III

Applications and Systems Considerations

9

DC Motor Drives

Ralph Staus
Pennsylvania State University

9.1 DC Motor Basics

The DC motor consists of two basic parts: a stationary magnetic field and a current-carrying coil on the armature. The force produced by the interaction of these two components produces a torque that causes the armature to rotate. The stationary magnetic field is produced by a permanent magnet for many small DC motors. Large and extended speed range motors use an electromagnet to produce the stationary field permitting the drive to control the field strength. The armature coils consists of a series of individual coils connected to the DC power source through a commutator and brushes. As the armature rotates, the commutator switches successive coils into the circuit to keep the armature coil and magnetic poles in the same relative position.

The field flux ϕ (Eq. 9.1) is a function of the field current I_f and a proportionality constant k_f. The torque T produced (Eq. 9.2) is related to the field flux and armature current i_a by the proportionality constant k_t. The speed of a DC motor is controlled by the torque produced by the motor and the torque required by the load. When the motor torque exceeds the load requirement, the rotational speed of the motor increases.

$$\phi = k_f I_f \tag{9.1}$$

$$T = k_t \phi i_a \tag{9.2}$$

The armature current is in response to the applied voltage V (Eq. 9.3) and is opposed by a countervoltage (e_a) produced by the armature coil rotating through the stationary magnetic field and the armature resistance (R_a). The countervoltage (Eq. 9.4) produced by the armature is proportional to the strength of the stationary field and the rotational speed (S). Below the rated base speed of the motor the current in the stationary magnetic field coil is kept constant. Therefore, at values below base speed the DC motor speed is a function of the applied voltage and resistive loss in the armature.

$$V = e_a + R_a i_a \tag{9.3}$$

$$e_a = k_e \phi S \tag{9.4}$$

Some DC motors have an additional winding in series with the armature to increase field strength in proportion to the armature current. With this series field, the voltage at the motor terminals is proportional to the speed of the motor without the reduction due to armature resistance. The improved performance permits open-loop speed control providing a reasonable steady-state response.

These equations for DC motor speed control are valid for steady-state analysis but do not account for the inertia of the motor or the inductance of the armature winding. To provide for a quick response, the DC drive must provide additional torque (current) to overcome the motor inertia and additional voltage to overcome the armature inductance.

DC motors are often used at greater than the base speed of the motor. Base speed is the rotational speed where the motor produces rated horsepower at rated torque. Below this speed, the motor may be operated at rated torque without overloading. Above base speed, the motor torque must be limited to prevent exceeding the horsepower limit.

9.2 DC Speed Control

The first applications of variable-speed control for large (10 to 1000 Hp) motors are known as the Ward Leonard Motor-Generator (M-G) systems (Fig. 9.1). In these systems a large constant-speed AC motor is mechanically coupled to a DC generator. The voltage produced by a DC generator is a function of rotational speed and the strength of the magnetic field. Controlling the field current of the generator with a rheostat can efficiently control the voltage produced by the generator operating at a constant speed. A rheostat in the generator field circuit controlled the field current of a few amps while the DC generator produced current in hundreds of amps at the controlled voltage. The speed of the connected motor is a function of the voltage supplied by the generator and the field current of the motor. When the same DC generator powers several DC motors, rheostats in each of the motor field circuits allow individual motor speed control.

State-of-the-art steel industry bar mills through the 1950s used M-G systems. A typical mill installed in 1952 used a 7500 hp synchronous AC motor coupled to three DC generators. One generator was electrically connected to the reversing mill, the second connected to the two-high mill, and the third connected to the bar mill so the voltage applied to each could be separately controlled. The reversing mill and the two-high mill motors were operated with full field current to enable the use of the full torque capability of the motors. To enable the use of small rheostats to control significant generator field current that would be varied continuously, a small M-G was applied with the main generator field as its load. The use of armature contactors for direction and field current rheostats for generator voltage control provided the full range of required voltages.

