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Servo Drives

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A significant and very special class of industrial drives are those that are used for position control. These drives are typically called servo drives and the intelligent control of these drives is often called motion control. Some of the application areas of servo drives are machine tool servos, robotic actuator drives, electric vehicles, computer disk drives and the like. The power level for these drives usually range below 20 to 30 kW; however, drives with slightly lower control quality usually have power levels below 50 to 60 kW.

Servo drives must meet several quality requirements, such as:

1. High dynamic response, which can be realized only with special control schemes and special motors with a high torque/inertia torque ratio
2. Smooth torque production in order to achieve smooth rotation and the elimination of position angle oscillations
3. High reliability with quick maintenance and repair
4. Robust control, i.e., the ability of the drives to tolerate wide swings in load inertia or motor parameters

As a result of these quality requirements, the price of servo drives can be several times that of common industrial drives of the same size.

The control scheme for servo drives usually consists of three subordinate loops as shown in Fig. 15.1. The first and most inner one is the current control loop. The Y_I transfer function of the current controller is generally chosen in such a manner that the current closed loop must have a cutoff angular frequency of $\omega_{0I} \geq 1000$ r/s. The second control loop, referred to as the speed loop, usually has a closed-loop control band width of $\omega_{0\omega} \geq 300$ r/s. The outer loop, or position control loop, must accurately follow the position reference. All the control loops, as a rule, are proportional integral (PI) controllers; the position controller is the only one that often employs proportional, sometimes proportional differential controller. But if a parameter of the system changes in some reasonable fashion, e.g., the inertia torque in a robotics application, this control system cannot achieve fast and accurate position control without overshoot. In this case, other types of control schemes have been used such as feed-forward, optimal, and sliding mode control.

In some applications the servo drives require only torque control for positioning, e.g., in robotics applications. In this case, the torque control loop becomes the outer loop. For most drives a proportionality exists between torque and motor current; therefore, in this case torque control means current control. All the control loops, at present, usually employ digital control. Only the current loop, at high operating frequencies, is sometimes implemented with analog circuits. About 10% of all servo drives are used in single applications. In machine tools applications, where there are several axes of control, all the servo

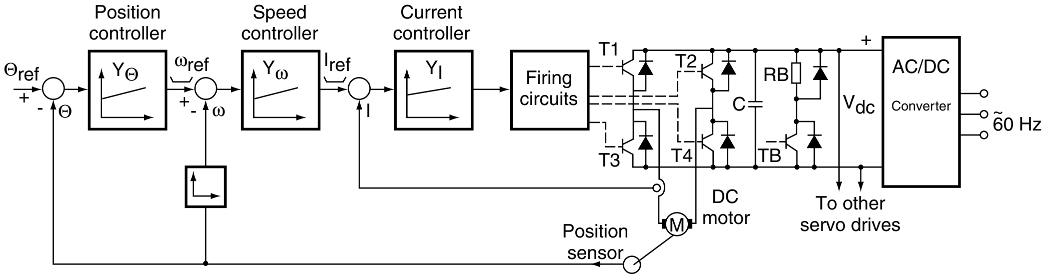

FIGURE 15.1 DC servo drive (with control scheme).

drives have a common DC supply, which is obtained from a standard AC supply through a common rectifier as shown in Fig. 15.1 When electric motors are used, they are either permanent magnet (PM) DC motors, permanent magnet synchronous motors or, rarely, induction motors. For low-power applications stepping motors can be used, but this type of motor exhibits a considerable amount of torque pulsation. The switched reluctance motor (SRM) can also be used. The permanent magnet for DC and synchronous motors is manufactured from various types of ferrite (strontium ferrite, hard ferrite, etc.), ceramic or samarium cobalt.

Servo motors normally come with different built-in sensors, e.g., encoder or resolver for position control and tachometer for velocity control. The motors generally are of a rugged design.

15.1 DC Drives

At present most servo drives are DC drives. The servo motor with permanent magnet excitation permits a 400 to 1000% torque overload. The torque limitation areas are shown in Fig. 15.2. Area I is the continuous operating area; area II is the intermittent operating area; and area III can be used only for accelerating and decelerating. These areas are limited by absolute maximum speed, an absolute commutation limit and the peak stall torque. The speed and the torque (current) control loops must take into account these limitations of the DC servo motors. DC servo motors have such low torque (size) ratings that normally their rated voltage must be less than 100 to 200 V. Therefore, DC servo drives when supplied from an AC source use a transformer for the creation of the supply with a reasonably rated value of voltage.

