Introduction to Modern Power Electronics

Chap.-6
DC to DC Converters

Dr. U. T. Shami

6.1 STATIC DC SWITCHES

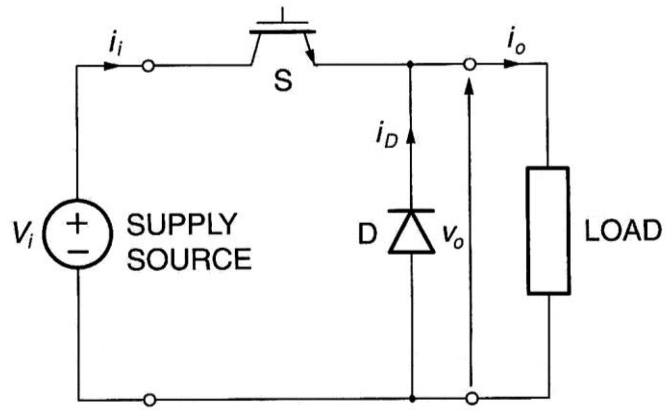


Figure 6.1 Static dc switch based on a fully controlled semiconductor power switch.

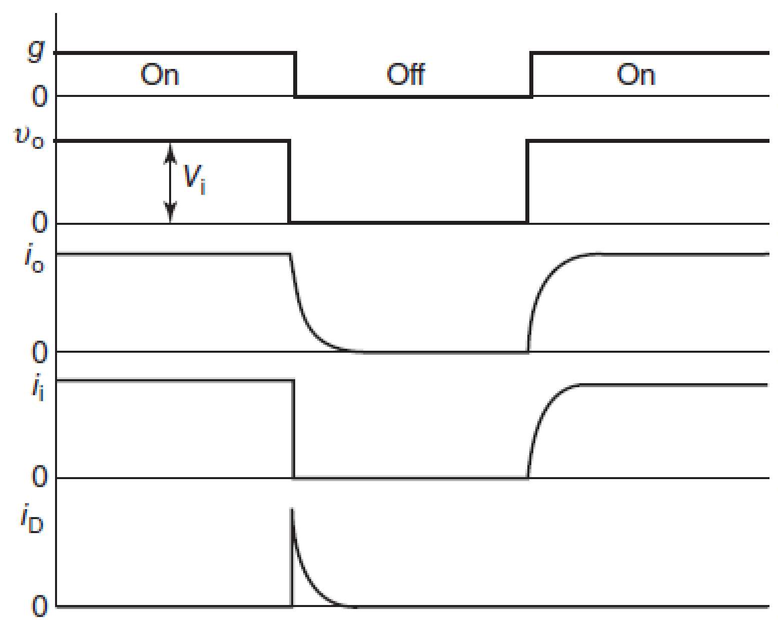


Figure 6.2 Voltage and current waveforms in the static dc switch.

6.1 STATIC DC SWITCHES

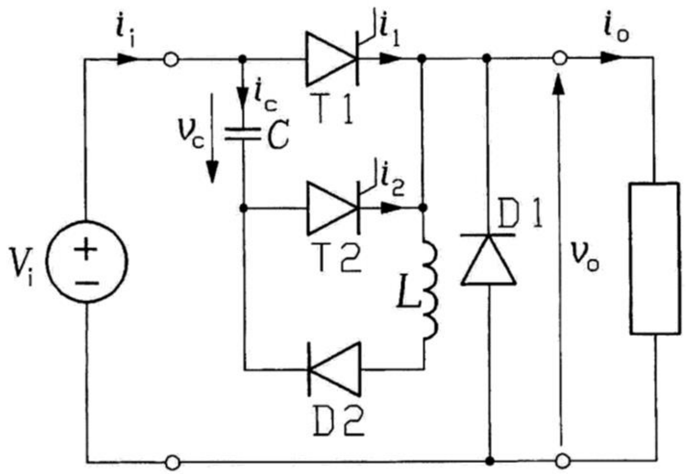


Figure 6.3 SCR-based static dc switch with a resonant commutating circuit.

