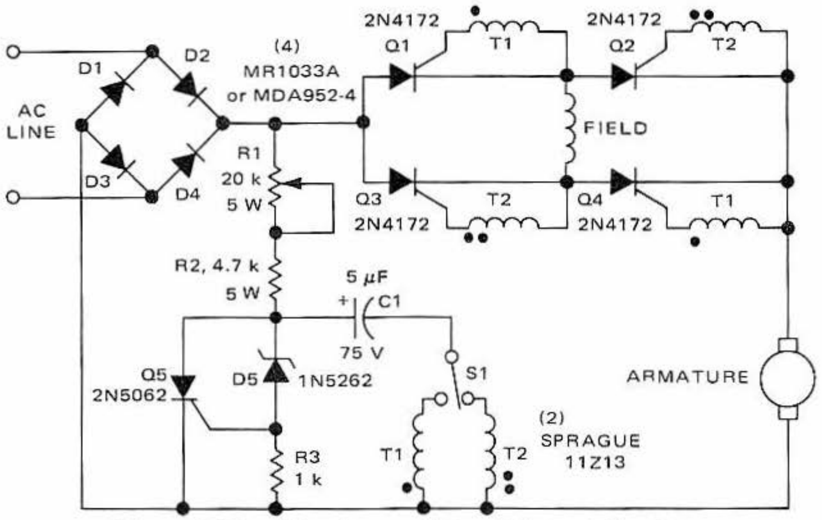


Figure 1-28 – Direction- and Speed-Control Circuit for Series-Wound or Universal Motor

A pulse circuit is used to drive the SCRs through either transformer T1 or T2. The pulse required to fire the SCR is obtained from the energy stored in capacitor C1. This capacitor charges to the voltage of zener diode D5 through potentiometer R1 and resistor R2. As the capacitor voltage exceeds the zener voltage, the zener conducts, delivering current to the gate of SCR Q5. This turns Q5 on, which discharges C1 through either T1 or T2, depending on the position of S1. This creates the desired triggering pulse. Once Q5 is on it remains on for the duration of the half cycle. This clamps the voltage across C1 to the forward voltage drop of Q5. When the supply voltage drops to zero, Q5 turns off, permitting C1 to begin charging when the supply voltage begins to increase.

The speed of the motor can be controlled by potentiometer R1. The larger the resistance in the circuit, the longer C1 requires to charge to the voltage of zener D5. This determines the conduction angle of either Q1 and Q4, or Q2 and Q3, thus setting the average motor voltage, and thereby the speed.

If a shunt-wound motor is to be used, then the circuit shown in Figure 1-29 is required. This circuit operates like the one shown in Figure 1-28; the only differences are that the field is placed across the rectified supply and the armature is placed in the SCR bridge. Thus the field current is unidirectional, but armature current is reversible, and consequently the motor's direction of rotation is reversible. Potentiometer R1 controls the speed as explained previously.

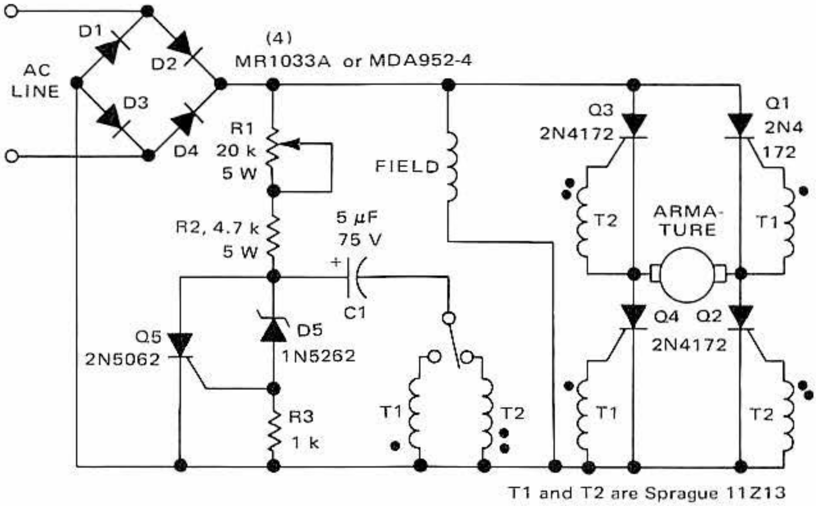


Figure 1-29 – Direction- and Speed-Control Circuit for Shunt-Wound Motor

Excellent results were obtained when these circuits were used to control 1/15 hp, 115 V, 5,000 r/min motors. This circuit will control larger fractional-horsepower motors provided the motor current requirements are within the semiconductor ratings. Higher-current devices will permit control of even larger motors. The operation of the motor under worst case must not cause anode currents to exceed the ratings of the semiconductor.

