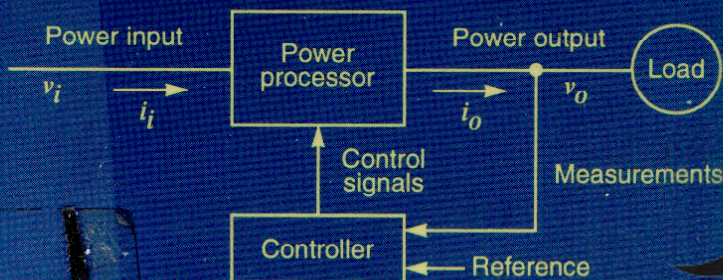


Second Edition

POWER ELECTRONICS

Converters,
Applications,
and Design



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MOHAN / UNDELAND / ROBBINS

POWER ELECTRONICS

Converters, Applications, and Design

SECOND EDITION

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This example shows that as a first approximation, to illustrate the principle of operation, it is reasonable to assume either a constant v_{C1} or constant i_{L1} and i_{L2} in this problem. ■

7-7 FULL-BRIDGE dc-dc CONVERTER

There are three distinct applications of the full-bridge switch-mode converters shown in Fig. 7-27:

- dc motor drives
- dc-to-ac (sine-wave) conversion in single-phase uninterruptible ac power supplies
- dc-to-ac (high intermediate frequency) conversion in switch-mode transformer-isolated dc power supplies

Even though the full-bridge topology remains the same in each of these three applications, the type of control depends on the application. However, the full-bridge converter, as used in dc motor drives, is covered in this “generic” chapter because it provides a good basis for understanding the switch-mode dc-to-ac (sine-wave) converters of Chapter 8.

In the full-bridge converter shown in Fig. 7-27, the input is a fixed-magnitude dc voltage V_d . The output of the converter in this chapter is a dc voltage V_o , which can be controlled in magnitude as well as polarity. Similarly, the magnitude and the direction of the output current i_o can be controlled. Therefore, a full-bridge converter such as that shown in Fig. 7-27 can operate in all four quadrants of the i_o - v_o plane, and the power flow through the converter can be in either direction.

In a converter topology such as that of the full-bridge converter shown in Fig. 7-27, where diodes are connected in antiparallel with the switches, a distinction must be made between the on state versus the conducting state of a switch. Because of the diodes in antiparallel with the switches, when a switch is turned on, it may or may not conduct a current, depending on the direction of the output current i_o . If the switch conducts a current, then it is in a conducting state. No such distinction is required when the switch is turned off.

The full-bridge converter consists of two legs, A and B. Each leg consists of two switches and their antiparallel diodes. The two switches in each leg are switched in such

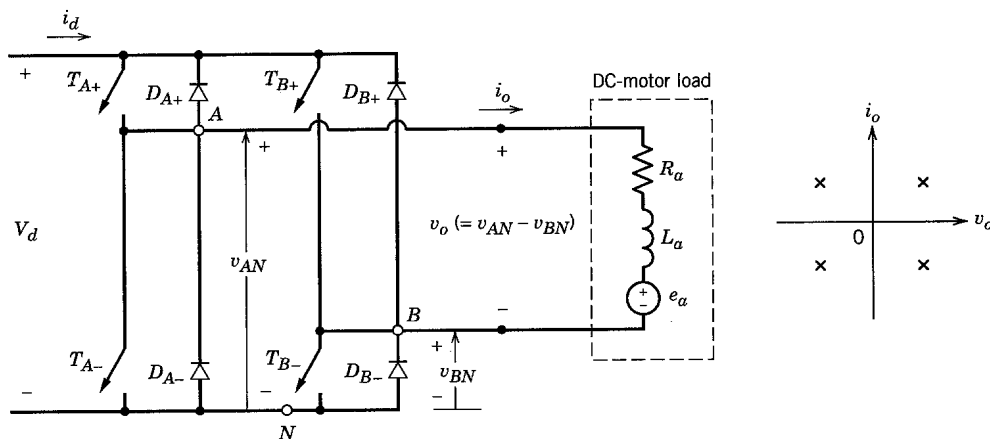


Figure 7-27 Full-bridge dc-dc converter.

a way that when one of them is in its off state, the other switch is on. Therefore, the two switches are never off simultaneously. In practice, they are both off for a short time interval, known as the blanking time, to avoid short circuiting of the dc input. This blanking time is neglected in this chapter since we are assuming the switches to be ideal, capable of turning off instantaneously.