The motor supply circuits are shown in Fig. 15.1. The four-quadrant transistor chopper with a commutation frequency of 5 to 20 kHz ensures a very good dynamic control of the motor with very little, usually below 1 to 2 μs, dead time (the time between turn-off of one transistor and turn-on of the next). The transistors are either MOSFETs (metal oxide semiconductor field effect transistors) or IGBTs (insulated gate bipolar transistors).

The servo drives are normally unable to return the braking energy to the AC supply: the energy is lost in the DC circuit resistance, i.e., RB in Fig. 15.1. The resistor current is controlled by the transistor TB. During braking, DC current flows through the capacitor C and the DC voltage increases. When this voltage achieves its maximum permitted value, the transitor TB turns on, and DC current flows through resistance RB and then the DC voltage decreases to the minimum value when transitor TB turns off. Thus, during braking, the DC line voltage is maintained between a maximum and a minimum value.

The control scheme for the chopper transistors is presented in Fig. 15.3. A so-called overlapping control is commonly used. The T_C time-cycle is derived from the times αT_C and $(1 - \alpha)T_C$. The T_1 and T_4 transistors turn on during the time period $(1 - \alpha)T_C$, and the T_2 and T_3 transistors turn on during the time period αT_C; however, the turn-on and turn-off times of the odd and even transistors are shifted, i.e., overlapping, by $(1–2\alpha)T_C/2$ as shown in Fig. 15.3. If α is between 0 and 0.5 the motor voltage is positive and if α is between 0.5 and 1.0 the motor voltage becomes negative as illustrated in Fig. 15.3. A very important advantage of this control scheme is that the motor voltage and current waveforms repeat twice during one period (T_C) of the transistor control.

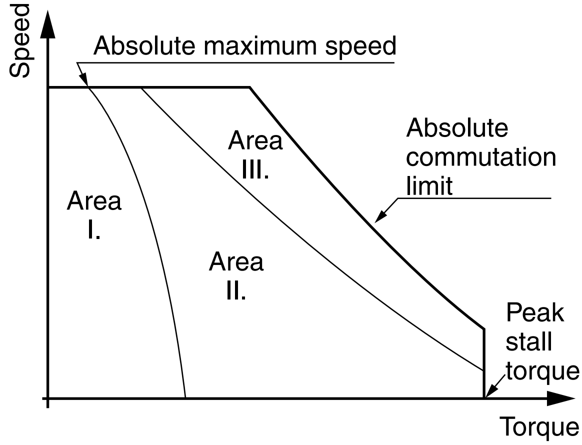

FIGURE 15.2 Limitations on the operating areas of the DC servo motors.

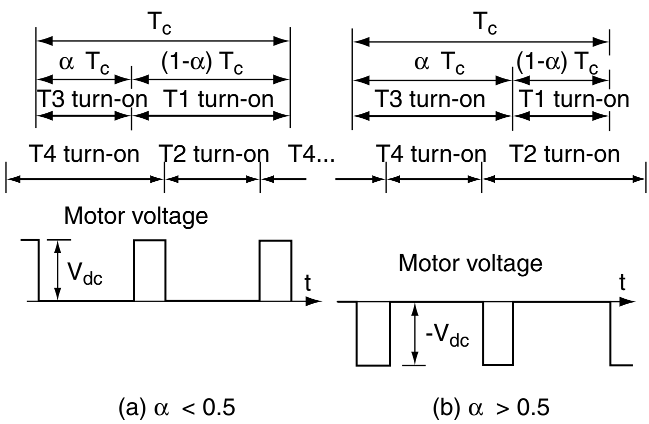

FIGURE 15.3 DC chopper transistor control.

As a result of the high-frequency control, the motor current (and torque) consists only of high-frequency harmonics with very low amplitudes, usually under 1% of the motor's rated current. This means that in both the transient and steady states the motor current and torque consist of virtually only a DC component and therefore there are no speed (or position) oscillations.

15.2 Induction Motor Drives

The induction servo motor with a squirrel cage rotor has very small rotor inertia torque, high reliability, and it is very economical. However, the control system for the induction motor is very complicated, expensive, and the quality of the control is sensitive to motor parameter changes. Therefore this motor is not widely used.

