Motor Controls

Although some applications simply use a motor to drive a load at a constant or relatively constant speed (up to motor nameplate rating), most applications require some type of control device to adjust motor speed, sometimes from zero to speeds above rated. Other situations require velocity, torque and position control. The type and degree of control capability needed is determined by the application and by the type of motor used.

Up to this point in the Handbook, we have discussed motor theory, types and construction in a fairly straightforward manner. When discussing motor controls, however, it soon becomes obvious that there is an extremely wide range of control methods available today, ranging in complexity from the simple series rheostat to sophisticated electronic controls. The range of controls can be extended further with the addition of feedback transducers such as encoders and tachometers, which allow position and speed to be controlled quite accurately.

In addition, refinements in motor technology such as brushless DC and improvements in stepper motor construction have increased motion control options even further. These improvements are being driven by industry demands for motion control accuracy and by the need to develop more torque from a smaller motor frame size. As automation and control systems increase in number and complexity, new demands for improved performance will continue to be placed on motor and control manufacturers.

In the following sections, we will discuss the many aspects of motion control as they apply to a variety of control systems and motor types. The reader should be aware that choosing a motor control method is simply another form of problem solving. The more specifics you know about the problem, the simpler it will be to select a control method.

Certain criteria such as the power source (AC or DC), the degree of control required, the system controller type, the process you need to control, and your budget will all affect your decision. An understanding of these criteria will also allow you to narrow your focus on a particular type of motor and control very early in the process, making the decision easier.
8.1 MOTION CONTROL SYSTEMS

No discussion of motor controls would be complete without a basic understanding of the larger world of motion control systems. In order to select the most appropriate motor and control method, the designer must know what role the motor will play in the total process control system. If the system is controlling a number of similar processes, such as a series of conveyors that transport a relatively constant load on a continuous basis, then the motor selection and motion control method may be quite straightforward. If the motor must drive varying loads at a constant speed, or at speeds that must be synchronized with other processes, or if precise positioning is needed to perform a process, then motor and control selection becomes more demanding.

In complex process control systems, the system control and the motor control must be considered as well as the interface between the two.

Process Types

Process control systems, as the name implies, are used to control processes. This could be a batch process such as mixing ingredients in a food processing plant or mixing chemicals used in paint production. In either case, a specific number of individual steps are performed to get a batch of raw materials prepared for a process that is performed on the entire batch.

Another type of process is the continuous process where raw materials enter one side of a system and a fabricated or finished product exits the other side. A web printing press is an example of a continuous process. The blank paper is fed from a roll through the printer heads where ink is applied, then into an ink dryer, and finally through a variety of finishing machines that fold, bind and cut the continuous web into finished printed booklets.

Discrete processing requires a series of precisely sequenced events to occur in order to produce a finished product. A cellular manufacturing operation where a piece of raw metal stock is placed in a machine which sequentially bores or drills holes (on one or more axes), taps the holes with varying thread sizes, and performs other similar functions to produce a finished subassembly is an example of discrete processing.

Control System Components

Most control systems consist of similar functional elements that are used to regulate the flow of materials through the system and to control the timing and sequencing of events or processes.

System Controller: The system controller provides the intelligence for the process control system. It may be a programmable logic controller (PLC), a microprocessor, an analog computer or a series of relays. Its primary function is to act as the system’s timekeeper and traffic manager so that all of the functions occur at the right time and in the right order.

Actuators: Electromechanical actuators convert electrical power to some form of physical action. Motors are actuators. They can accept a control signal and move a conveyor belt to transport material to the next process. They can turn a shaft a set number of degrees to position a product for a specific operation to be performed on it. They can be used for intermittent or continuous processes depending on the type of motor and the requirements of the application. Other examples of actuators are brakes, clutches, solenoids, relays, valves and pumps.
**Actuator Controls:** Actuator controls (such as motor controls) function as system controllers in very simple systems. In more complex control systems where the motor is one of many actuators, the motor control is usually under the command of a separate system controller.

**Sensors:** A variety of sensors are used in process control systems to determine the status of each process. They are used to measure velocity, position, weight, volume, tension, temperature, pressure, etc. They are transducers that convert a physical property to an electrical signal which can be interpreted by the controller. The sensor output causes the controller to trigger some form of actuator to begin, end or interrupt a process.

**Signal Interfaces:** Sensors, actuators and controllers all operate on a variety of signal levels and types. Therefore, interfaces must be employed to translate signals or boost signal levels from one device to another. For example, the output of a digital computer must be converted to an analog signal before it can be used by a brushless DC motor control. Conversely, the output of an analog transducer must be converted to a digital signal before a digital computer can act on it. The voltage or current levels of sensor outputs are often too low to be interpreted by a controller, and therefore need to pass through an amplifier stage before being processed.

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**Control System Types**

Control system operation is usually divided into two basic types:
1) open-loop (no feedback), and
2) closed-loop (with feedback).

The type of system used depends on the type of application and the degree of control needed to control the process.

**Open-Loop Operation:** Open-loop control systems do not utilize feedback. In other words, the input to the system is set at a level to achieve the desired output and the state of the output has no effect on the input. See Fig. 8-1.

A simple motor-driven conveyor transporting boxes from one work area to another, at a set speed, is an example of an open-loop system. The speed is set by the conveyor operator and will vary only slightly depending on the load. If a person at the end of the conveyor fails to remove the boxes in a timely manner, the boxes will drop off the end of the conveyor. The motor speed will not adjust for variations in the output unless someone physically reduces the speed or turns the power off. The boxes dropping off the end of the conveyor (the output) have no effect on the motor speed (the input).

**Closed-Loop Operation:** A closed-loop system measures the output of the process and feeds a signal back to a junction point at the input of the system.
where it is compared to the input signal. The input defines the desired output. Changes in load or component values can cause the output to differ from the input. This error signal causes the output of the system to change in a way that acts to reduce the error signal to zero.

A conveyor used in an automatic parts inspection process is an example of a closed-loop system. Since the parts must pass through a camera’s field of view at a steady rate, the velocity of the conveyor must be held constant. Refer to Fig. 8-2. A tachometer, located at the drive output, feeds back a continuous signal to the system input that is proportional to the velocity of the output shaft. This feedback signal is compared to a reference input signal. Any variation in the output signal results in an error signal which causes the motor control to alter the speed of the motor until the error signal is reduced to zero.

The accuracy of such a system will depend on the calibration and stability of the input reference and the accuracy of the transducer converting the output quantity (velocity) to a voltage for feedback purposes. The input reference, feedback transducer calibration and stability are not included in the feedback loop, and as a result, are not subject to the loop’s self-regulation.

**Servo Control Systems**: Servo systems are closed-loop systems that follow a velocity, torque or position command. Servo systems can be divided into three basic types based on the type of input signals used to control the output.  
1) *Type 0* results in a constant position output when a constant input is applied.  
2) *Type 1* results in a constant velocity output when a constant input is applied.  
3) *Type 2* results in a constant acceleration output when a constant input is applied.

Various types of system controllers can be used to improve the response of a servo system by adjusting the error between the output signal and the input signal in different ways.  
1) *Proportional (P)* controllers adjust the system gain.  
2) *Proportional plus Integral (PI)* controllers adjust the gain and also increase the type number of the system by one, allowing other inputs to be accepted.  
3) *Proportional plus Derivative (PD)* controllers allow the gain and the transient response of the system to be changed.  
4) The *Proportional plus Integral plus Derivative (PID)* controller allows the gain, system type and transient response to be changed in order to improve operation.

For detailed information on servo control theory, the reader should consult the many reference sources available on the subject.
Motors used in servo drive systems must have certain performance characteristics:
1) linear speed / torque characteristics,
2) smooth torque delivery,
3) rugged construction,
4) high torque-to-inertia ratio,
5) high torque-to-power input, and
6) low electrical time constant.

The performance requirements of the system will determine which of these features are necessary. However, linear speed / torque characteristics are generally considered critical requirements for servo applications.

8.2 MOTOR OPERATING CHARACTERISTICS

Motor controls can be designed to regulate speed, torque, velocity and position. In some cases, acceleration and deceleration time constants can also be regulated. When motor velocity vs. torque is plotted on ±x and ±y axes, it reveals the characteristic speed / torque curve. In this discussion, velocity and speed are often used interchangeably. If you refer to Chapter 1, you’ll recall that speed is mathematically represented as the absolute value of velocity and therefore has no directional component.

Figure 8-3 shows the four quadrants of motor operation. Torque (T) is plotted on the “x” axis while angular velocity (ω) is plotted on the “y” axis. The direction of rotation (clockwise or counterclockwise) determines if a positive or negative torque or velocity is generated. Operating a motor within these four quadrants will produce various speed / torque relationships that will facilitate varying degrees of motion control. The designer needs to evaluate the degree of control that is required by the application early in the motor and control selection process to determine which motor is best suited for the application.

Different motors and controls exploit various aspects of the four quadrants better than others. A motor which can operate in all four quadrants offers more control over speed and torque and direction of rotation. The down side is that a motor control system, capable of four-quadrant operation, is usually costlier.

Fig. 8-3: Four quadrants of motor operation.
When selecting a motor control method, it is often advisable to discuss the control aspects with the motor or control manufacturer. Sometimes, solutions can be provided early in the design phase which will save considerable amounts of design time and money. For instance, servo motors are designed for high performance applications, which makes them more costly. However, not all four-quadrant applications require servo motor performance. Therefore, a system designer can often save money if the requirements of the application can be met by a less costly motor control system.

**Single Quadrant Operation**

A typical speed / torque curve for a permanent magnet (PM) motor or brushless DC motor is shown in Fig. 8-4a. The direction of shaft rotation is clockwise. By convention, when a motor shaft turns in a clockwise direction, it delivers some degree of positive torque at a given positive velocity. These characteristics are plotted in the first quadrant of the graph. A motor operating in the first quadrant is doing work. It is generating a force to displace a mass at a certain speed.

**Two Quadrant Operation**

Figure 8-4b shows the characteristics for the same brushless DC motor running in a counterclockwise direction. The velocity and torque are negative since the direction of rotation is reversed. All motors are capable of first quadrant operation. Reversible motors can operate in the first and third quadrants. This simply means that they can provide positive torque at a positive velocity and negative torque at a negative velocity.