1.7 Permanent-Magnet-Motor Speed Control

The circuit shown in Figure 1-30 can be used to control the speed of a permanent-magnet motor. It was tested with a 35 volt motor. A step-down transformer was used to permit circuit values that gave phase control over the full half cycle. This is not actually necessary as the SCR could have been phased back to keep the average motor voltage below its maximum rating. However, if a motor designed for a higher voltage were to be used, component values would have to be modified. If a transformer is not used, the maximum average voltage can be set by placing a resistor in the position shown by R1. The higher the value of this resistor, the lower the maximum average voltage will be.

The full-wave bridge (D1-D4) provides power to the motor and control circuits every half cycle. SCR Q1 is turned on when the charge on capacitor C1 exceeds the sum of the voltage drops in diode D5 and the

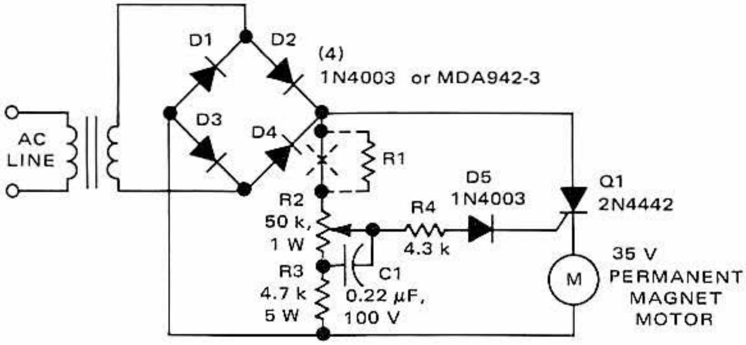


Figure 1-30 – Speed Control for a Permanent-Magnet Motor

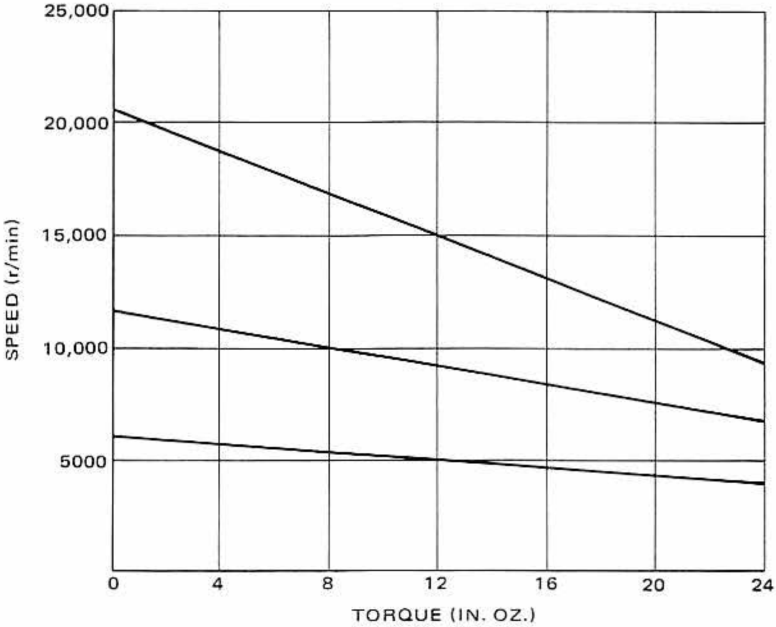


Figure 1-31 – Speed-Torque Characteristics of Controlled Permanent-Magnet Motor

gate of Q1, plus the back emf of the motor. The time required to fire Q1 is set by the potentiometer, which governs the charging rate of the capacitor. As the motor load is increased, the back emf is reduced, and for any potentiometer setting, Q1 turns on sooner thereby compensating for the increased load.