The bar mill consisted of five motors each requiring individual speed control. The product (steel bar) exit speed of each reduction stand must match the entering speed of the subsequent stand. The exit speed of each stand is a function of the entering speed and the bar reduction. In the mill, the speed of the product exiting a stand increased if the reduction rolls were moved closer together by the operator on

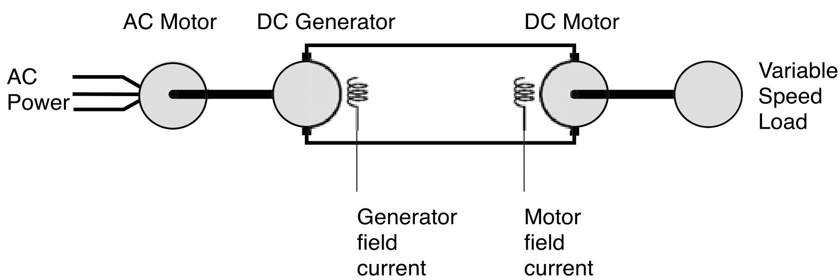

FIGURE 9.1 M-G system.

the production floor. As the floor operator adjusted the roll gap to produce the proper size, the field currents required adjustment. A second operator would monitor the size of the loop formed between the stands and adjust the rheostats to compensate for the roll gap changes.

With the introduction of semiconductors, systems were installed to take advantage of the diode. In the 1960s, large DC motors were replacing steam power turbines at many mills. Rather than installing a M-G set, a diode bank and an associated transformer provided a constant DC power source. The DC motor and gear reducers were selected to operate above base speed in the constant horsepower range. The goal was to increase efficiency and reduce maintenance costs. In the M-G set, both the AC motor and the DC generator were less then 100% efficient and each required maintenance of brushes and bearings. The solid-state constant DC voltage source increased efficiency and reduced maintenance costs. Speed regulation still used rheostats and the motor speed control was open loop. One significant disadvantage of the diode DC voltage source compared with the M-G source was the inability to regenerate power. Motor speed could not be reduced rapidly without having a bank of resistors to dissipate the excess energy. The M-G set would convert from a consumer of electric power to a supplier when the load speed was faster than the desired.

Transistor developments in the 1960s and 1970s brought further gains to large DC motor control. With the introduction of transistorized field current regulators, the motor speed was controlled electronically with a rapid closed-loop response. A small DC generator, referred to as a tachometer, provided a voltage proportional to the motor speed. The transistor field current regulator compared the tachometer feedback to the speed set point and adjusted the field current to control the motor speed.

The use of rheostats and early transistor regulators were inefficient for speed control when applied in the armature circuit. With the development of new systems using pulse width modulated (PWM) voltage regulators, the armature voltage for small motors could be controlled. Systems up to several horsepower were successfully applied to DC motors using permanent magnet fields. The power dissipated by the transistor when gated-on is minimal and the power while gated-off is zero. However, the power the transistor is required to dissipate while turning on and off limited the size of these systems. The application of PWM transistors as field current regulators to large DC motors of hundreds of horsepower provided the efficiency and closed-loop response of transistorized control to large systems.

The introduction of thyristor or silicon-controlled rectifiers (SCRs) provided for the revolution in control of large DC motors. SCRs were applied in both the field current regulators and the armature voltage regulators. With the SCR came increased efficiency, the ability to regenerate power, and high power capability. DC drives and motors from a few horsepower to hundreds of horsepower could be operated and controlled efficiently in all four quadrants when powered by three-phase line voltage. In addition, systems were developed for DC-to-DC control for the operation of battery-powered equipment.

The latest development in the DC motor control is the introduction of the insulated gate bipolar transistor (IGBT) to large power systems. These transistors have a fast switching time that reduces the power the transistor is required to dissipate. With the introduction of the IGBT came a movement to apply the concepts and lessons learned to large AC systems. Predictions were made that DC systems were obsolete and would soon be replaced. However, DC systems have proved to be dependable and cost-effective. They are still being applied when the application is suitable for economic reasons.

9.3 DC Drive Basics

Speed regulation in analogue drives is accomplished with a proportional–integral–derivative (PID) regulator for the voltage output. The input to the equation was the speed error and the output is used to drive the voltage regulator. A faster response is obtained by using the output of the PID equation as the input to the current regulator. A second PID regulator uses the output of the current regulator as an input to control the voltage. When additional speed is required, additional current is called for. The current regulator call for more voltage force increased current. The increased current provides additional torque resulting in increased speed.