**Controlling Motors with Linear Speed / Torque Characteristics**

Motor design engineers have learned that controlling motor speed is easier when the motor exhibits linear speed / torque characteristics. A close look at the relationship between velocity and torque and how certain motor designs can exploit their

![Fig. 8-4: Typical PM or brushless DC motor speed / torque curves: a) forward direction, positive velocity, positive torque (left), and b) reverse direction, negative velocity, negative torque (right).](image-url)
linear characteristics will help the reader to understand why these motors provide more versatile control capability.

In Chapter 1, Section 1.2, we learned that force \( F \) on a current-carrying conductor immersed in a magnetic field is a product of the magnetic flux density \( B \), the conductor’s current \( I \) and the length of the conductor \( l \):

\[
F = BIl \tag{1}
\]

A somewhat similar effect occurs when a conductor of length \( l \) is moved with velocity \( v \) through a magnetic field \( B \). A voltage \( V \) appears between the ends of the conductor according to the relationship:

\[
E = \int_0^l (v \times B) \, dl \tag{2}
\]

This formula reduces to \( E = Blv \). In a motor, the effect of current on the force generated and the effect of velocity on voltage occur together. Motion is produced by applied current and a generated voltage is produced by the resulting motion. The generated voltage \( E \) always acts to oppose and limit the normal applied current flow. It is referred to as counter emf or back emf.

In rotating machines, the conductors take the form of coiled turns. The torque developed on each turn of such a coil is often alternately expressed as the product of the current and the rate of change of the flux linking the turn. Therefore:

\[
T = i \frac{d\lambda}{d\theta} \tag{3}
\]

where \( \lambda \) is magnetic flux linking the winding and \( \theta \) corresponds to the angular displacement.

Similarly, the voltage generated in each turn of the coil may be expressed as the rate of change of flux linkage with respect to time.

\[
E = \frac{d\lambda}{d\theta} \tag{4}
\]

Since \( \lambda \) is a function of rotary position \( \theta \)

\[\text{Fig. 8-5: Equivalent circuit for a single winding of a PM type or a brushless type DC motor.}\]

the equation may be written:

\[
E = \frac{d\lambda}{d\theta} \times \frac{d\theta}{dt} \tag{4}
\]

where \( \frac{d\theta}{dt} = \text{angular velocity.} \)

Figure 8-5 shows the equivalent electric circuit for one phase of a PM brush-type DC motor. The same circuit also applies to a brushless DC motor. It is represented by a voltage source \( V \) connected to a series combination of \( R_w \) (winding resistance), \( L_w \) (winding inductance), with shunt resistance \( R_L \) and a voltage source \( E_g \) representing the counter emf. The resistance \( R_L \) is usually of a high enough value that its effect on motor operation is insignificant and can therefore be omitted from the circuit model.

Since the normal commutation function connects each phase or combination of phases in sequence to the voltage source \( V \), the circuit model for the overall motor is represented by the same basic circuit, except for the fact that the circuit values may represent more than one winding “on” at a time. The circuit model shows that the voltage generator \( E_g \) acts in opposition to the normally applied source voltage \( V \). Consequently, the current flowing in the phase will result from \( V-E_g \) acting across the impedance made up of \( R_w \) and \( L_w \).

The equation for the motor equivalent circuit is written:

\[
V = L_w \frac{di}{dt} + R_w i + E_g \tag{5}
\]

For the steady state analysis and since the inductance of the typical motor is usually small enough that it can be ignored, the
The above equation can be reduced to:
\[ V = R_w I + E_s \]  
[6]

or
\[ V = R_w I + K_e \omega \]  
[7]

where \( K_e \) is a function of turns and magnetic flux. \( K_e \) is called the voltage constant. It is a proportionality constant that relates the generated voltage to shaft speed (\( \omega \)).

If the motor current (I) is constant, a proportional torque is produced:
\[ T = K_t I \]  
[8]

where \( K_t \) is a function of turns and magnetic flux. \( K_t \) is called the torque constant and is a proportionality constant that relates current to developed torque.

Solving the torque equation for current and substituting the resulting expression for I in the voltage equation yields:
\[ V = \frac{TR}{K_t K_e} + K_e \omega \]  
[9]

Solving for \( \omega \) results in a linear equation relating velocity (\( \omega \)) to the developed torque (\( T \)):
\[ \omega = \frac{V}{K_e} - \frac{R_w T}{K_t K_e} \]  
[10]

where
\[ -\frac{R_w}{K_t K_e} \]  
is the slope

and
\[ \frac{V}{K_e} \]  
is the axis intercept.

The intercept corresponds to the operating point at which \( T = 0 \) (no load). Therefore:
\[ \omega_{NL} = \frac{V}{K_e} \]  
[11]

Torque at stall may be solved in similar fashion by setting \( \omega = 0 \).
\[ T_s = \frac{VK}{R_w} \]  
[12]

Figure 8-6 shows a plot of the speed/torque relationship. Both no-load and stall torque are influenced equally by changes in applied voltage (\( V \)). Increasing \( V \) shifts the speed/torque characteristic outward away from the axis in a parallel fashion. A given motor will therefore display parallel speed/torque characteristics corresponding to the different applied voltages as shown in Fig. 8-7.

Figure 8-7 shows the typical speed/torque characteristic of either a PM brush-type or a brushless DC motor.
Fig. 8-8: Effect on speed / torque curve of varying $R_W$.

Resistance has the effect of increasing the slope of the speed vs. torque characteristic while no-load speed remains unaffected. Figure 8-8 illustrates the effect of changing $R_W$. The motor design variables that affect $K_t$ and $K_e$ tend to have interrelated effects on the speed / torque characteristics. In developing the model for the speed/torque characteristic we assumed that the winding inductance ($L_W$) was negligible.

A further examination of the speed / torque equation reveals that velocity ($\omega$) decreases as the torque load ($T$) is increased with voltage ($V$) held constant. This is the expected result, and is typical of a permanent magnet DC motor. Similarly, velocity ($\omega$) will increase with increasingly applied voltage if the torque is held constant. This relationship is significant in the control of motor speed. An increase in torque load will decrease the motor speed, but the speed can be corrected by a small increase in the applied voltage.

Speed control of PM brush-type and brushless DC motors is accomplished by adjusting the voltage applied to the motor. Figure 8-9 illustrates how a constant speed is maintained by varying the voltage. If the load is held constant, the speed ($\omega_c$) can be maintained by applying a constant voltage ($V_c$). But if the load increases, as illustrated by the dashed line ($L_2$) and the voltage remains constant, the speed will decrease to $\omega_2$. In order to maintain the constant speed ($\omega_c$), the voltage must be increased to $V_2$. Likewise, if the load decreases ($L_1$), the speed will increase unless the voltage is reduced to $V_1$. With a smooth stepless range of voltage adjustment, the motor may be operated at any point ($T, \omega$) within the rated maximum torque and rotor speed.

Fig. 8-9: Controlling DC motor speed by varying applied voltage.

Rating Point: Figure 8-10 shows a speed / torque characteristic curve for a typical 1/4 hp DC motor. The rating point, in this example, corresponds to a voltage of 130 VDC, a torque of 100 oz-in. and a speed of 2500 RPM. We learned earlier that we can maintain a constant speed by increasing or decreasing the voltage proportionally to changes in load. In this example the voltage limit is set at $V_{\max}$. This is the maximum voltage that can be applied to

Fig. 8-10: Typical speed / torque characteristics for a 1/4 hp DC motor.
the motor for safe operation. It also establishes a limit on the amount of torque which can be delivered at higher speeds, which we will illustrate next.

**Regulated Speed:** Many motor applications require a regulated speed over a varying load range. A conveyor application where a constant speed must be maintained regardless of the number of items on the conveyor is an example. Theoretically, a DC motor could maintain a constant speed for any load if it had an unlimited current and voltage source. In reality however, every motor and control has a current and voltage limit. In many electronic controls, the current limit is adjustable, allowing for variable torque in addition to variable speed.

If the 1/4 hp motor in Fig. 8-10 was attached to a control device, a series of regulated speed characteristic curves could be developed like those shown in Fig. 8-11. The current curve has also been added to show the effects of current limiting on regulated speed.

![Fig. 8-11: Regulated speed curves for a typical 1/4 hp DC motor and speed control.](image)

The dashed vertical line represents the current limit point for this motor and control. Some controls provide a trim potentiometer which allows this point to be adjusted. Adjusting the current limit increases or decreases the available torque.

The regulated speed curves show that for a rated speed (\(\omega_r\)) of 2500 RPM, this system is capable of delivering above-rated torque at a constant speed up to a point near the current limit value. Just prior to the current limit value, the speed will start to drop off sharply until it reaches current limit at which time the motor will stall. The degree of drop off or slope of the regulated speed curve is determined by the design of the motor and control.

If the motor is operated at a speed lower than the rated 2500 RPM (\(\omega_1\)), it will again deliver a maximum torque up to the current limit point. At lower speeds however, it will not require as much voltage. At higher than rated speeds (\(\omega_2\)), the motor speed will be affected by the voltage limit. It will deliver a constant speed until the voltage limit is reached. The speed will then decrease at a rate determined by the slope of the \(V_{\text{max}}\) curve until it reaches current limit, at which time the motor stalls. The regulated speed / torque curves indicate how much the speed will vary over a given torque range.

**Four Quadrant Operation**

Some applications require a greater degree of motor control. For instance, the motor may be required to reverse while running, thus generating a negative torque while running at a positive velocity, or vice versa. To accomplish this, a motor and its control must be able to operate in the second or fourth quadrants where load torque is in the direction of rotation. Motors with linear speed / torque characteristic provide the best four quadrant operation. Servo application which follow a velocity, torque or position command require four quadrant operation to achieve optimum system
response. That is why a linear speed / torque relationship is a strict servo motor requirement.

**Reversing Motor Direction:**

Now that we have examined the control theory of motors with linear speed / torque characteristics, we can demonstrate their control capabilities by showing a typical four quadrant application.

Figure 8-12 shows a linear speed / torque characteristic curve typical of a PM brush-type as well as a brushless DC motor. Since it is applying a positive torque at a positive velocity, the characteristics are plotted in the first quadrant. Point 1 on the characteristic curve represents the operating point for a given load value. Assume for this example that the motor runs constantly and is being controlled by a system controller. At certain points in the process the motor must reverse direction when it receives the command from the controller. For simplicity of discussion, all losses due to windings, hysteresis and other physical properties are considered negligible in this example.