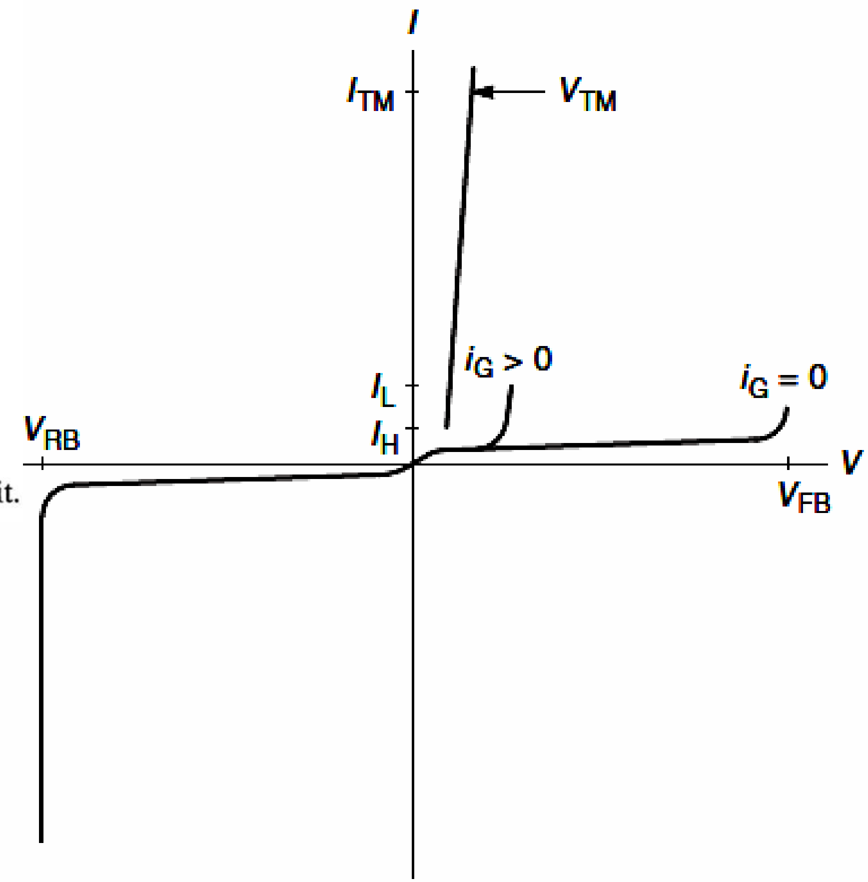
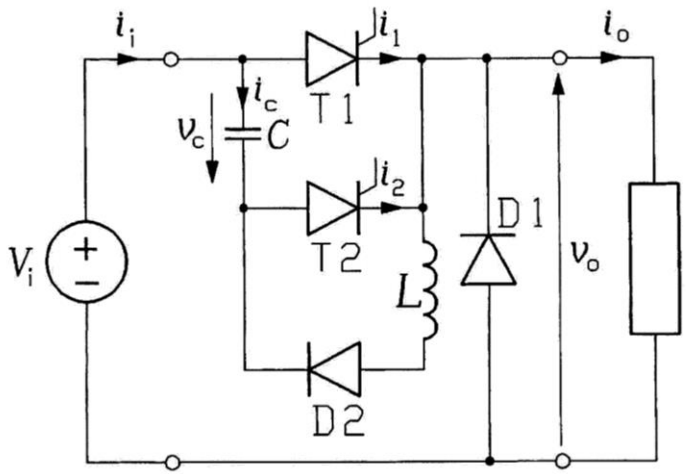


Figure 2.6 Voltage–current characteristic of the SCR.