This circuit demonstrated excellent speed control from 0 to 20,500 r/min as shown in Figure 1-31. When a load was placed on the motor, the control was smooth over the speed range. At light loads and slow speeds (up to 12,000 r/min), some degree of pulsation was noticed. This is caused by the back emf of the motor rising above the capacitor voltage setting, thus preventing SCR Q1 from turning on. When the motor slows down sufficiently, the SCR turns on and speeds the motor up; the process then starts over again. The amount of pulsation is small enough that it is not objectionable. When the motor is loaded, this effect disappears.

1.8 Pulse-Width-Modulated DC-Motor Speed Control

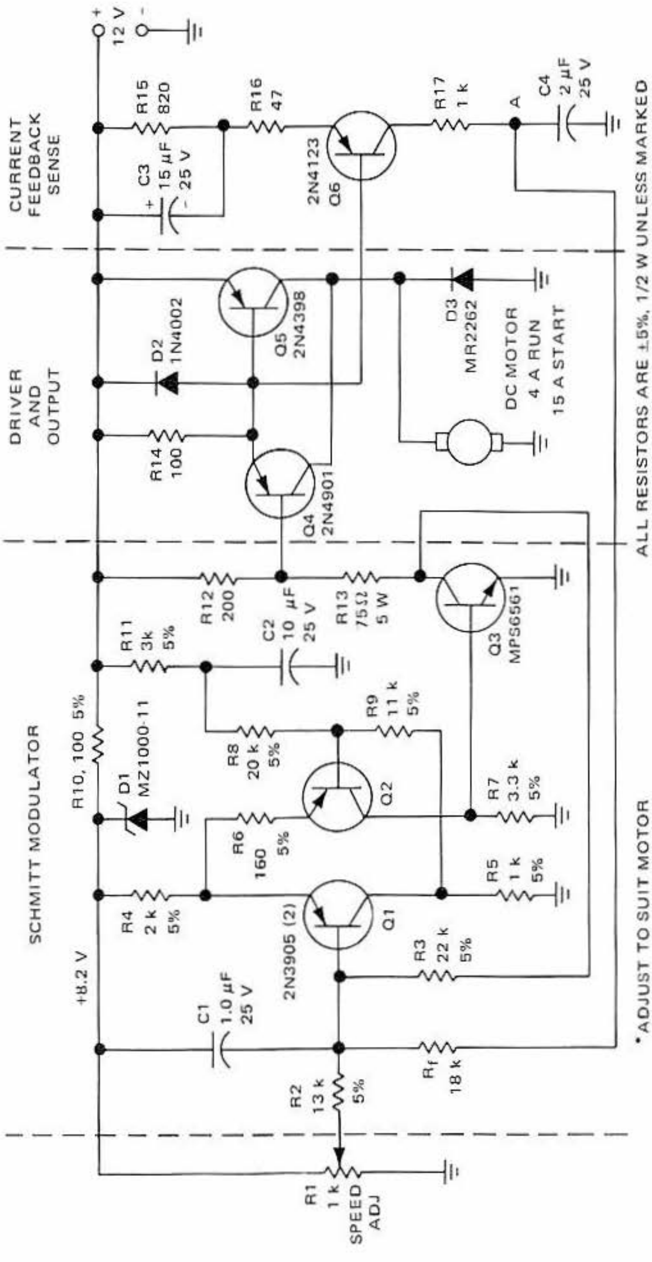
Figure 1-32 is the schematic diagram of a pulse-width-modulated dc-motor speed control. The circuit operates from a 12 volt dc source and is capable of driving motors with in-rush currents up to 20 amperes. The maximum allowable running current will obviously be less than 20 A, and will depend to a great extent on the heat sinking provided for Q5.

The modulated waveform is provided by the Schmitt trigger consisting of Q1 and Q2, phase-inversion stage Q3, and the delayed feedback, R3 and C1. The output is a variable-width, variable-frequency pulse waveform whose duty cycle and frequency are a function of the dc input. The dc input is the summation of the current through R2, which is connected to the speed-adjustment potentiometer R1, and the current through R_f, the overall feedback resistor.

The output of the modulator is fed to a Darlington-connected power-amplifier stage consisting of Q4 and Q5, which drives the dc motor. Free-wheeling diode D3 suppresses the inductive kickback of the motor. Diode D2 protects the base-emitter junction of Q5 against reverse breakdown due to voltage transients generated by the motor.