At the instant the motor receives the reverse command, the current direction will switch to a negative value and the motor will begin to operate in the second quadrant. In other words it will instantly begin to generate a negative torque while maintaining a positive velocity represented by point 2 on the graph.

At point 2, the current is reversed and the applied voltage is reversed. The motor is still putting out a positive velocity so the back emf, which is a function of velocity and which normally limits the current, now
becomes an additive component for the time it takes the velocity to decay to zero (point 3). This can be seen if we analyze the equivalent circuit formula:

\[ V = R_w I + E_g \]

Under first quadrant conditions, \( V \) and \( R_w I \) are both positive while the \( E_g \) component is negative. Therefore, \( E_g \) opposes the applied voltage. When the reverse command was given, the polarity of the applied voltage and current were both switched. The negative current immediately begins generating a negative torque. However, the rotor and shaft are still turning with a positive velocity. During the period of time from point 2 to point 3 as the positive velocity is decaying, the \( E_g \) component of the equation is still negative. Therefore, instead of opposing the applied voltage and limiting the current, \( E_g \) instantaneously aids in developing additional torque. Although this time is quite short, the motor control (if any) and the load must be able to tolerate the instantaneous increase in torque at point 2.

Once the velocity decays to zero at point 3, the motor stalls. Because \( E_g \) is a function of velocity which is now zero, there is no back emf until the current generates a force in the opposite direction. When the negative current exerts a force in the opposite direction, the resulting counterclockwise movement causes a back emf to develop and the motor velocity increases in the negative direction to a value limited by the load. This is represented by point 4.

Since quadrants three and four are mirror images of quadrants one and two, when the reverse command is given again a similar series of events occur in quadrants four and one (represented by points 5 and 6 on the graph) until the motor again returns to full load speed.

**Regenerative Drives:** When a motor performs work, it dissipates power in the form of heat and other losses. There are times when the motor must maintain a constant velocity or torque while being aided by other physical forces. For example, when a conveyor on an incline moves a box in an upward direction, it is performing work and normal losses occur. But when the same conveyor is reversed and the box is lowered, the motor is aided by the force of gravity and the mass of the box. The inertia of the load tends to over-haul the motor and puts power back into the power supply.

Most motor control systems do not offer regenerative capability. A control system must be specifically designed to absorb or store the additional power for a time until it can be dissipated. The example given earlier where a switch is thrown to reverse a DC motor is another example of where power must be absorbed momentarily by the control power supply. During the few seconds between the time the current is reversed and the motor stalls, power is being put back into the system because there is no back emf to limit the current.

### 8.3 Motor Control Types

Motor controls can be divided into two basic categories:

1) passive device speed controls, and
2) solid state controls.

Passive device controls consist of fixed or variable resistors, or variable transformers that are used to adjust the magnetic field strength, voltage levels or other motor characteristics (depending on the motor type), in order to control motor speed.

Solid state controls utilize more complex circuits consisting of active devices like diodes, thyristors, transistors, integrated circuits and in some cases, microprocessors to control motor voltage, power.
supply frequency, or to provide electronic commutation and thereby control motor speed.

Electronically commutated motors use logic circuits which develop rotating magnetic fields by rapidly switching coil currents on and off. The on/off timing of the logic circuits is usually controlled by built-in sensors or specialized motor construction features which monitor rotor position. Brushless DC, switched reluctance and stepper motors use electronic commutation. They cannot be operated by simply connecting them to a power source; the control is required for proper operation.

Electronically commutated motors with the appropriate controls can generally control position, direction of rotation and torque in addition to speed. Usually, they operate in closed-loop mode except for stepper motors which operate in open-loop mode because of their unique construction. These electronically commutated motors were discussed in Chapters 3 and 4. We will examine the control aspects of these motors later in this section.

## 8.4 PASSIVE DEVICE MOTOR CONTROLS

The most economical motor speed controls use passive devices such as variable resistors and transformers to control motor electromagnetic characteristics. These controls are described below for both DC and AC motors.

### Controlling DC Motor Speed

The speed and torque of a DC motor can be described by the following equations:

\[
\begin{align*}
RPM &= k \frac{V_a - I_a R_a}{\phi} \quad [13] \\
T &= K\phi I_a \quad [14]
\end{align*}
\]

where:
- \(RPM\) = revolutions/minute
- \(V_a\) = armature voltage
- \(I_a\) = armature current
- \(R_a\) = armature resistance
- \(\phi\) = field flux
- \(T\) = motor load or torque
- \(k, K\) = constants

Equation [13] indicates that speed can be varied by changing any of the variables, \(V_a, R_a\) or \(\phi\). Consequently, there are three methods by which the speed of a DC motor can be controlled:

1) **Field Weakening** — The field flux (\(\phi\)) in some motors can be altered by means of a series rheostat.

2) **Armature Resistance Control** — Voltage across the armature can be changed by introducing variable resistance in series with the armature resistance (\(R_a\)). Improved speed regulation can be obtained by incorporating two variable resistances, one in series and one in parallel with the armature.

3) **Armature Voltage Control** — Voltage across the armature (\(V_a\)) can be varied through the use of a controlled voltage source to a motor with separately excited field and armature circuits.

### Shunt-Wound DC Motor Passive Speed Controls

Let's apply the three basic methods of speed control to the various types of DC motors beginning with the shunt-wound type.

**Field Weakening Control:** In order to weaken the field of a shunt-wound DC motor, a rheostat can be connected in
series with the field winding while the armature voltage is kept at the “rated” or line voltage \( (V_1 = V_a) \). As shown in Fig. 8-13, the introduction of a field rheostat will permit adjustment of field current from point X (no additional resistance and full field current) to point Y (maximum resistance and minimum field current). An increase in field resistance will decrease the available field current and consequently, the field flux \( \phi \).

The effect of reducing the field flux while maintaining the armature voltage is an increase in motor speed. Therefore, field control or “field weakening” will normally produce speeds above the base (rated) speed. It should be noted, however, that the field can only be weakened within limits. Weakening the shunt-wound DC motor field beyond a certain point can result in excessively high and unstable speeds. It can also result in overheating the armature as can be seen from equation [2] in that a reduction of field flux \( \phi \) will produce a corresponding increase in armature current \( (I_a) \) in order to maintain a given load \( (T) \).

Furthermore, with an excessively weak field and a high armature current, the shunt-wound DC motor will be increasingly susceptible to armature reaction, excessive brush arcing and loss of breakdown torque. To prevent this, the maximum permissible limit for this speed control method is generally 150% of the motor’s rated basic speed. Furthermore, the maximum load of the motor must be reduced when operating above the basic speed so that its horsepower rating is not exceeded.

**Armature Resistance Control:** Essentially opposite to the field weakening method, armature resistance control calls for a variable resistance connected in series with the armature, while the field winding is excited at rated or line voltage. See Fig. 8-14. By reference to equation [13], if the voltage across the armature \( (V_a) \) is reduced (by increasing resistance), motor speed will decrease. Therefore, armature resistance control will always reduce speed below the rated base speed of the motor.

As indicated in equation [14], an increase in load will result in an increase in armature current which, in turn, causes an increase in voltage across the series-connected resistor. For this reason, if the motor is started with no load at some setting below the base speed and a load is subsequently applied, there will be a sharp drop in motor speed and a corresponding \( I^2 R \) power loss across the resistor. Therefore, the series resistor must have enough capacity to match the load current.

Using a resistor in series with either the armature or field is also very inefficient and is not considered practical for most applications. This method however, is relatively inexpensive and will effectively control DC motor speed both above and below the base speed in some applications.
**Shunted Armature Connection:** In a variation of the armature resistance method, both series and shunt resistors may be used “in tandem” to improve speed regulation characteristics of a DC shunt-wound motor by making the operating speed somewhat less susceptible to changes in load torque. This factor may become especially important in cases where the precise nature of the load torque is not well known, yet it is desirable to preset the operating speed.

In the shunted armature connection method, a variable resistor connected in parallel (shunt) with the armature acts to increase the current through the series resistance and thus reduce the difference between the no-load and the full-load current. The series resistance may be used to control armature voltage in the same way as with armature resistance control. See Fig. 8-15. Shunt resistors also assist dynamic braking and are, therefore, used in cases where a shunt motor is applied to a load which must be braked.

**Armature Voltage Control:**

There are two types of armature voltage control:

1) nonfeedback type, and
2) feedback type.

The nonfeedback control consists of a field power supply and a manually adjustable armature power supply. As motor

load changes, speed regulation is equivalent to the inherent regulation of the motor as shown in the speed / torque curves in Fig. 8-16.

![Fig. 8-15: Shunted armature speed control method.](image)

**Armature Voltage Control:**

The feedback type is a silicon controlled rectifier control and will be discussed with solid state controls in Section 8.5.

**Permanent Magnet (PM) Motor Passive Speed Controls**

The motor equations [13] and [14] at the beginning of this section can be applied to a permanent magnet (PM) motor. Notice, however, that a PM motor has a fixed field strength, and therefore, the field flux (\(f\)) cannot be varied. Hence, there are only two methods to control the speed of a PM motor.

**Armature Resistance Control:** This is the same method described for shunt-wound motors. A variable resistance placed in series with the armature can be varied to increase or decrease the voltage across the armature and cause the motor speed to change. See Fig. 8-17.

**Armature Voltage Control:**

By increasing or decreasing the voltage supply to the armature of a PM motor, the motor speed can be adjusted. Voltage adjustment can be achieved through the use of a variable voltage transformer.
Series Wound (Universal) Motor Passive Speed Controls

A series wound motor is suitable for AC or DC operation and is capable of supplying high starting torques, high speeds and high outputs. The speed of a series motor can be changed by varying the voltage across the motor. This can be achieved by either using a variable resistor, a variable voltage transformer (autotransformer) or an electronic control.

**Series Resistance Control:** A variable resistor or rheostat in series with the motor will decrease the speed of the motor at any load as the resistance is increased. In theory, the motor speed can be adjusted to a standstill. However, due to starting torque limitations, armature cogging and reduced ventilation, the minimum speed is usually limited to some higher value.

A series resistor introduces a voltage drop in the circuit directly proportional to the current flowing. The voltage across the resistor, therefore, will increase as the motor is loaded (since the motor current will increase with load). It follows that the voltage across the motor will decrease with an increase in load and the speed will drop more rapidly with load whenever a series resistor is used. The higher the resistance value, the greater the drop in speed as the load is increased. Also, a series resistor will have its greatest effect on the starting torque of the motor since at starting, the maximum current is flowing and will limit the motor voltage to its lowest value. The minimum full-load speed at which a series motor will operate on AC with a series resistor is usually limited by the starting torque available to start the load with that value of resistance.