The typical supply circuits for the induction servo motor are shown in Fig. 15.4. The AC supply voltage feeds the diode rectifier, which creates the DC link. The DC link consists of the capacitor C, braking resistor RB, and transistor TB. The control of the DC voltage during the braking operation is performed in the same manner as that for DC drives. The voltage source inverter is usually constructed with IGBT transistors and very fast parallel diodes. In the last several years, the use of IGBT modules with six transistors and six diodes has been the preferred configuration.

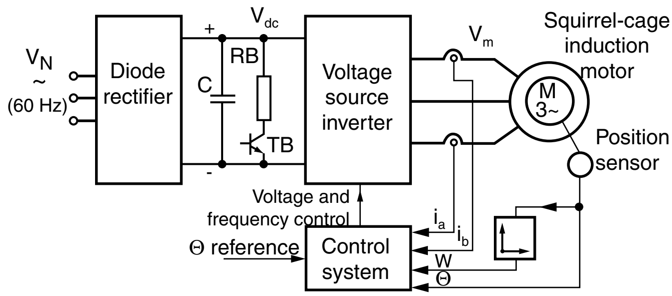

FIGURE 15.4 Servo drive with induction motor.

The drive does not need a transformer since high-voltage motors are available. If the AC phase voltage is V_N (rms value), then the DC link voltage will be $V_{dc} \cong 3/\pi\sqrt{6}V_N$ and the maximum possible motor phase voltage will be

$$V_m = \frac{2}{\pi}\frac{1}{\sqrt{2}} V_{dc} = 3\frac{\sqrt{12}}{\pi^2} V_N \cong 1.05 V_N \qquad (15.1)$$

Hence, if the rated voltage of the motor is equal to the AC supply voltage, then as a result of the voltage drop in both the rectifier and the inverter, the motor can operate with a rated flux between 0 Hz and the approximate frequency of the AC supply.

A position control system usually uses the indirect field oriented principle. The rotor flux is generated by the two phase currents as well as the speed, as shown in Fig. 15.4. The calculation is a function of the rotor time constant, which is dependent upon both the rotor resistance and rotor inductance. Variations in these parameters must be taken into consideration; however, the identification of the parameter changes is very complicated.

PM Synchronous Motor Drive

The permanent magnet synchronous motor is much more expensive than the squirrel cage induction motor, but the control system of the PM synchronous motor drive is much simpler than that used for the induction motor. When compared to DC motors, PM synchronous motors normally have less inertia torque and require less maintenance. As a result of these features, the PM synchronous servo drive has become one of the most popular types of servo drives. The converter circuits for PM synchronous motor drives are identical to those for induction motors as shown in Fig. 15.4. PM synchronous motors, such as induction servo motors, are usually manufactured for high voltage and therefore transformers are not required in their use.

There are two classes of PM synchronous motors:

1. Those with a square flux density distribution along the rotor air gap surface, as shown in Fig. 15.5a, which produces a trapezoidal back-emf (electromotive force) in the stator coil—the so-called trapezoid PM machines.
2. Those with a sinusoidal flux density distribution, as shown in Fig. 15.5b, which produces a sinusoidal back-emf—the so-called sinusoidal PM machines.

In the trapezoidal machines the angle β illustrated in Fig. 15.5a is the width of the magnet. In general, $\beta \cong 180°$. In Fig. 15.6 the trapezoidal machine with $\beta = 180°$ is presented and a two-pole machine is assumed. In steady-state the machine is rotated with constant synchronous speed, which is a function of the number of pole pairs p and the frequency of the stator supply f_1

$$\omega_1 = \frac{2\pi f_1}{p} = \text{const} \qquad (15.2)$$

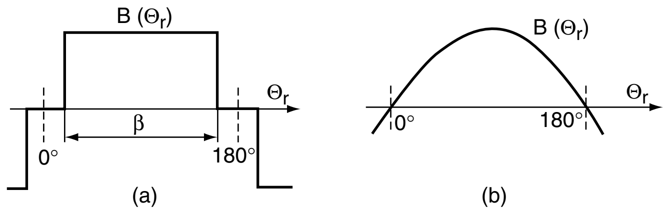

FIGURE 15.5 Two types of PM synchronous servo motors: (a) with square flux density distribution (trapezoidal PM machines); (b) with sinusoidal flux density distribution (sinusoidal PM machines).