The overall feedback voltage used to maintain constant motor speed is generated by sensing the forward base-emitter voltage of Q5, causing Q6 to conduct a greater amount of current as the load is increased. The voltage at point A will then rise and Q1 will begin to conduct for a shorter period of time. This means that the duty cycle of Q2 through Q5 will increase and a larger average voltage will be applied to the motor, thus compensating for the increased load.

The curves shown in Figure 1-33 are the open-loop operating characteristics of a 12 volt, 4 ampere dc motor. Figure 1-34 shows the effect of controlling this motor with the circuit shown in Figure 1-32. As can be seen, the operating characteristics are considerably improved.



*ADJUST TO SUIT MOTOR

ALL RESISTORS ARE ±5%, 1/2 W UNLESS MARKED

Figure 1-32 – DC Motor Speed Control with Current Feedback from V_{BE} Sensing

The data for Figure 1-34 were taken at −20°C, +25°C and +65°C, with a 12 volt supply voltage. Figure 1-35 shows the effects of varying the power-supply voltage at 25°C. Zener diode D1 is used to provide a regulated voltage to speed-adjustment potentiometer R1, and to the two stages of the Schmitt trigger. This minimizes the effects of power-supply variations on this part of the circuit and tends to keep the duty cycle and frequency independent of the supply voltage. However, the average voltage applied to the motor is a direct function of the supply voltage. Thus some means must be provided to compensate for this, and that is the reason for

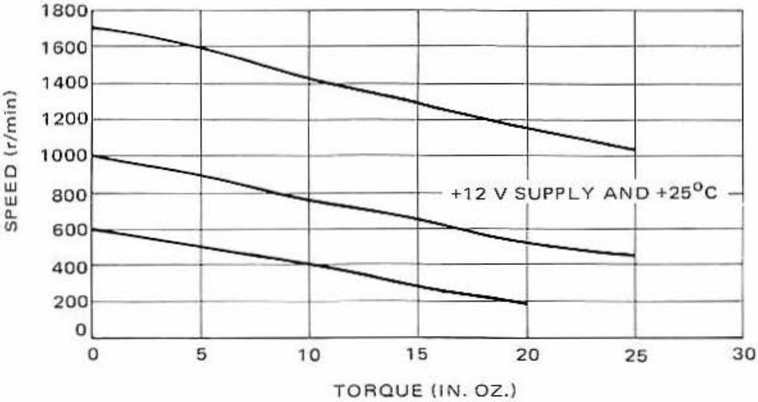


Figure 1-33 – Open-Loop Operating Characteristics of DC Motor

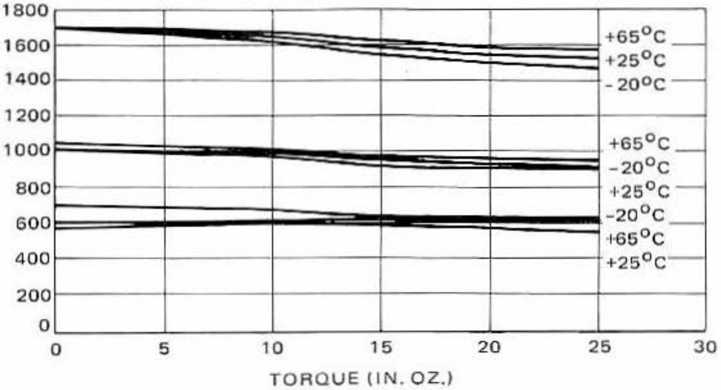


Figure 1-34 – Temperature Characteristics of Motor Controlled by Speed Control Circuit with Current-Sensitive Feedback