Typically on AC, the speed range of a series motor using a variable series resistor will be from 1.5:1 to 3:1, depending upon the motor. On DC, the speed range will be increased because of the improved regulation and corresponding increase in starting torque. Typical characteristic curves for a series motor are shown in Figs. 8-18a and b.

**Shunt Resistance Control:**

A series motor can also be controlled by shunting an adjustable resistor across the armature. The speed range is usually limited by this method because of the increased current passing through the field coils and the corresponding heating effect. A wide speed range may only be employed if the application has a very intermittent duty cycle.

Using the same motor as above, typical characteristic curves are shown in Figs. 8-18c and d. Although the speed range is limited, this method of control improves the
speed regulation of the motor and maintains good starting torque characteristics. It is an excellent method for matching motor speeds.

A combination of series and shunt resistors is sometimes used to obtain characteristics between the two types of controls.

**Variable Transformer Control:** By using a variable transformer to vary the voltage across a series motor, speed ranges of 4:1 to 7:1 are typical depending upon the motor. If a full-wave bridge is used to convert the output of the transformer to DC, the speed range will be increased because of improved regulation and starting torque. Figures 8-18e and f show typical characteristic curves for the motor used in Figs. 8-18a, b, c and d.

### AC Motor Passive Speed Controls

One of the principal characteristics of the AC induction motor is its ability to maintain constant or essentially constant speed under normal voltage and load variations. Therefore, this type of motor does not lend itself to a simple method of speed control over a wide range.
Some types of loads, however, make practical some degree of speed adjustment if the proper motor and control means are chosen. First, it should be understood that there are variations of conventional induction motors which are designed for the express purpose of improved speed control. These motor types may employ wound rotors with variable resistance, brush shifting means and other special features. This discussion, however, will be confined to induction motors having the conventional squirrel cage nonsynchronous, reluctance synchronous and hysteresis synchronous rotors.

The speed of an AC motor is related to the power supply frequency (Hz) by the equation:

\[
RPM = \frac{120f}{P} \quad [15]
\]

where:

- \( RPM \) = revolutions/minute (nominal synchronous speed)
- \( f \) = frequency (Hz)
- \( P \) = number of poles

The above speed represents the synchronous speed of the revolving magnetic field of the stator in a nonsynchronous motor or the actual rotor speed of a synchronous motor.

While a synchronous AC motor rotates at the exact speed defined by the above formula, the nonsynchronous motor never operates at synchronous speed. The difference between the synchronous speed and the actual speed is known as rotor “slip”:

\[
\text{Slip} = \frac{\text{Sync. Speed} - \text{Actual Speed}}{\text{Sync. Speed}} \quad [15]
\]

The magnitude of slip depends upon the rotor design, power input and motor load. As in the case of the DC motor, the speed of an induction motor can be made to vary by changing any of the variables in the fundamental speed equation, such as:

1) adjusting supply frequency,
2) changing the number of stator poles,
3) adjusting power input, and
4) controlling rotor slip.

The change in frequency method requires the use of solid state driven power supplies and falls in the category of solid state controls, which will be discussed in Section 8.5.

**Change in the Number of Stator Poles**

The pole-changing method (Fig. 8-19) is also suitable for both synchronous and nonsynchronous motors, but has the limitation of offering only a few speeds (usually no more than four), which are widely separated from each other. By nature, the pole-changing method requires that a portion of the winding be idle during the operation of one or more speeds. This results in motor inefficiency and a considerable reduction in the output rating for any given frame size. Switching methods for pole-changing are also expensive and complicated, making

---

**Fig. 8-19: Simplified pole-changing circuit.**

---
the method useful in relatively few applications.

## Changing Rotor Slip

The changing of rotor slip is simpler, less costly and the most widely used technique for varying the speed of an AC induction motor.

There are three types of nonsynchronous motors to which this method is best suited: shaded pole, permanent split capacitor and polyphase. The latter is not widely used in fractional horsepower motor sizes.

**NOTE: Due to the sensitivity of the centrifugal or relay starting switches, the rotor slip method should not be applied to split-phase start and capacitor start motors unless the speed will never go low enough to engage the starting switch. If the motor is running at reduced speed with the starting switch closed, the auxiliary winding or switch contacts would soon burn out.**

To obtain the optimum speed control effectiveness in applications employing the change in rotor slip method, the following guidelines should be followed:

1) *Since the principle is based on changing the power input, it is important to match the motor closely with the load.* This will ensure that with a change of power input, a noticeable change in speed will result.

2) *The load should have a substantial component of inertia.* If the load is not of the fan or blower type, it may be necessary to add a fly-wheel to provide this necessary inertia. **NOTE: A noninertial load cannot be satisfactorily controlled by the change in rotor slip method.**

3) *It is advisable to use a rotor specifically designed and constructed for high slip (high degree of slope of the speed/torque curve).* This will aid in obtaining the maximum speed change for a given change in motor power input.

There are several ways to change the power input to an induction motor, and thereby increase or decrease the amount of slip. Listed below are those which are most frequently used.

### Series Resistance Method:
A variable resistor can be used to vary voltage across the winding of an induction motor. See Figs. 8-20a and b. Series resistance can be used with either shaded pole or PSC motors.

### Variable Voltage Transformer Method:
This method may be used in place of a series resistor to reduce voltage across the winding. It has the advantage of maintaining substantially the same voltage under the starting condition when the current is higher than during the running condition.

![Diagram of Motor and Variable Resistor](image)

*Fig. 8-20: a) Simplified series resistance circuit (top), and b) change of motor speed by series resistance method (bottom).*
mode. There is also much less power lost as heat than with a resistor. See Fig. 8-21.

By reducing the voltage across the main winding of a PSC motor, full voltage is maintained across the capacitor winding, providing more stable operation at lower speeds. See Figs. 8-22a and b.

**Shunt Resistance Method:**
Also confined to the PSC motor, this method has been found to provide stable speed in four-pole, 60 Hz motors up to 1/100 hp (7.5W) over a range from 1500 RPM down to 900 RPM with a constant torque output. See Figs. 8-23a and b. With this method, it is necessary to use a high slip type rotor.

**Tapped Winding Method:**
This method is most widely used in shaded pole fan motors. The change in input is obtained by changing motor impedance through the use of various portions of the total winding. See Fig. 8-24. The number of speeds is determined by the number of taps introduced into the winding. In addi-
**Winding Function Change Method:** Applicable only to the PSC motor, the winding change method can be used in applications requiring no more than two speeds. See Fig. 8-25. The functions of the main and the capacitor (starting) windings can be switched to provide “high” and “low” speeds. High speed is obtained when the winding with fewer turns is functioning as the main, while lower speed is achieved with the winding with more turns functioning as the main. This is an extremely efficient technique, but it does require that the motor winding be exactly tailored to the load in order to provide the desired two speeds.

### 8.5 SOLID STATE ELECTRONIC (ACTIVE) MOTOR CONTROLS

Advances in solid state electronics such as VLSI technology as well as improved manufacturing techniques like surface mount component technology have led to many improvements in motor controls. The continuing drive for miniaturization has led to smaller controls which offer better performance and greater reliability than their predecessors. Many of these changes have also driven down the cost of controls.

Control system designers are discovering that an electronic control, when matched with the right motor, can offer a method.

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**Active vs. Passive Control of DC Motor Speed**

In Section 8.4, you’ll recall that the speed of a DC motor can be varied by changing any of the variables in the basic speed formula:

$$RPM = k \frac{V_a - I_a R_a}{\phi}$$

Passive devices such as resistors increase the motor circuit resistance, causing increased power dissipation in the form of heat. This additional heat produces no useful work and decreases the overall efficiency of the system. With the development of semiconductors, it became possible to vary motor speed through voltage switching rather than by adding resistance to the drive circuit.

Instead of varying the level of resistance, switching amplifiers vary the time during which full line voltage is applied to the armature. The net effect is an average voltage which is roughly equivalent to a
voltage level obtained by the variable resistance-type control.

To see how these two techniques work, think of two simple circuits, each with a light bulb, a power source and a current control device. In Fig. 8-26a, a variable resistance controller is used. In Fig. 8-26b, a switch is connected in series with the light bulb and power source. In the variable resistance system, the resistor can be regulated to control the current and produce a light intensity from 0 to maximum rated.

Fig. 8-26: a) Simplified variable resistance control circuit (top), and b) switching circuit technique (bottom).

In the switching system there are only two possible states: “on” or “off.” To vary the light intensity, the switch may be turned on and off many times per second. Each combination of on/off states represents one cycle. Since semiconductor switching can take place at very high frequencies, the eye perceives an average intensity somewhere between off and maximum. The longer the bulb is left in the “on” state during each cycle, the brighter the light will seem to glow.

In a similar fashion, semiconductors vary motor speed by switching voltage to the motor windings on and off very rapidly. The longer the voltage is “on”, the higher the average voltage will be and concurrently, the higher the resultant motor speed.

**Pure DC vs. Rectified AC**

The quality of the direct current and voltage used to drive a motor has a significant effect on its efficiency. Before we discuss the various solid state controls used to control DC motor speed, it is important to review some basic DC theory and to see how DC motors are affected by various grades of DC.

**AC Rectification:** Rectification is essentially the conversion of alternating current (AC) to unidirectional current (DC). It is the most economical means of generating DC, since it utilizes commercially available AC sources. However, the degree to which the alternating current is converted will determine the overall efficiency of the motor and control system.

A simple diode can be used for half-wave rectification. Full-wave rectification can be obtained by using two diodes in a center-tapped transformer circuit. A four-diode bridge circuit will also provide full-wave output. These circuits are shown in Fig. 8-27.

Fig. 8-27: Typical half-wave (top) and full-wave (middle and bottom) rectification circuits employing diodes.

Later we will see how SCRs are used to create full and half-wave rectification in DC motor controls. We can see from the wave shapes (current diagrams) that rectification provides unidirectional current, but
not uniform or pure DC. It is the measure of departure from pure direct current that can have a significant effect on motor efficiency.