We should note that if the converter switches in each leg are switched in such a way that both the switches in a leg are not off simultaneously, then the output current i_o in Fig. 7-27 will flow continuously. Therefore, the output voltage is solely dictated by the status of the switches. For example, consider leg A in Fig. 7-27. The output voltage v_{AN} , with respect to the negative dc bus N , is dictated by the switch states as follows: When T_{A+} is on, the output current will flow through T_{A+} if i_o is positive or it will flow through D_{A+} if i_o is negative. In either case, T_{A+} being on ensures that point A in Fig. 7-27 is at the same potential as the positive terminal of the dc input, and therefore

$$v_{AN} = V_d \quad (\text{if } T_{A+} \text{ is on and } T_{A-} \text{ is off}) \quad (7-66a)$$

Similarly, when T_{A-} is on, a negative i_o will flow through T_{A-} (since D_{A+} is reverse biased) and a positive i_o will flow through D_{A-} . Therefore

$$v_{AN} = 0 \quad (\text{if } T_{A-} \text{ is on and } T_{A+} \text{ is off}) \quad (7-66b)$$

Equations 7-66a and 7-66b show that v_{AN} depends only on the switch status and is independent of the direction of i_o . Therefore, the output voltage of the converter leg A, averaged over one switching frequency time period T_s , depends only on the input voltage V_d and the duty ratio of T_{A+} :

$$V_{AN} = \frac{V_d t_{\text{on}} + 0 \cdot t_{\text{off}}}{T_s} = V_d \cdot \text{duty ratio of } T_{A+} \quad (7-67)$$

where t_{on} and t_{off} are the on and off intervals of T_{A+} , respectively.

Similar arguments apply to the converter leg B, and V_{BN} depends on V_d and the duty ratio of the switch T_{B+} :

$$V_{BN} = V_d \cdot \text{duty ratio of } T_{B+} \quad (7-68)$$

independent of the direction of i_o . Therefore, the converter output $V_o (= V_{AN} - V_{BN})$ can be controlled by controlling the switch duty ratios and is independent of the magnitude and the direction of i_o .

(It should be noted that it is possible to control the output voltage of a converter leg by turning both switches off simultaneously for some time interval. However, this scheme would make the output voltage dependent on the direction of i_o in Fig. 7-27. This is obviously undesirable, since it would introduce nonlinearity in the relationship between the control voltage and the average output voltage. Therefore, such a scheme will not be considered with a load, such as a dc motor load, shown in Fig. 7-27.)

In the single-switch converters discussed previously, the polarity of the output voltage is unidirectional, and therefore, the converter switch is pulse-width modulated by comparing a switching-frequency sawtooth waveform with the control voltage v_{control} . In contrast, the output voltage of the full-bridge converter is reversible in polarity and therefore, a switching-frequency triangular waveform is used for PWM of the converter switches. Two such PWM switching strategies are described below:

1. *PWM with bipolar voltage switching*, where (T_{A+}, T_{B-}) and (T_{A-}, T_{B+}) are treated as two switch pairs; switches in each pair are turned on and off simultaneously.

2. *PWM with unipolar voltage switching* is also referred to as the *double-PWM switching*. Here the switches in each inverter leg are controlled independently of the other leg.

As we mentioned earlier, the output current through these PWM full-bridge dc-dc converters, while supplying dc loads of the type shown in Fig. 7-27, does not become discontinuous at low values of I_o , unlike the single-switch converters discussed in the previous sections.

In the full-bridge converter of Fig. 7-27, the input current i_d changes direction instantaneously. Therefore, it is important that the input to this converter be a dc voltage source with a low internal impedance. In practice, the large filter-capacitor shown in the block diagram of Fig. 7-1 provides this low-impedance path to i_d .

7-7-1 PWM WITH BIPOLAR VOLTAGE SWITCHING

In this type of voltage switching, switches (T_{A+} , T_{B-}) and (T_{B+} , T_{A-}) are treated as two switch pairs (two switches in a pair are simultaneously turned on and off). One of the two switch pairs is always on.