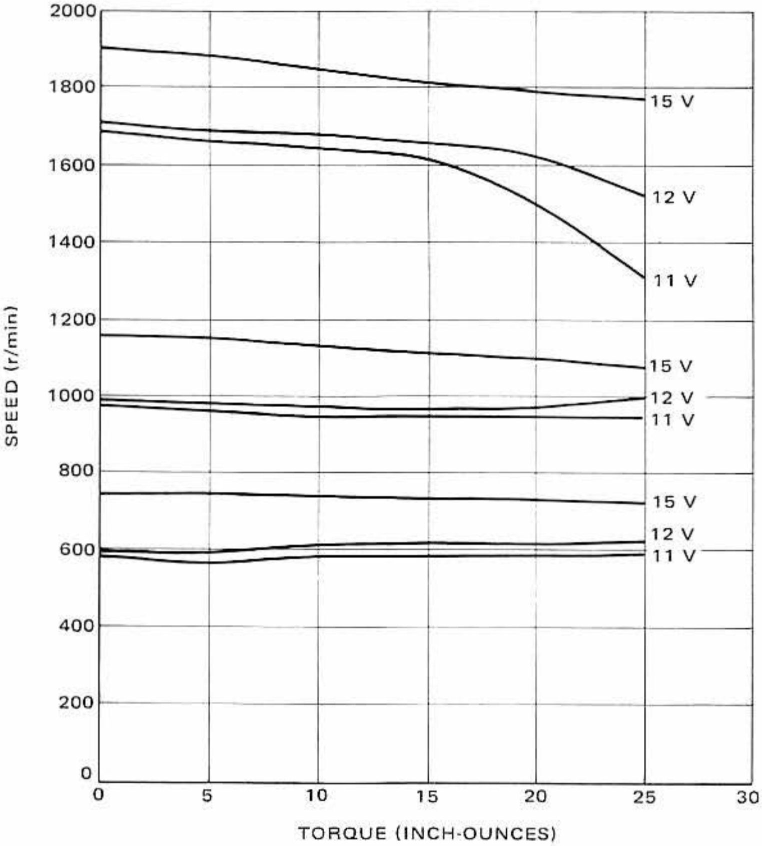


Figure 1-35 – Effect of Different Supply Voltages on Speed Control Circuit with Current-Sensitive Feedback

Parts List for Figure 1-36

CAPACITORS
C1 – 10 nF
C2 – 1.0 μF
C3 – 8 μF, 15 V
C4 – 50 μF, 15 V
C5 – 1.0 μF

DIODES
D1 – 1N4001
D2 – 1N4001
D3 – 1N4001
D4 – 1N4738
D5 – 1N4001
D6 – MR2262

RESISTORS
R1 – 27 kΩ
R2 – 10 kΩ
R3 – 10 kΩ
R4 – 10 kΩ
R5 – 10 kΩ
R6 – 10 kΩ
R7 – 10 kΩ
R8 – 2 kΩ
R9 – 10 kΩ
R10 – 47Ω
R11 – 10 kΩ
R12 – 1 kΩ
R13 – 1 kΩ
R14 – 470 Ω
R15 – 47 Ω
R16 – 47 Ω
R17 – 10 kΩ
R18 – 22 kΩ
R19 – 2 kΩ
R20 – 1 kΩ
R21 – 11 kΩ
R22 – 10 kΩ
R23 – 160 Ω
R24 – 3.3 kΩ
R25 – 200 Ω
R26 – 75 Ω
R27 – 100 Ω

TRANSISTORS
Q1 – MRD300
Q2 – 2N4123
Q3 – 2N4123
Q4 – 2N4221
Q5 – 2N3903
Q6 – 2N3903
Q7 – 2N4125
Q8 – 2N3905
Q9 – 2N3905
Q10 – MPS6561
Q11 – 2N4901
Q12 – 2N4398