**Form Factor:** Form factor is a measure of departure from pure DC. It is defined as the root-mean-square (rms) value of the current divided by the average value of the current. Pure DC has a form factor of 1.0 or unity. For half-wave rectified current, the form factor is 1.57. For full-wave rectified current, the form factor is 1.11 when measured with a resistive load.

The form factor is an important consideration with motors designed to operate on direct current. When operated from rectified power vs. pure DC, the increase in motor heating for a constant output is approximately proportional to the square of the form factor. For example, a motor operating from half-wave rectified DC current will have approximately 2½ times the heat rise of the same motor operating on unity form factor DC.

To accommodate the increased heating effect of high form factor current, continuous duty applications generally require a larger (and more costly) motor to drive a given load. Stated another way, a designer may save money by using a low cost, high form factor speed control, only to sacrifice much of the savings by using a larger motor to keep the motor operating temperatures within design limits.

High form factor also means that a high peak current is required to maintain an average current output for a given power requirement, thus contributing to rapid brush and commutator wear.

**Filtering:** Filtering methods act to “smooth out” the rectified current or voltage waveform by means of series inductance and/or parallel capacitance. The effects of filtering can be seen in the waveforms in Fig. 8-28.

**Typical Feedback Controller Speed**

<table>
<thead>
<tr>
<th>Type</th>
<th>Form Factor</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-Wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unfiltered</td>
<td>1.6 - 2.0</td>
<td>65%</td>
</tr>
<tr>
<td>Half-Wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filtered</td>
<td>1.1 - 1.5</td>
<td>120%</td>
</tr>
<tr>
<td>Full-Wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unfiltered</td>
<td>1.1 - 1.6</td>
<td>80%</td>
</tr>
<tr>
<td>Full-Wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filtered</td>
<td>1.0 - 1.1</td>
<td>130%</td>
</tr>
</tbody>
</table>

**SCR Phase Control of DC Shunt and PM Motor Speeds**

While the speed of a shunt-wound motor can be changed by varying either the field or armature voltage, a PM motor’s speed can be varied only by changing the supply voltage to its armature. Some controls utilize the field weakening method.
for shunt-wound motor speed control. This is not the preferred method however, since changing the field voltage directly affects the output torque capability of the motor and should only be used where relatively light loads are encountered. Changing the motor armature voltage, on the other hand, allows full torque to be developed.

Most motor controllers for the fractional horsepower DC shunt-wound and PM motors use silicon controlled rectifiers (SCRs) as the control element for varying the power applied to the motor. The SCRs control the armature voltage and thus, the motor’s speed.

An SCR is a three-terminal device made from four layers of alternating P and N-type semiconductor materials. See Fig. 8-30. It functions as a diode (only conducts current in the forward direction), but will do so only when a trigger voltage is applied to its gate.

Once an SCR is fired, the gate signal can be removed without stopping conduction. Conduction ceases when the positive voltage is removed from the anode. The typical gate signal required to activate an SCR is about two volts and 10 milliamps for three microseconds. Although these values are representative trigger requirements, an SCR gate can tolerate much higher power inputs without damage.

The rectifying capabilities of SCRs make them popular in speed controls. They can be directly connected to the AC source to form a half-wave rectifier without AC-to-DC conversion circuitry. When an SCR is used to rectify alternating current, the point during the positive half cycle of the input current at which the rectifier is turned on can be adjusted by the timing of the application of the trigger signal to the gate. At the end of the positive half cycle, the SCR will turn off as the applied polarity of the voltage reverses. By controlling the phase relationship of the trigger to the zero axis crossing of the positive half cycle of alternating current, the amount of power transmitted through the SCR can be varied. This is called phase control. One or more SCRs can be used to provide phase-controlled half-wave, full-wave or multiple-phase control.

The combination of a counter emf sensing element, a triggering unit whose phase is controlled by the counter emf sensor, and one or more SCRs constitutes a basic feedback speed controller.

**Half-Wave SCR Controls:** In a half-wave SCR motor control, the gate signaling characteristics of the SCR are used for speed selection and as feedback for compensation of load changes.

![Fig. 8-30: Function diagram and standard schematic symbol for a silicon controlled rectifier (SCR).](image)

The circuit illustrated in Fig. 8-31 uses the counter emf of the motor as a feedback control voltage (motor speed is proportional to counter emf). Gate firing occurs...
when the divided fraction of the supply voltage (developed at the center arm of the potentiometer) exceeds the counter emf developed by the motor. At this moment and for the remaining portion of the half cycle, the input voltage is applied to the motor. If the motor should slow down due to an increase in load, the counter emf will be lower and the SCR will automatically fire sooner in the cycle (thus allowing the SCR to be on for a larger portion of the half cycle). The voltage waveforms associated with this control operation are shown in Fig. 8-32. With this circuit, the SCR can be controlled only through the 0 to 90 degree range.

Half-wave rectified SCR controls, while inexpensive, do not operate a motor at its full potential. For example, a motor operating from a half-wave rectified DC current will have approximately 2½ times the temperature rise of the same motor operating on pure DC. Since motor life is inversely related to temperature, the motor will have a much shorter life. This temperature rise is directly related to the form factor discussed earlier.

**Full-Wave SCR Controls:**

Full-wave SCR controls optimize a motor’s performance. They can be constructed using two SCRs with a center-tapped transformer or as a full-wave bridge where two of the diodes are replaced by SCRs. See Figs. 8-33a and b.

By using full-wave rectification in conjunction with filtering to smooth the rectified current or voltage waveform, the form factor is improved significantly. Refer to Fig. 8-29 for the effects of filtering on form factor.

Like the half-wave control, the timing of the control signal of the full-wave SCR determines the “firing angle” (the electrical angle from the zero crossing point when the SCR fires). See Fig. 8-34. When the SCR is switched on, current flows to the motor winding. The position of the firing angle determines the average voltage and in turn,
Fig. 8-34: The effect of the firing angle on the average voltage of a full-wave SCR control.

IR Compensation: Speed can be maintained at a nearly constant level regardless of changes in motor load with the addition of IR compensation. While the voltage developed by a tachometer is sometimes used as an output speed signal, in most controllers it is the counter emf generated by the motor that is compared with a reference voltage to regulate speed.

To compensate for varying loads, the applied armature voltage and armature current (proportional to load) are sensed. The difference (V-IR) is proportional to motor speed. This voltage is compared to the reference voltage established by the external speed setting potentiometer. The difference or error is used to automatically increase or decrease the armature voltage and thus, the motor shaft speed. If the controller senses a counter emf that is lower than the reference voltage, it will increase power to the motor. This will increase the speed and the generated counter emf. This action will continue until the difference between the counter emf and the reference voltage equals zero. If the counter emf exceeds the reference voltage, the controller will decrease the power to the motor.

Figure 8-35 illustrates an SCR speed control consisting of a counter emf sensing element, an emf phase-controlled triggering unit and an SCR. Inherent motor characteristics combined with a reflected load make it impractical to achieve regulation closer than about 1% using counter emf and armature current as the feedback signals. However, a tachometer generator can be incorporated as the feedback element to achieve speed regulation approaching 0.1%. In Chapter 9 we will discuss feedback devices such as tachometer generators and encoders in greater detail.

Fig. 8-35: Interrelationship of elements in a basic SCR feedback speed control.

Other Compensation Techniques

In addition to providing feedback circuitry which adjusts output power to maintain constant speed as load varies, the following features can also be included in a well-designed SCR control.

Line Voltage Compensation:
AC line voltage typically varies by as much as ± 10%. Since motor speed is proportional to voltage, motor speed will fluctuate as the line voltage varies. Hence, it is important to incorporate line voltage compensation circuitry features in the motor control to maintain speed settings.

**Temperature Compensation:** A motor’s armature winding resistance ($R_a$) is not always constant during its operation. It rises and falls with the ambient and operating temperature and can cause control instability. Selection of circuitry components with low temperature coefficients can help reduce speed changes caused by temperature variations. However, some temperature compensation devices must also be built into the control circuit to sense the winding temperature and make up for the resistance variations due to temperature change.

**Torque Limiting (Current Limiting):** In some drive applications, a limit must be placed on maximum torque output. For example, a winding machine may require that wire tension be limited to a maximum to avoid breakage.

Since motor torque can be expressed by the equation $T = kI_a$, torque is directly proportional to armature current. Therefore, limiting the current to the armature also limits the torque. A controller with a torque limiting circuit can draw current up to a preset value, after which the motor’s speed will “drop off.” The nature of the drop-off is dependent on control design, initial speed, inertia, rate of torque increase, etc.

In addition to maintaining a limiting torque, torque control is also useful for soft starting (controlled acceleration) of loads that are essentially inertial in nature.

**Surge Suppression:** An abnormal voltage “spike” can damage the sensitive components of a controller. A transient protector or surge suppressor should be used to divert the voltage surges. Thyrectors and varistors are two devices commonly used for this purpose. Figure 8-36 shows a varistor used in a bridge circuit to protect a controller’s circuitry.

**RFI Suppression:** Any instantaneous change in voltage across an energy storage network will result in the emission of RFI (radio frequency interference). The RFI that is created is simultaneously propagated through the air and conducted through the elements of the system. In the case of electronic motor controls, rapidly changing voltage across a capacitor through the use of an SCR or arcing at the motor brushes may result in RFI which may cause disturbances in nearby electrical apparatus.

RFI can be prevented from reaching places through the use of filters for the conducted portion and shielding for the portion propagated through the air.

The shielding of electrical equipment to prevent the propagation of RFI through air is difficult. This is because the strength of the RFI signal at any given distance from the source depends not only on the orientation of the RFI source with respect to the receiver, but also on the amount of amplification of RFI due to the antenna action of objects to which it is physically connected. For this reason, shielding
should be individually designed for each application.

Prevention of conducted RFI from reaching and introducing noise to the supply line can be accomplished with a filter placed between the line and the control as shown in Fig. 8-37.

![Fig. 8-37: Simple RFI filter.](image)

A simple filter design consists of an inductance choke put in series with the input and a bypass capacitor put across the line. The impedance of the choke increases with increased frequency. Its impedance is negligible at 60 Hz but presents a high impedance at the frequency of the RFI range, which causes some portion of the conducted RFI to drop across it. The impedance of the capacitor decreases with increased frequency. It is virtually an open circuit at 60 Hz but almost a short circuit at the RFI frequency, and so some portion of the RFI is shunted across it.