The switching signals are generated by comparing a switching-frequency triangular waveform (v_{tri}) with the control voltage $v_{control}$. When $v_{control} > v_{tri}$, T_{A+} and T_{B-} are turned on. Otherwise, T_{A-} and T_{B+} are turned on. The switch duty ratios can be obtained from the waveforms in Fig. 7-28a as follows by arbitrarily choosing a time origin as shown in the figure:

$$v_{tri} = \hat{V}_{tri} \frac{t}{T_s/4} \quad 0 < t < \frac{1}{4}T_s \quad (7-69)$$

At $t = t_1$ in Fig. 7-28a, $v_{tri} = v_{control}$. Therefore, from Eq. 7-69

$$t_1 = \frac{v_{control}}{\hat{V}_{tri}} \frac{T_s}{4} \quad (7-70)$$

By studying Fig. 7-28, we find that the on duration t_{on} of switch pair 1 (T_{A+} , T_{B-}) is

$$t_{on} = 2t_1 + \frac{1}{2}T_s \quad (7-71)$$

Therefore, their duty ratio from Eq. 7-71 is

$$D_1 = \frac{t_{on}}{T_s} = \frac{1}{2} \left(1 + \frac{v_{control}}{\hat{V}_{tri}} \right) \quad (T_{A+}, T_{B-}) \quad (7-72)$$

Therefore, the duty ratio D_2 of the switch pair 2 (T_{B+} , T_{A-}) is

$$D_2 = 1 - D_1 \quad (T_{B+}, T_{A-}) \quad (7-73)$$

By using the foregoing duty ratios, we can obtain V_{AN} and V_{BN} in Fig. 7-28 from Eqs. 7-67 and 7-68; respectively. Therefore,

$$V_o = V_{AN} - V_{BN} = D_1 V_d - D_2 V_d = (2D_1 - 1)V_d \quad (7-74)$$

Substituting D_1 from Eq. 7-72 into Eq. 7-74 yields

$$V_o = \frac{V_d}{\hat{V}_{tri}} v_{control} = k v_{control} \quad (7-75)$$

instantaneously. Neglecting τ_e in Eq. 13-28, the change in speed from the steady-state condition can be obtained as

$$\omega_m(s) = \frac{V_t(s)}{k_E(s\tau_m + 1)} = \frac{\Delta v_t}{k_E s(s\tau_m + 1)} = \frac{\Delta v_t}{k_E} \frac{1/\tau_m}{s(s + 1/\tau_m)} \quad (13-29)$$

recognizing that $V_t(s) = \Delta v_t/s$. From Eq. 13-29

$$\Delta\omega_m(t) = \frac{\Delta v_t}{k_E} (1 - e^{-t/\tau_m}) \quad (13-30)$$

where τ_m is the mechanical time constant with which the speed changes in response to a step change in the terminal voltage, as shown in Fig. 13-9a. The corresponding change in the armature current is plotted in Fig. 13-9b. Note that if the motor current is limited by the converter during large transients, the torque produced by the motor is simply $k_T I_{a,\max}$.

13-6-2 POWER ELECTRONIC CONVERTER

Based on the previous discussion, a power electronic converter supplying a dc motor should have the following capabilities:

1. The converter should allow both its output voltage and current to reverse in order to yield a four-quadrant operation as shown in Fig. 13-3.
2. The converter should be able to operate in a current-controlled mode by holding the current at its maximum acceptable value during fast acceleration and deceleration. The dynamic current limit is generally several times higher than the continuous steady-state current rating of the motor.
3. For accurate control of position, the average voltage output of the converter should vary linearly with its control input, independent of the load on the motor. This item is further discussed in Section 13-6-5.
4. The converter should produce an armature current with a good form factor and should minimize the fluctuations in torque and speed of the motor.

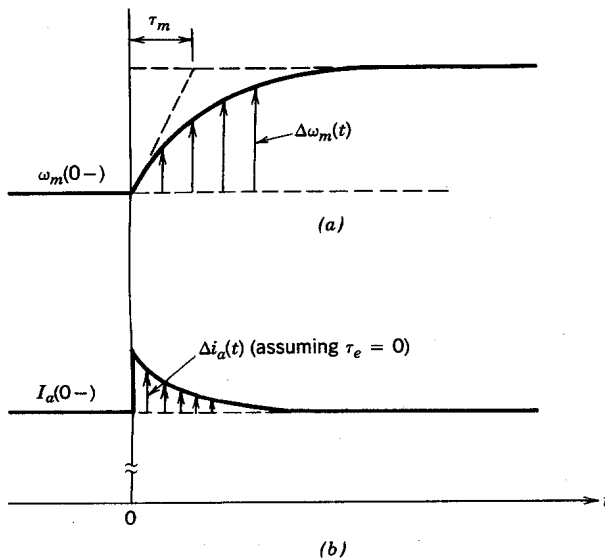


Figure 13-9
Mechanical time constant τ_m ;
load torque is assumed to be
constant.