In analog drives, a field current regulator provides the current for full field except when speed greater than base speed is required. The regulator monitors armature voltage and reduces the field current when the armature voltage is driven above rated values. Since the armature current is proportional to the motor torque and the current regulator is clamped at the rated value, an armature voltage above the rated value indicates the speed regulator output for a speed above the base value. Motor speed is proportional to armature voltage and inversely proportional to field current (see Eq. 9.5). Therefore:

- Reducing the field current reduces the field flux (Eq. 9.1).
- Reducing the field flux reduces the armature counter emf (Eq. 9.4).
- Reducing the armature counter emf increases the armature current (Eq. 9.3).
- Increasing the armature current increases the motor torque (Eq. 9.2).
- Increasing the motor torque increases the motor speed.
- Increasing the motor speed causes the regulator to decrease the armature voltage.

The system stabilizes with the armature voltage at base value and the field reduced within the range referred to as "weak field."

Modern digital microprocessor drives use a lookup table to determine the proper field current for the motor speed. The velocity feedback is fed to the field current regulator along with the armature voltage to determine the correct value of field current.

9.4 Transistor PWM DC Drives

The transistor PWM drive (Fig. 9.2) provides an efficient control for small motors nominally less then 5 hp. These drives operate at voltages and current levels limited by the transistors selected. The incoming AC voltage is rectified and filtered. The transistors are switched on/off to provide an average DC voltage (Fig. 9.3) to the motor. A switching frequency of 4 to 10 kHz prevents the motor speed from responding to individual cycles of the switching supply. The use of permanent magnet motors eliminated the need for field current regulators. A dedicated transformer determines the DC voltage supplied to the transistor regulator. The transformer is selected to provide the most efficient level of filtered DC and is an integral part of the drive system.

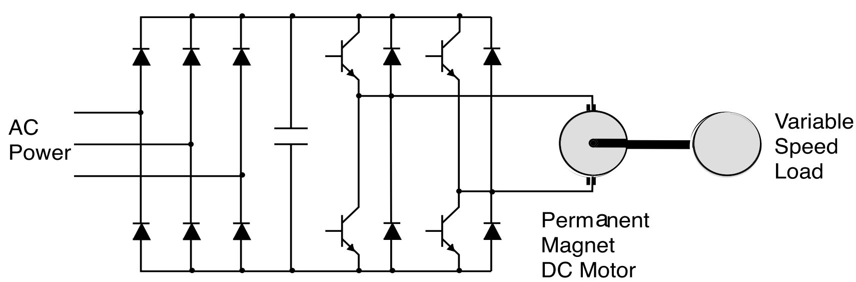

FIGURE 9.2 Transistor PWM system.

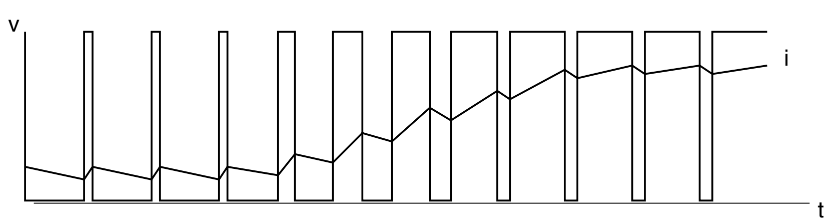

FIGURE 9.3 Transistor PWM output.

9.5 SCR DC Drives

DC drives for large DC motor use thyristors, commonly called SCRs, to convert incoming three-phase AC voltage to a regulated DC value. The use of 12 SCRs allows operation of the drive in all four quadrants of operation. The four quadrants are:

1. Forward motoring
2. Forward braking, regenerating power
3. Reverse motoring
4. Reverse braking, regenerating power

During operation in each of these quadrants, the SCRs are gated on at a phase angle to provide the DC voltage required. The angle is defined as the time in degrees from when the AC phase becomes the most positive or negative. The connection of the SCRs from the incoming AC power source to the drive output is shown in Fig. 9.4. The AC waveform in Fig. 9.5 starts with the SCRs from A phase to DC+ and B phase to DC– gated on. At 40° after the crossing point of the AC voltage, the SCR connects C phase to DC–. When this SCR begins to conduct, the B phase to DC– turn off. At 60° later the B phase to DC+ SCR is gated on and the motor is now connected from phase B to C. SCRs then connect B-A, C-A, C-B, A-B