**Pulse Width Modulation Control of DC Motor Speed**

Pulse width modulation (PWM) circuits use transistor switches instead of SCRs as voltage control devices. The circuits are similar in their basic function. In a pulse width modulation control, a DC-to-pulse-width converter converts a control signal voltage to an appropriate pulse width or "firing angle" resulting in the correct average voltage for a given desired speed setting.

When the transistor is switched on, current flows in the winding. Just like the SCR control, the firing angle in a PWM circuit (the electrical angle between the start of the cycle and the angle at which the transistor begins to conduct) determines the average voltage and in turn the output speed. A wider pulse width will result in a higher average voltage. See Fig. 8-38.

![Fig. 8-38: Effect of pulse width on average voltage in a PWM circuit.](image)

Figure 8-39 shows that a power amplifier is used to amplify the control voltage to provide the actual drive current, while a feedback circuit tracks the armature voltage level.

![Fig. 8-39: Typical PWM control circuit.](image)

PWM controls operate from pure DC and require an external power supply with a high degree of rectification and filtering. As a result they can be costlier than SCR controls.
However, unlike SCRs which can turn current on but not off, transistors are not dependent on the negative cycle of the AC source for turning off the winding current. Because the PWM drive operates from a pure DC source, the relationship between pulse width and motor voltage is linear (Fig. 8-40) and has little lag. This gives PWM controls the quick response necessary for many servo applications.

The pulse repetition rate (cycle duration) ranges from 1–100 kHz, depending on the characteristics of the motor and application. The transistor’s ability to generate a wide range of pulse widths gives PWM controllers a very wide speed range and precise control of peak motor current.

**Fig. 8-40: Linear characteristics of a PWM control.**

### Electronic Commutation of DC Motors

Some motors are controlled through electronic commutation. Brushless DC and DC stepper motors are examples of electronically commutated motors. Both of these motors were described in Chapter 3. Electronically commutated motors cannot be operated by connecting them to a power supply. The control is required for commutation (motor action) as well as for speed, position and torque control. In this section, we will examine the types of controls used with brushless DC motors and stepper motors and the effects they produce on the motors.

### Brushless DC Motor Controls

Brushless DC motor controls perform a variety of functions. One primary function of the control is commutation. Commutation takes place by sequentially switching the current in one or more stator phase windings to generate a revolving magnetic field. The magnets in the rotor cause motor action by chasing the revolving magnetic field generated in the stator windings.

The on/off switching of phase current is a function of rotor position. Rotor position is determined by sensors located in the motor itself. The rotor position information is fed to the commutation logic circuits in the control which determines the correct firing sequence of the transistors that supply current to the windings. Since the current is switched just before the magnets in the rotor align with the magnetic field generated in the stator, and since the current switching is governed by the rotor position, the rotor never catches up with the field. Brushless DC motors run at higher speeds than PM DC motors because their speed is not limited by the frictional components of mechanical commutation, but by the voltage limit of the control circuit and motor windings.

**Trapezoidal vs. Sinusoidal Characteristics:** Brushless DC motors can exhibit either trapezoidal or sinusoidal torque characteristics. It is the arrangement and type of windings as well as the physical characteristics of the stator and rotor that determine whether a motor...
will produce trapezoidal or sinusoidal waveforms.

The back emf of a DC motor always follows the waveform which a motor produces when it is externally driven. In other words, as a result of the motor’s construction, the waveform which it produces when it is run like a generator determines the characteristics of the back emf. The commutation cycle and ultimately the torque output are dependent on the back emf. The shape of the waveform, therefore, is important. There is considerable difference of opinion among motor manufacturers as to which wave shape is better.

Figure 8-41 shows the overlapping torque waveforms of an externally driven, three-phase DC motor with sinusoidal characteristics. From the curve we can see that torque is a function of rotor position. If you follow a single waveform you’ll see that minimum torque occurs when the waveform crosses the axis. It then progresses to a maximum torque value before returning to a state of stable equilibrium. The back emf waveform follows this same path. Peak torque at constant current occurs when the back emf peaks. Therefore, in a brushless DC motor, by sensing the rotor position and timing the commutation circuits so that the phase coils are turned on near the top of the back emf waveform, we will generate a torque ripple output similar to the waveform shown in Fig. 8-42.

**Fig. 8-41: Overlapping torque waveforms of a sinusoidal DC motor being driven as a generator.**

**Fig. 8-42: Torque ripple of a sinusoidal brushless DC motor.**
The torque output has a considerable amount of ripple. This could be reduced by increasing the number of motor phases and thus commutating on shorter cycles. This approach adds considerable cost to the control since more transistors and logic circuits are needed for commutation.

Another way to reduce the amount of ripple is to construct the motor to produce a trapezoidal characteristic waveform. Figure 8-43 shows overlapping torque waveforms of an externally-driven trapezoidal DC motor. Notice that the tops of the waveforms are flat by design. Therefore, if the commutation takes place at or near the top of the waveform, there is less ripple than with the sinusoidal design. This is represented by the bold line at the top of the waveforms in Fig. 8-43.

In general, motors with sinusoidal outputs are easier to construct and therefore, less costly. However, they generate considerably more torque ripple. High accuracy sinusoidal controls in combination with high resolution position sensors can produce very smooth torque outputs from a sinusoidal motor. However, the additional control circuitry and sensors add to the cost of the system.

Brushless DC motors with trapezoidal characteristics have flat torque curves and lend themselves to digital and pulse width modulation control techniques. The controls for trapezoidal characteristic motors are more cost-effective to produce than those for sinusoidal motors having the same number of phases. Figure 8-44 shows the relationship between the various waveforms of a three-phase brushless DC motor with trapezoidal characteristics.

**Fig. 8-43: Output waveforms of a DC motor with trapezoidal characteristics.**

**Fig. 8-44: Waveform relationships in a three-phase brushless DC motor with two phases energized and one off at all times.**
Brushless DC motors can be used as servo motors depending on the application. They are capable of four quadrant operation and develop considerably more torque per frame size than their PM DC counterparts. Most brushless DC controls provide variable current limiting. Acceleration and deceleration response times are usually adjustable.

**Stepper Motor Controls**

Stepper motors can carry out extremely varied patterns of precise movements. Position is determined by the number of steps taken in either direction of rotation. Velocity is determined by the step rate. To produce the same sequence by other means might involve more expensive apparatus (resolvers, tachometer generators, etc.) and considerably more system maintenance. Perhaps the most distinct advantage of stepper motors is that they can perform a variety of complex operations with a noncumulative unloaded step error of 3% to 5% maximum of one step.

The basic function of any stepper control, no matter how simple or complex, is to provide the means of directing a stepper motor to complete a specific sequence of steps. Stepping is accomplished through the sequential energization of the motor’s phases. The heart of any stepper system, the driver, is the device which actually conducts current from the power supply to the motor windings. This is accomplished via power transistors (represented by switches in Fig. 8-45). There are three principle types of stepper drivers:

1) Series R (also known as L/R),
2) chopper, and
3) bilevel.

Each can be configured in unipolar and bipolar modes which will be explained later in this section.

To prevent motor overheating, each power driver circuit uses a different method to limit current beyond the specified maximum for the motor. The differences in system performance are reflected in the time required for each driver type to bring the stepper motor up to full current, and the shape of their phase current vs. time curves.

**Series R (L/R) Driver:** The simplest, least expensive stepper driver is the Series R (or L/R) driver. In this scheme, resistors are connected in series with the motor windings. See Fig. 8-46. These resistors limit the maximum winding current to a safe operating level by adding to the divisor in the formula:

\[ I_{\text{max}} = \frac{V}{R_{\text{series}} + R_{\text{Winding}}} \]

The electrical time constant for current rise is:

\[ \frac{L_{\text{Motor}}}{R_{\text{Series}} + R_{\text{Winding}}} \]

To get adequate high speed performance, winding current must rise and decay quickly. This is accomplished by using high resistance series resistors to minimize the time constant, and correspondingly, high power supply voltages to attain adequate levels of current. Since a significant amount of energy is dissipated as heat in the resistors, Series R drivers are limited to applications which can tolerate additional heat and relatively low system efficiency. Advantages of Series R are low initial cost, system size and simplicity.
**Chopper Driver:** With chopper drivers, external resistors are not used to limit the maximum flow of current. Limited only by the relatively small winding resistance, current would tend to rise to an unsafe level. To prevent this, the chopper driver will turn off the voltage across the windings when current reaches a preset maximum. See Fig. 8-47. The driver then monitors current decay, until it reaches a minimum level at which it reapplys the voltage to the windings.

Instead of a pure exponential curve, chopper drivers produce a sawtooth shaped current waveform like the one shown in Fig. 8-47. Since chopper drivers do not dissipate energy through series resistors, it is practical to increase voltage for much higher horsepower output. The on-and-off chopping action maintains current at safe operating levels. The high supply voltages used by these drives allow chopper drivers to reach maximum currents much faster than Series R drivers.
The one operational characteristic inherent in chopper circuits that may cause problems in some applications is the tendency for oscillating current to produce system resonances at certain frequencies or motor speeds. Vertical dips on the speed/torque curve represent narrow speed ranges in which the torque dips unexpectedly. These resonance effects can be diminished and sometimes eliminated by using electronic compensation circuitry.

**Bilevel Driver:** Rather than chopping current at a prescribed maximum, bilevel drivers switch between two separate input voltage levels. See Fig. 8-48. To bring the motor windings rapidly up to maximum current, a relatively high voltage (typically above 24 V) is initially applied. Once the desired operating level has been reached, the driver quickly switches to a much lower maintenance voltage (typically under 10 V).

This dual voltage approach provides the rapid acceleration which is not possible with a Series R design, while minimizing some of the resonance effects found in uncompensated chopper drivers. The principle disadvantages encountered with bilevel drivers are the added expense for switches or transistors and the dual power supply needed to deliver the two voltages used by the scheme.
Unipolar vs. Bipolar Modes

Each of three drive circuits used in stepper motor applications can be configured into three basic modes:
1) unipolar,
2) bipolar series, and
3) bipolar parallel.

Each mode has advantages and disadvantages in terms of cost and performance. See Fig. 8-49. In the unipolar mode, two of the four windings are energized at any given instant, and current flows in only one direction through each winding. The sequence in which the windings are energized determines the direction of shaft rotation. In bipolar operation, all windings are on simultaneously. Rotation is produced by changing the direction of the phase current in the windings. No matter which method is used, the rotor “sees” the same changes in direction of magnetic flux in the motor stator.