5. The converter output should respond as quickly as possible to its control input, thus allowing the converter to be represented essentially by a constant gain without a dead time in the overall servo drive transfer function model.

A linear power amplifier satisfies all the requirements listed above. However, because of its low energy efficiency, this choice is limited to a very low power range. Therefore, the choice must be made between switch-mode dc-dc converters of the type discussed in Chapter 7 or the line-frequency-controlled converters discussed in Chapter 6. Here, only the switch-mode dc-dc converters are described. Drives with line-frequency converters can be analyzed in the same manner.

A full-bridge switch-mode dc-dc converter produces a four-quadrant controllable dc output. This full-bridge dc-dc converter (also called an H-bridge) was discussed in Chapter 7. The overall system is shown in Fig. 13-10, where the line-frequency ac input is rectified into dc by means of a diode rectifier of the type discussed in Chapter 5 and filtered by means of a filter capacitor. An energy dissipation circuit is included to prevent the filter capacitor voltage from becoming large in case of braking of the dc motor.

As discussed in Chapter 7, all four switches in the converter of Fig. 13-10 are switched during each cycle of the switching frequency. This results in a true four-quadrant operation with a continuous-current conduction, where both V_t and I_a can smoothly reverse, independent of each other. Ignoring the effect of blanking time, the average voltage output of the converter varies linearly with the input control voltage v_{control} , independent of the load:

$$V_t = k_c v_{\text{control}} \quad (13-31)$$

where k_c is the gain of the converter.

As discussed in Sections 7-7-1 and 7-7-2 of Chapter 7, either a PWM bipolar voltage-switching scheme or a PWM unipolar voltage-switching scheme can be used. Thus, the converter in Fig. 13-6 can be replaced by an amplifier gain k_c given by Eq. 13-31.

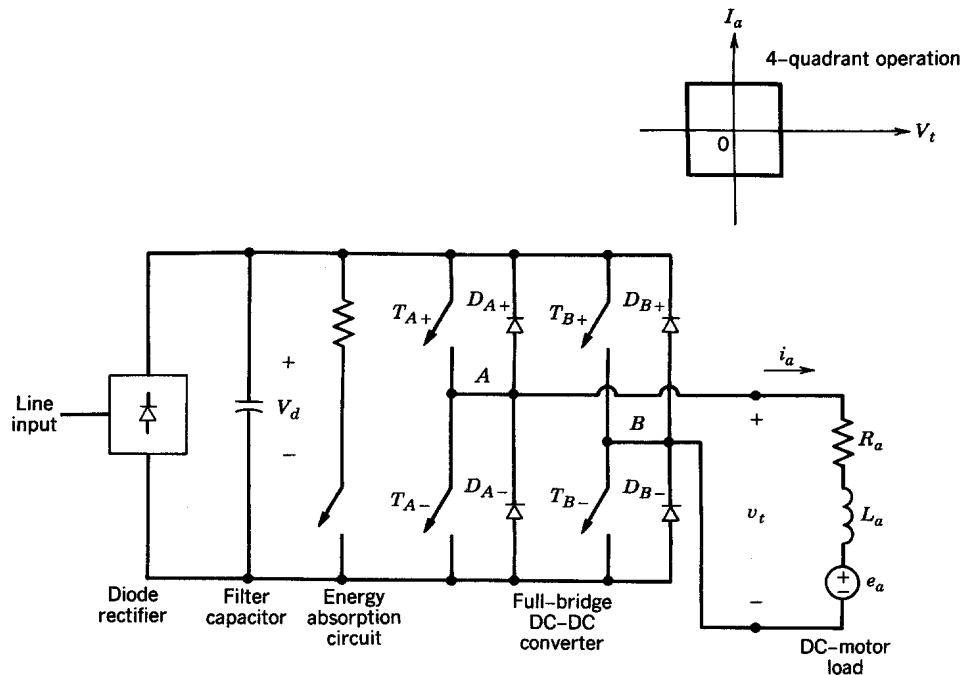


Figure 13-10 A dc motor servo drive; four-quadrant operation.