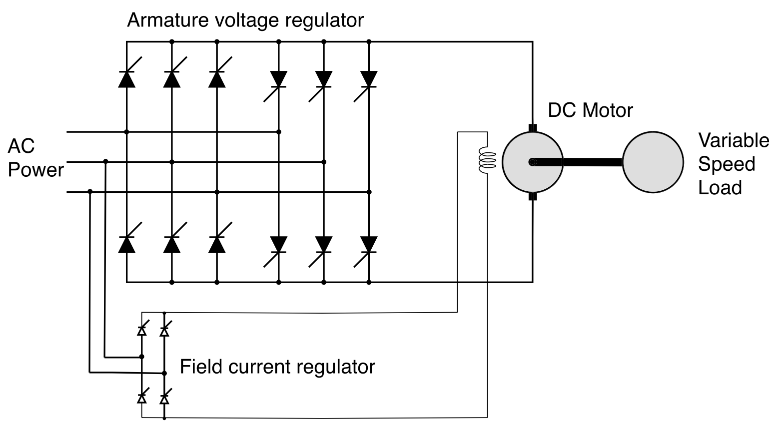

FIGURE 9.4 SCR system.

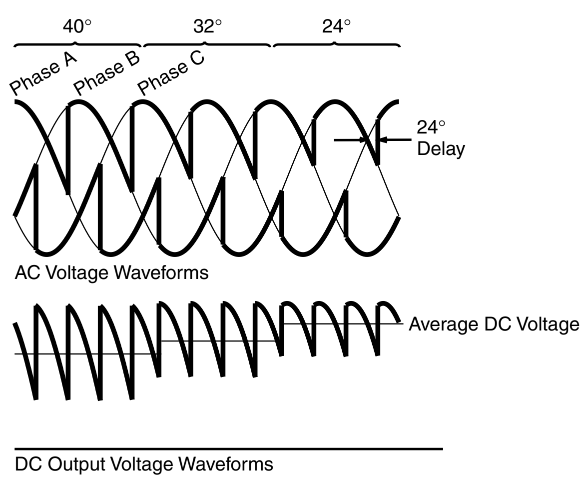

FIGURE 9.5 SCR system output.

before restarting the sequence with A-C. The resultant DC output waveform is shown in Fig. 9.5 as is its relation to the AC waveform. The resultant average DC is a function of the phase angle. The average DC output for 40°, 32°, and 24° firing phase angles is illustrated. The DC drive would function as a rectifier if the SCRs were gated on with a phase angle of 0°. The SCR provides unique advantages for the DC drive. First, the voltage across the SCR during the turn-on time is significantly less than the voltage switched in PWM drives. Second, the SCR does not switch off with current flowing. When the subsequent SCR turns on, the SCR is reverse-biased and current flow stops. The power consumed by the switching device is a function of the switched voltage, the switched current, and the switching time. The disadvantage of the SCR drive is the distortion of the AC power waveform due to line notching. The SCR proved to be well suited for operation at 480 V AC and from 10 to 1000 A.

Field current regulators require only single-phase power and only four SCRs. The field winding in the motor has significant inductance and the additional voltage ripple from using a single-phase source does not induce significant ripple in the field flux. In addition, the field is never operated with a negative current, eliminating the need for the complementary set required in the armature circuit when reversing the direction of the motor.

The disadvantage to SCR drives is the distortion to the incoming power waveform and the currents drawn during switching. As the drive switches from phase A to B, the drives turn on the SCR for phase B while the phase A SCR is conducting. Since the phase A SCR has a finite time requirement to stop conduction, this effectively shorts the two phases together. Additional inductance must be added to reduce the current during this time. The quantity of inductance required from isolation transformers or line reactors is based on the motor, drive, and power source parameters. The commutating inductance has been neglected in Fig. 9.5 for simplicity.

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