Unipolar Circuits: Unipolar drive circuits are generally simpler, more reliable and less expensive. They require only four drive transistors and a single power supply. Though they deliver somewhat lower torque for a given power input at low speeds, they usually produce higher torques at higher speeds.

Bipolar Circuits: With bipolar circuits, as many as eight power transistors or four power transistors and a dual power supply are needed. This adds cost and vulnerability to failure. But when high torque and very low speeds are application requirements and there are constraints on motor size, a bipolar driver may be the most desirable alternative. Since all four phases are energized at any given instant, the bipolar circuit generates a stronger magnetic field, delivering more torque to do the work.

Fig. 8-49 Simplified representations of unipolar (top), bipolar series (left) and bipolar parallel (right) drive schemes.
Under static or low speed conditions, bipolar drivers can increase torque output by 20% to 40%. When connected in parallel, effective phase resistance and inductance are reduced by half. This allows current per phase to be increased to 140% of the “two-phase on” unipolar rating. When connected in series, the effective number of winding turns is increased, so the series bipolar circuit makes more efficient use of the windings. Voltage across the windings can be increased, while keeping current low (70% of the “two-phase on” unipolar rating). In some cases this permits less expensive power supplies and drive components to be used.

**Stepper Motor Performance**

Stepper motors operate in either of two speed ranges:
1) error-free-start-stop (EFSS), and
2) slew.

This combination of two operating ranges is unique to the “stepping” design. For each increment in the phase energization sequence, the stepper motor takes a precise known angular step. As mentioned earlier, the rotor follows the established magnetic field through a series of detent positions one at a time, with a noncumulative unloaded step error of no more than 3% to 5%, provided the speed and acceleration capabilities of the motor are not exceeded.

If an application requires that the motor get from position “a” to position “b” as quickly as possible, a stepper motor must be carefully accelerated or “ramped” from its low to high speed range or it will lose synchronism with the magnetic field. Just as an internal combustion engine will stall if accelerated too quickly, “racing” a stepper will cause it to act unpredictably. In a typical application the motor may be commanded to “ramp” between low and high speed ranges many times, and each time the shape (slope) of the ramp will be an important factor in maintaining step accuracy.

**Operating Speeds:** The term EFSS (error-free-start-stop) is used to describe the stepper’s low speed operating region. In EFSS, the motor phases are switched relatively slowly, usually no faster than 1500 steps per second (even slower with larger motors). The maximum EFSS rate is dependent on load torque and load inertia. See Fig. 8-50. In the EFSS region,

![Graph showing the relationship between torque and frequency with and without resonance compensation.](image)

Fig. 8-50: EFSS and slew curves for a 34 frame single-stack stepper. Dashed lines are EFSS curves for zero, one and four times the stepper motor’s rotor inertia.
the motor can be started and stopped instantaneously without losing steps. If one or two phases are left on, the rotor will stop at the exact detent position corresponding to those phases.

**Slew Speed:** The high speed area of operation in a stepper is called the slew region. Here the windings can be sequenced quickly (up to 20,000 steps per second with the smallest stepper motors). If the sequence is suddenly stopped while the motor is operating in the slew region, inertia will cause the rotor to go beyond the desired holding position by at least four steps and possibly more.

In order to reach the slew region, the motor must first be started in EFSS and carefully accelerated to the desired slew speed. Then after rotating a particular number of steps at the higher step rate, the motor must be “ramped down” or decelerated to a suitable EFSS speed before it can be stopped at the desired position. In this way, “ramping” allows us to dramatically reduce traverse time.

By starting in EFSS and then ramping up to slew, we can run for most of the traverse at the higher slew speed, and still come to a complete stop at the desired point without losing (or gaining) steps. Of course, the shape of the required velocity profile is dependent on the ability of the motor to accelerate the load.

**Operational Limitations**

There are certain inherent regions within which a stepper motor will not provide stable operation. At both the natural frequency of the motor, and the mid-frequency resonance region, stepper motors may oscillate noisily, lose steps or even stall. Electronic and mechanical means can be used to compensate for these effects, and they do present an added dimension to be considered in the application process.

**Low-Frequency Resonance:**

The low-frequency resonance region of a stepper motor is usually a narrow band centered between 80 and 200 steps per second (sps). In this region, the motor load must contain some friction, either inherent or added by the user, to assure stable operation. Although it is possible to calculate with some certainty the amount of friction required, system performance should always be verified by actual testing.

**Mid-Frequency Resonance:**

Mid-frequency resonance is the term used to refer to a region within the mid to upper stepping rates in which there is a steep drop-off in available torque. In this area, motor performance is extremely erratic and stalling can occur. Once this region is passed, normal operation resumes. The actual location and width of the mid-frequency resonance region is dependent on the type of control, the power supply voltage and the motor load conditions. However, speed / torque curves provided by the manufacturer usually indicate probable unstable areas. Although continuous operation in resonance areas is not possible without some type of damping, steppers can operate at these speeds momentarily during acceleration and deceleration.

Since resonance is a function of motor design, load characteristics and control circuitry, it can often be avoided, compensated for or even eliminated by a variety of techniques.

**Ramping**— If operation beyond the mid-frequency resonance region meets application requirements, it may be possible to ramp through it by properly matching motor to load. Since steppers are normally used in processes which require frequent acceleration and deceleration, the effects of resonance can generally be overcome.

**Electronic Antiresonance Techniques**—Various electronic methods are available to minimize resonance effects. A common
and relatively inexpensive technique is to “half-step” the motor by energizing the windings alternately one and two at a time. The motor takes two half steps to advance a full step angle. This produces smoother shaft rotation with reduced resonance effects.

When extended mid-frequency operation is unavoidable, more sophisticated antiresonance circuitry is needed to electronically dampen the instabilities that cause resonance. Contact the motor manufacturer for more information.

Mechanical Dampers—Several mechanical methods may be used to successfully overcome the effects of resonance. Viscous inertia, ferro-fluidic and eddy current dampers all operate on the principle that a sacrifice in the rate of acceleration produced by adding inertia produces increased momentum to cancel out oscillation in the resonance region.

Viscous inertia dampers are coupled to the stepper motor shaft opposite the load. A damping rotor rotates in a fixed housing filled with a viscous fluid. Once the motor is brought up to speed, the inertia sets up an added momentum which damps the oscillations in the resonant area. Ferrofluidic dampers create inertia in a nonmagnetic housing filled with magnetic particles. Energy is absorbed by the interaction of inertia, mass and housing. Eddy current devices substitute a cup made from conductive material (usually aluminum) for inertia and fluid. As the shaft rotates, eddy currents are built up in the aluminum cup. The damper then acts like a friction drag on shaft rotation and resists deviation from operating velocity.

Oscillation (Ringing): Another control system characteristic which can be a factor in positioning application is the tendency for stepper rotors to oscillate or “ring” when the pulse train is stopped. See Fig. 8-51. The ringing effect usually lasts no longer than a few hundred milliseconds. If this poses a problem, there are several ways to damp stepper motor systems.

Motor plugging circuits make it possible to electronically damp oscillation by “backstepping” the stepper motor so that the rotor is at zero velocity when it reaches the desired final position. With delayed last step damping, the EFSS rate is selected so that the rotor overshoots the next to last position and reaches the final detent with zero velocity. It can then be held with little or no oscillation. Either method effectively reduces motor oscillation. See Fig. 8-52.

Inertia: Inertia plays an important role in stepper applications. To obtain desired operation, the load inertia must be within the capability of the motor control system to accelerate and decelerate. Too much load inertia can cause the motor to lose steps or stall during acceleration. If
there is insufficient load inertia, the width of the resonance region may be too large.

To determine whether or not inertia will pose a problem in an application, first consult the motor control performance characteristics. If the intended operation is within acceptable design guidelines, inertia should be manageable. If the desired stepping rate is within the midfrequency region and the load system cannot be altered to allow a different stepping rate, more inertia may be added, or electronic means may be employed to arrive at a balanced combination of motor, load and control.

8.6 SOLID STATE ELECTRONIC (ACTIVE) CONTROL OF AC MOTORS

Advances in AC motor control have been slower to evolve than those for DC motors. As a result, AC motors have been slow to shake their image as constant speed drives. Nevertheless, progress is being made in many areas. Adjustable frequency AC drives are becoming more prevalent even for motors in the fractional horsepower range. These drives offer programmability of functions such as preset speeds, resonance compensation, and acceleration and deceleration rate control. Some sophisticated controls combine voltage and frequency control within the same unit. Other controls with specialized memory chips allow for keyboard-programmable, motor air gap flux adjustments.

It is beyond the scope of this Handbook to cover all of the latest innovations in electronic AC motor controls. However, familiarization with some of the basic solid state control methods is necessary.

Change in Frequency Method

As mentioned earlier, one way to control AC motor speed is by changing the power supply frequency. This is based on the speed formula for AC motors. The speed of an AC motor is related to the power supply frequency (Hz) by the equation:

\[ \text{RPM} = \frac{120}{\frac{f}{P}} \]

where:
- \( \text{RPM} \) = revolutions/minute (nominal synchronous speed)
- \( f \) = frequency (Hz)
- \( P \) = number of poles

Change in frequency has the advantage of providing stepless speed changes over a relatively wide range, and may be used with either synchronous or nonsynchronous induction motors. The synchronous motor has the obvious advantage of following the speed adjustment called for by the control. The nonsynchronous motor, even though it develops more torque per frame size, will slip in speed from the control setting depending upon motor load. The major disadvantage encountered with this method is the relatively high cost of the frequency changing power supply.

With an increasing number of manufacturers making three-phase adjustable frequency drives, the three-phase motor is gaining popularity in adjustable speed applications. This is particularly true where ruggedness, reliability and low maintenance are requirements.

Polyphase Power Supplies:
Small motors wound for operation with two-phase power supplies seem to be best suited for adjustable frequency applications. These motors will provide performance similar to three-phase designs, but the two-phase adjustable frequency power

8-39
supply is more practical. Small two-phase motors can be optimized to operate over a range of 10 to 120 Hz by proper voltage adjustment. The voltage must be increased as the frequency is increased in order to compensate for the change in motor reactance. See Fig. 8-53.