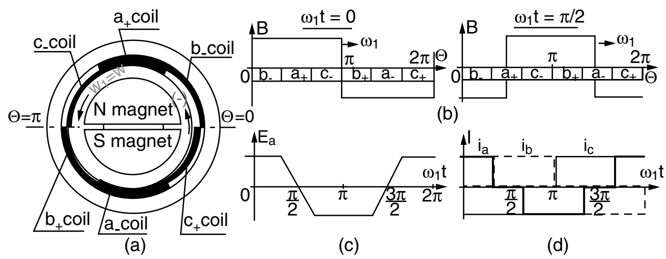

FIGURE 15.6 Trapezoidal PM machines with $\beta = 180°$: (a) motor construction; (b) flux density displacement at $\omega_1 t = 0$ and $\omega_1 t = 90$; (c) back-emf vs. time; (d) motor phase currents vs. time.

Consider Fig. 15.6a or b where the machine is expanded along the stator air gap surface. In the range $-60° \leq \omega_1 t \leq 60°$, the *a* phase conductors are located under the maximum flux density B, i.e., *a*+ is under +B and *a*− is under −B. Hence in this timeframe in the *a* phase the maximum value of the back-emf E_a is induced as shown in Fig. 15.6c. For $\omega_1 t \geq 60°$, E_a begins to decrease since the *a*+ conductors (or *a*−) are in the flux density of different directions. As shown in Fig. 15.6b at $\omega_1 t = \pi/2$ half of the *a* phase coil will be under a positive and the other half under a negative value of the flux density; therefore, at this time $E_a = 0$. As a result this analysis indicates that the back-emf-time function is a trapezoidal shape of the form shown in Fig. 15.6c.

Suppose that the drive control only permits stator current to flow in two phases at any time. With reference to Fig. 15.6a, positive current is supplied to phase *a* and negative current is supplied to phase *c*. The resulting stator phase currents are shown in Fig. 15.6d. This current distribution is achieved by the appropriate phase current commutations through the use of a position sensor signal (once for every 60°). The motor torque will be

$$T = cBI \tag{15.3}$$

where *c* is a motor constant. The torque will not have ripples if the current is constant and this constant current is ensured by DC current control just as it is for DC servo drives. But now under control are only the transistors that belong to the two current conducting phases. As a result of the high-frequency current control, the torque is essentially constant; however, during the phase current commutations, i.e., every $\omega_1 t = 60°$, current control is not possible. Hence, torque oscillations occur at a frequency of $6f_1$, which is a considerable disadvantage of trapezoidal machines.

In the sinusoidal PM machines the sinusoidal flux density distribution will produce a constant torque only if the phase currents are also sinusoidal. The sinusoidal values can be characterized by vectors as shown in Fig. 15.7. The $\bar{\Lambda}_p$ pole flux linkage vector and the $\bar{I}$ current vector will produce the torque

$$T = c_1 \bar{\Lambda}_p x \bar{I} = c_1 \Lambda_p I \sin(\Lambda_p I) \tag{15.4}$$

where c_1 is a constant. Therefore, if the angle between these two vectors is equal to 90°, as shown in Fig. 15.7, the torque is maximized. Current control is normally achieved as shown in Fig. 15.7b. The position

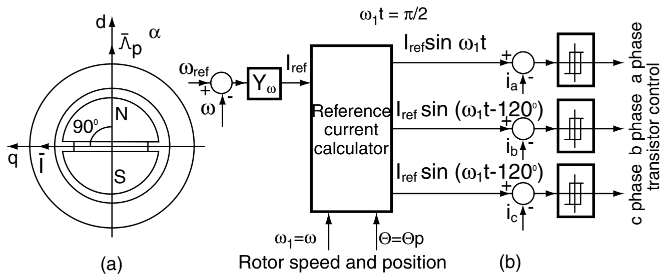

FIGURE 15.7 Sinusoidal PM machines: (a) pole flux and current vector orientation; (b) control schemes.

sensor signal requires the creation of three sinusoidal phase current reference signals, which generate the current vector with a 90° displacement from the pole flux vector. The three Schmidt triggers ensure two-point phase current control with the desired hysteresis. Because the phase current hysteresis is very small the motor torque ripples are very high frequency and have very small values. The important advantage of sinusoidal machine drives is that there are no torque oscillations with $6f_1$ frequency, as is the case with trapezoidal machines.

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