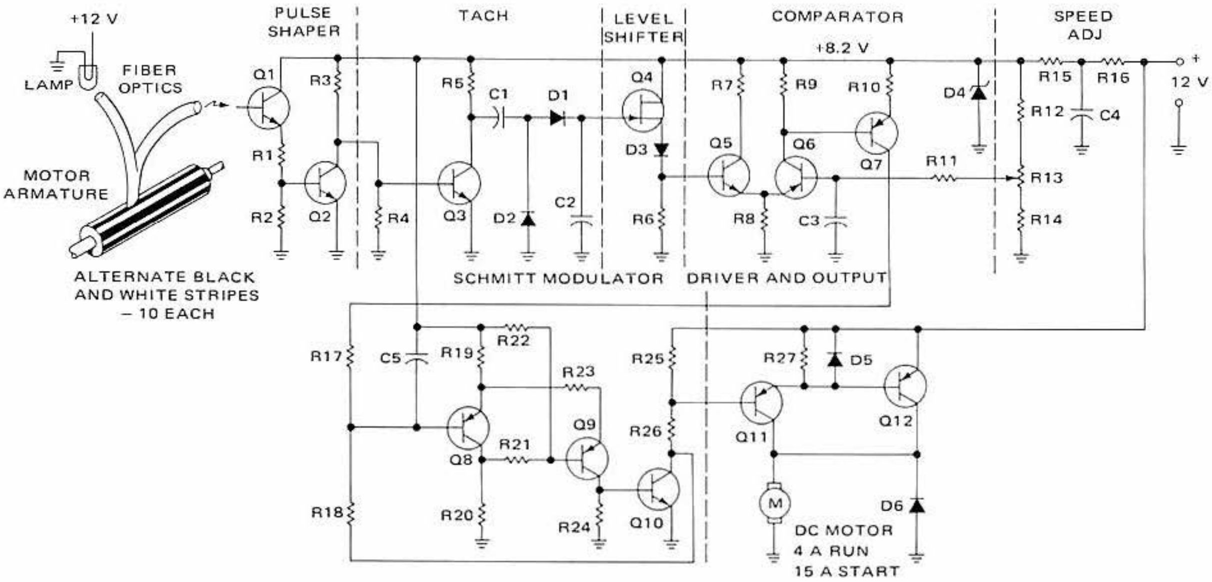


Figure 1-36 — Regulated DC Motor Control with Feedback from Optical Pickoff connecting the voltage divider consisting of R5, R8, R9 and R11 to the 12 volt supply. If the voltage increases, Q2 will conduct for a shorter time, reducing the duty cycle of the voltage applied to the motor, thereby keeping the average voltage seen by the motor constant.

Although this circuit can significantly improve the speed-torque characteristics of the motor, it has one major disadvantage. Resistor R15 (820 ohms in Figure 1-32) must be selected for the particular motor used and for the base-emitter drop of power transistor Q5. This can be accomplished by setting the no-load speed at one half the rated speed with rated dc applied. The motor is then loaded to full load, and R15 selected to restore the speed to the no-load speed.

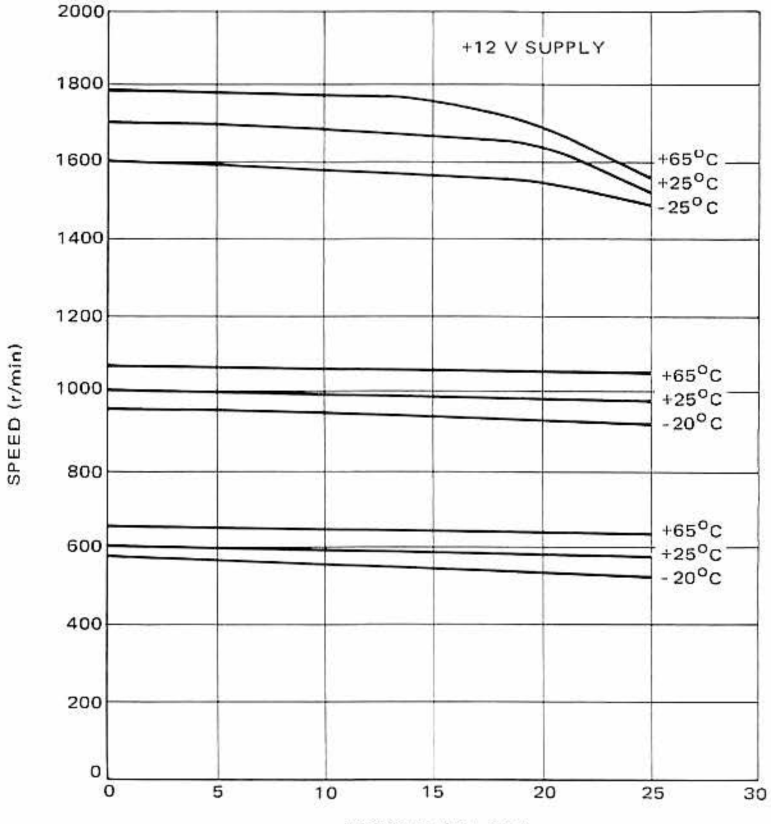


Figure 1-37 – Temperature Characteristics of Motor Controlled by Speed Control Circuit with Optical Feedback

To further improve the motor's speed-torque characteristics, the circuit shown in Figure 1-36 can be used. This circuit illustrates a dc-motor speed control using an optical pick-off to complete the closed-loop system.