One of two basic techniques are used to obtain adjustable frequency power:

1) **Six Step Method**—This method is named for the shape of the waveform it generates. See Fig. 8-54. Line voltage is rectified to an adjustable DC level. This voltage is then fed into an inverter which produces an alternating square wave voltage. At low motor speeds, the six step inverter can produce pulsations of torque and speed, called cogging.

Six step inverters also produce harmonics in the output waveform which cause motor heating without contributing to motor torque.

2) **Pulse Width Modulation (PWM)**—With PWM, line voltage is rectified to a constant potential DC voltage. This DC voltage level is fed into a PWM inverter which generates a series of short pulses at varying widths to yield the voltage, frequency and harmonic relationship desired. See Fig. 8-55. The average voltage is determined by the width of the pulse (wide for high average voltage and determined by the rate at which polarity is reversed (which is much smaller than the pulse rate, so there are many pulses per cycle).

One disadvantage is that PWM inverters produce high frequency minor currents at the pulse repetition frequencies. The rapid high voltage pulses can also produce insulation stresses, and noise and vibration problems in motors. There are several variations of these two techniques. Since they produce non-
sinusoidal waveforms, they cause additional motor heating which may require that the motor be derated from the output that is obtainable from a pure sine wave.

Small polyphase motors are often rated for dual frequency (50/60 Hz) use at a single voltage level. These motors will run hotter on 50 Hz than 60 Hz because the input will be higher on 50 Hz and their ability to self-regulate will be reduced due to the reduction in speed to approximately 5/6 of the 60 Hz speed.

**Single-Phase Power Supplies:** On single-phase power supplies, split-phase start or capacitor start motors are least suitable for dual frequency operation. It is difficult to find a starting relay suitable for dual frequency operation. When a centrifugal cut-out switch is used instead of a relay it is difficult to obtain the correct operating speed. In addition, if a 60 Hz split-phase motor is designed to operate close to its temperature and magnetic limits, then operation on 50 Hz will not be satisfactory since the current and watts will increase excessively and the motor will overheat. This could even occur at no load.

The permanent split capacitor (single-phase power supply) motor presents a problem in adjustable frequency operation over a range of frequencies. This is primarily because the capacitor value should be decreased with an increase in frequency and vice versa. However, when specifically designed for the purpose, the permanent split capacitor motor is the best choice for operation in the narrow frequency range of 50 to 60 Hz.

When the frequency is changed from 60 to 50 Hz, the current in the main winding will increase and the current in the capacitor winding will decrease so that the total current may actually remain approximately the same regardless of the frequency. Generally speaking, any PSC motor can be wound so that it will accommodate the same input power at 50 or 60 Hz.

However, a dual frequency, constant voltage design sacrifices power output compared with single-phase versions. Therefore, for a given frame size, optimized dual frequency motors will have lower hp ratings than single frequency motors.

**Vector Control of Induction Motors**

AC motors have long been used as constant speed drives while their DC counterparts have been employed in numerous variable speed and positioning applications. This phenomenon is due to the DC motor’s inherent adaptability to variable speed techniques and its linear speed/torque characteristics.

This adaptability is a function of DC motor construction and the ability to control torque and motor field flux independently. We learned earlier that by weakening the magnetic field of a DC motor, the field current is also weakened and consequently, the back emf is reduced. If the armature voltage is held constant while weakening the field flux, motor speed increases. DC motors become very unstable at high speeds due to brush arcing and armature reaction. Therefore, high speed DC motors require special construction to overcome these inefficiencies.

AC motors which have no brushes and more rugged construction have been unsuitable for variable speed applications because their torque and field flux are interrelated. Any change in either one will cause a corresponding reaction in the other. Vector control (or field-oriented control) allows independent control of an induction motor’s field flux and rotor current to achieve linear torque characteristics like those of DC motors. To do that, the motor control must regulate the instantaneous magnitude and phase of the stator currents.
or voltages in order to develop a linear relationship between torque and slip frequency. This involves numerous calculations and algorithms. Although vector control techniques have been known for some time, they have only become cost-effective with recent advances in microprocessors and integrated circuit technology.

The instantaneous angular position of the field flux vector rotating at synchronous speed must be known for accurate vector control. This can be measured (direct vector control) or it can be estimated from the computed slip which is based on the rotor time constant, Tr (indirect method). The rotor time constant is a function of rotor resistance and inductance and can vary significantly from its nominal value depending on operating conditions. It is critical that Tr be tuned correctly. If it isn’t, the calculated slip will be in error and consequently so will the field flux vector. If the estimated Tr is not matched to actual Tr, field orientation will be lost and the actual torque will differ from the expected torque. A popular method for calculating Tr is by using the inverse Gamma form model equivalent circuit, but that is beyond the scope of this Handbook. It suffices to say that vector controllers require extensive processing power in order to achieve effective results.

Machine tool spindle drives have benefited from the use of vector controlled induction motors. They can be operated at higher speeds than thyristor-controlled DC motors for increased application performance and they require less maintenance, both of which often justify the cost of the controls.

Switched Reluctance Motor Control

The switched reluctance motor was described in Chapter 4. It possesses qualities of both AC and DC motors. The switched reluctance motor has been receiving more attention in recent years as a variable speed drive for the same reasons that vector control of induction motors has grown in popularity: faster processors and decreasing cost of building and implementing controls.

But unlike induction motors which are a staple in the industry, switched reluctance motors are not widely used nor understood by designers. Therefore, there is considerable controversy over the methods of controlling switched reluctance motors, especially in servo systems or four quadrant operation.

Since they possess AC motor qualities, they require signal processing in order to compensate for inherent nonlinear properties. Control algorithms are needed to smooth irregularities from the motor as well as from the rotor position feedback devices that are required. A considerable degree of wave shaping is also required on the input side of these motors.

Rotor position is a critical factor in controlling a switched reluctance motor. Transducers for measuring position and current add considerable cost to the system. Although there are several methods for estimating the rotor position, they are cumbersome and can often create undesired effects.

8.7 MOTOR CONTROL ENCLOSURE STANDARDS

Some motor controls are provided in separate enclosures for simple applications where the motor speed is controlled manually or where the motor control is used as a stand-alone device. Other times, a motor control is simply one element of a more complex motion control system and is mounted in a large central equipment enclosure with other process control equipment. In the latter applications, the
manufacturer may provide the control without an enclosure.

Motor control enclosures, like motors themselves, are rated and tested against safety criteria established by various third party standards organizations such as the National Electrical Manufacturers Association (NEMA) and Underwriters Laboratories (UL). Designing to these standards is voluntary and compliance to standards is at the manufacturer’s discretion. When a control enclosure meets various third party standards, end-users are assured of certain safety and operating characteristics.

Standard UL-508 covers safety design requirements for industrial control equipment enclosures. UL-50 covers cabinets, cut-out boxes and junction boxes. NEMA has also established standards for industrial control equipment enclosures to meet a wide range of applications.

A brief overview of NEMA enclosure types is given below. If additional information or specific details are required about motor enclosure standards, the reader should contact the various standards organizations and industry associations listed in Appendix 1.

**NEMA Type 1:** This type of enclosure is suitable for indoor general applications under normal atmospheric conditions. Type 1 enclosures protect users from touching the equipment and protect the control from falling dirt.

**NEMA Type 2:** This is a general purpose indoor enclosure with drip shield protection to protect the control from falling liquid or dirt. It is not intended to protect against dust or internal condensation.

**NEMA Type 3:** These enclosures are for outdoor use and provide some protection from windblown dust, rain and moisture. They also protect the control from external ice formation. They will not protect against internal condensation or icing.

**NEMA Type 3R:** The same as Type 3, this enclosure only protects against falling rain, sleet and external ice formation.

**NEMA Type 3S:** Also the same as Type 3, this enclosure meets additional provisions for operating external controls when ice-laden.

**NEMA Type 4:** These enclosures are for indoor or outdoor use and protect against windblown dust and rain, splashing water and forcefully directed water from a hose. They do not protect against internal condensation or icing.

**NEMA Type 4X:** The same as Type 4, this enclosure provides added protection against corrosion.

**NEMA Type 6:** These enclosures are for indoor or outdoor use and can withstand temporary submersion in water at a limited depth.

**NEMA Type 6P:** The same as Type 6, this enclosure also has the ability to withstand submersion for prolonged periods.

**NEMA Type 11:** These enclosures are intended for indoor or outdoor use and protect against corrosive liquids and gases. They can be submerged in oil for added protection against fumes and gases.

**NEMA Type 12:** These enclosures are for indoor use and provide a degree of protection against dust, falling dirt and dripping noncorrosive liquids.

**NEMA Type 13:** These enclosures are for indoor use and provide a degree of protection against dust, spraying water, oil and noncorrosive coolant.

**NEMA Type 7 (Class I, Groups A, B, C and D indoor):** These enclosures are intended for hazardous areas as defined by the National Elec-
trical Code. They meet explosion, hydro-
static and temperature tests.

**NEMA Type 9 (Class II, Groups E, F and G indoor):**
These enclosures are intended for use in Class II hazardous areas as defined by the National Electrical Code. They also pro-
tect against the ingress of dust.

In addition to local standards, an inter-
national classification system has been es-
tablished by the International Electrotechni-
cal Commission (IEC) to rate the sealing
effectiveness of electrical equipment enclo-
sures. IEC-529 utilizes an alpha-numerical
system. See Fig. 8-56. The letters “IP”
stand for “Ingress Protection” and are fol-
lowed by two numerical digits which indi-
cate degrees of protection against solid
objects and moisture.

The first digit indicates the degree of
protection that the enclosure offers against
solid object entry:
0 - No special protection.
1 - Protection from solid objects larger
   than 50 mm.
2 - Protection from solid objects not
   greater than 80 mm in length and 12
   mm in diameter.
3 - Protection from entry by objects
   greater than 2.5 mm in diameter.
4 - Protection from objects greater than
   1.0 mm in diameter.
5 - Protection from dust.
6 - Dust-tight.

The second digit indicates the degree
of protection that the enclosure offers
against moisture:
0 - No special protection.
1 - Protection from dripping water.
2 - Protection from vertically dripping
   water.
3 - Protection from sprayed water.
4 - Protection from splashed water.
5 - Protection from water jets.
6 - Protection from heavy seas.
7 - Immersion protection.
8 - Continuous submersion protection.

IEC-529 does not cover mechanical
damage, explosions or harsh environmental
conditions such as high humidity or corro-
sive fumes.
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**Fig. 8-56: IEC-529 enclosure classifications.**