The motor armature is painted with alternate black and white stripes. A total of twenty stripes was used for the circuit show. A bundle of noncoherent fiber optics is used to transmit light from a 12 volt lamp to the armature, and transmit reflected light from the armature to the input of Q1, a MRD-300 phototransistor. The light transmitted from bulb to armature to phototransistor is chopped at a frequency determined by the speed of the motor.

The output of the phototransistor is fed into a pulse-shaping circuit, and then into a tachometer circuit whose dc output is proportional to the input frequency. The output of the tachometer is fed to Q4, a junction field-effect transistor. The JFET provides a high input impedance to minimize loading on the tachometer circuit, and a reasonably low output impedance to drive the differential amplifier. In addition, it acts as a level shifter to ensure that there is sufficent output to bias the differential amplifier when the tachometer output is zero. The diode in series with the source lead of the FET is used for temperature compensation.

The differential amplifier compares the fixed-speed-adjust voltage from R13 to the output of the tachometer level shifter, and generates an output voltage that is proportional to the difference, or error, between the two. Capacitor C3 is used to prevent motor-speed overshoot when the speed-adjustment potentiometer is changed rapidly.

The T network (R15, R16 and C4) and zener diode D4 are used to reduce supply voltage variations to the pulse shaper, tachometer, level shifter and comparator circuits.

The output of the comparator is amplified and fed into a pulse-width modulator similar to the one shown in Figure 1-32.

The output of the modulator is then fed into a Darlington circuit consisting of Q11 and Q12, which drives the motor.

The feedback for this circuit is derived from a direct measurement of the armature speed of the motor. This permits the speed of the motor to be well regulated as shown in Figure 1-37. An alternate method of temperature-compensating the circuit can be accomplished by removing diode D3 and adding diodes in series with R9. Two or more diodes will probably be necessary for best temperature compensation, but one may yield satisfactory results.

Figure 1-38 shows the results of power-supply voltage variations. The effects at lower supply voltages are greater since the pulse width reaches 100% and cannot be increased further to provide additional average motor voltage required by the load.

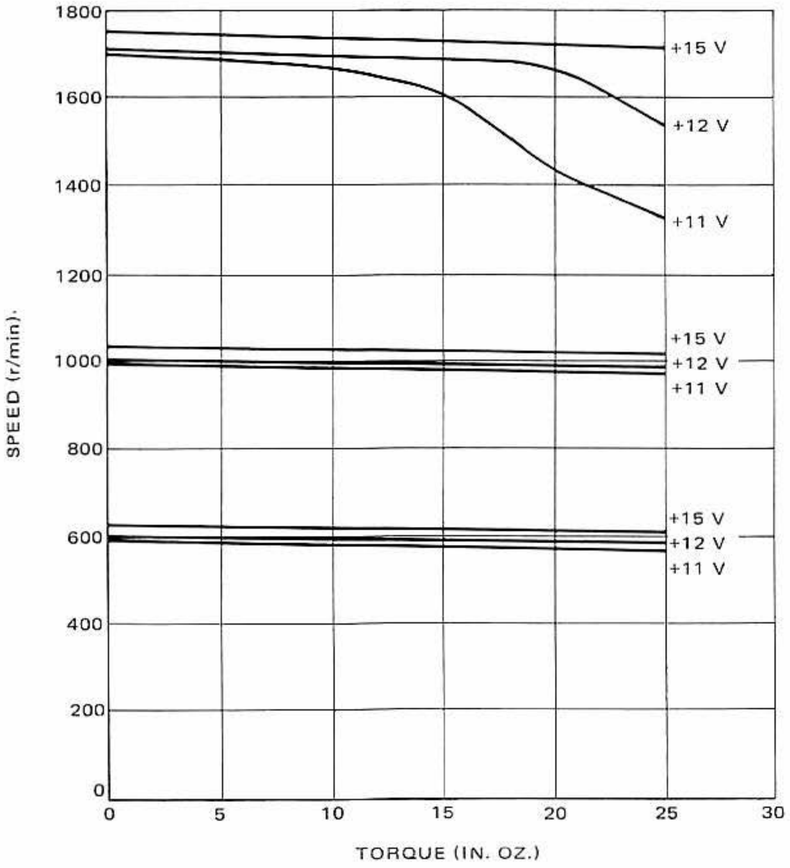


Figure 1-38 – Effect of Different Supply Voltages on Speed Control Circuit with Optical Feedback

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