6.1 STATIC DC SWITCHES



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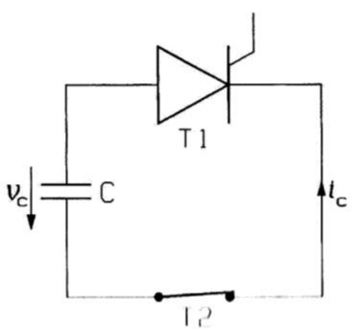
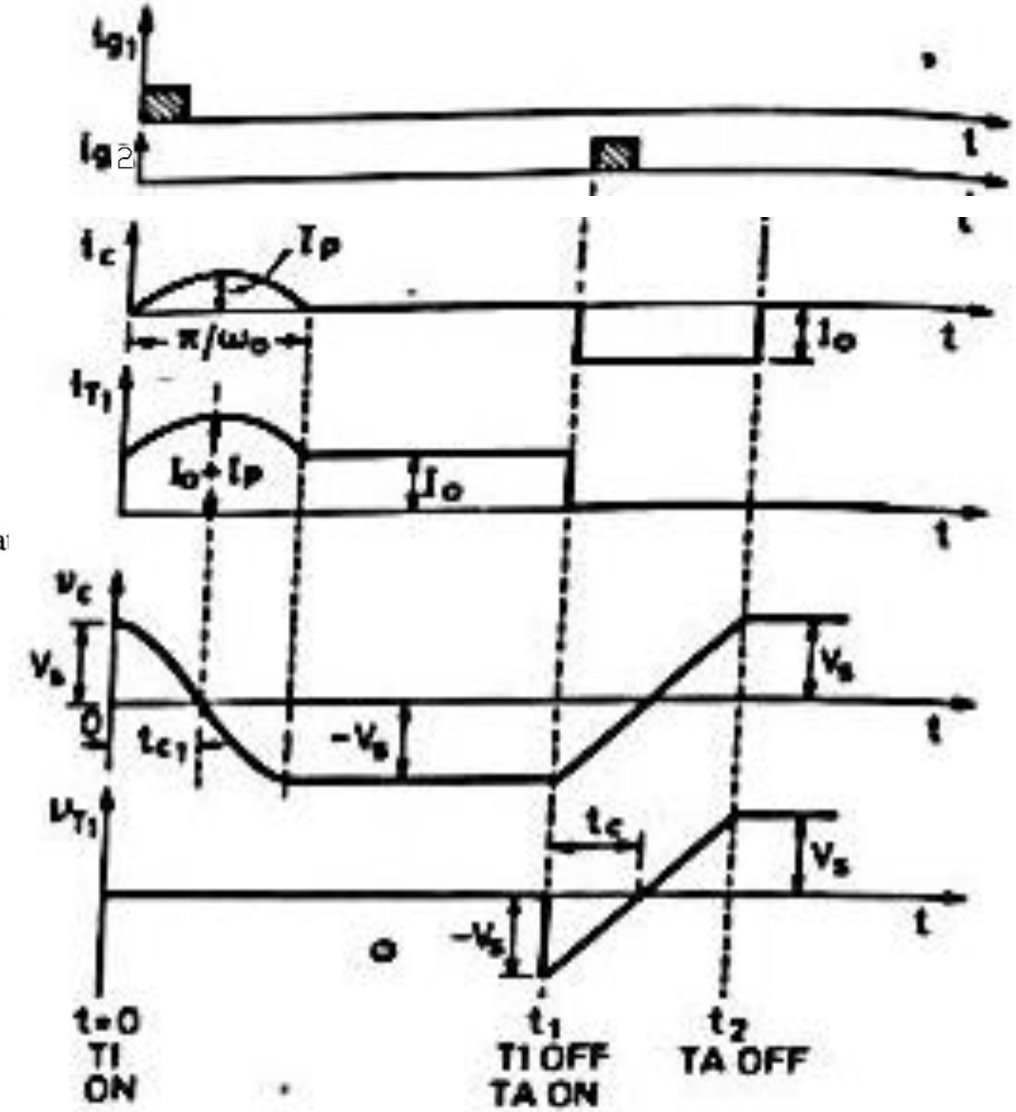


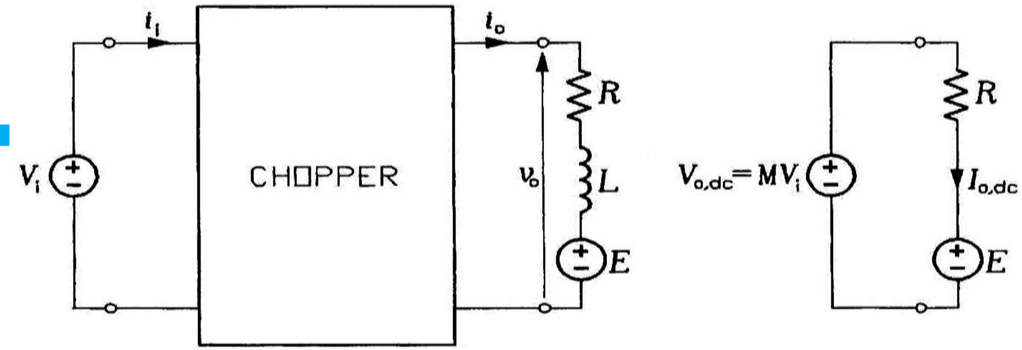
Figure 6.4 Subcircuit of an SCR-based static dc switch.

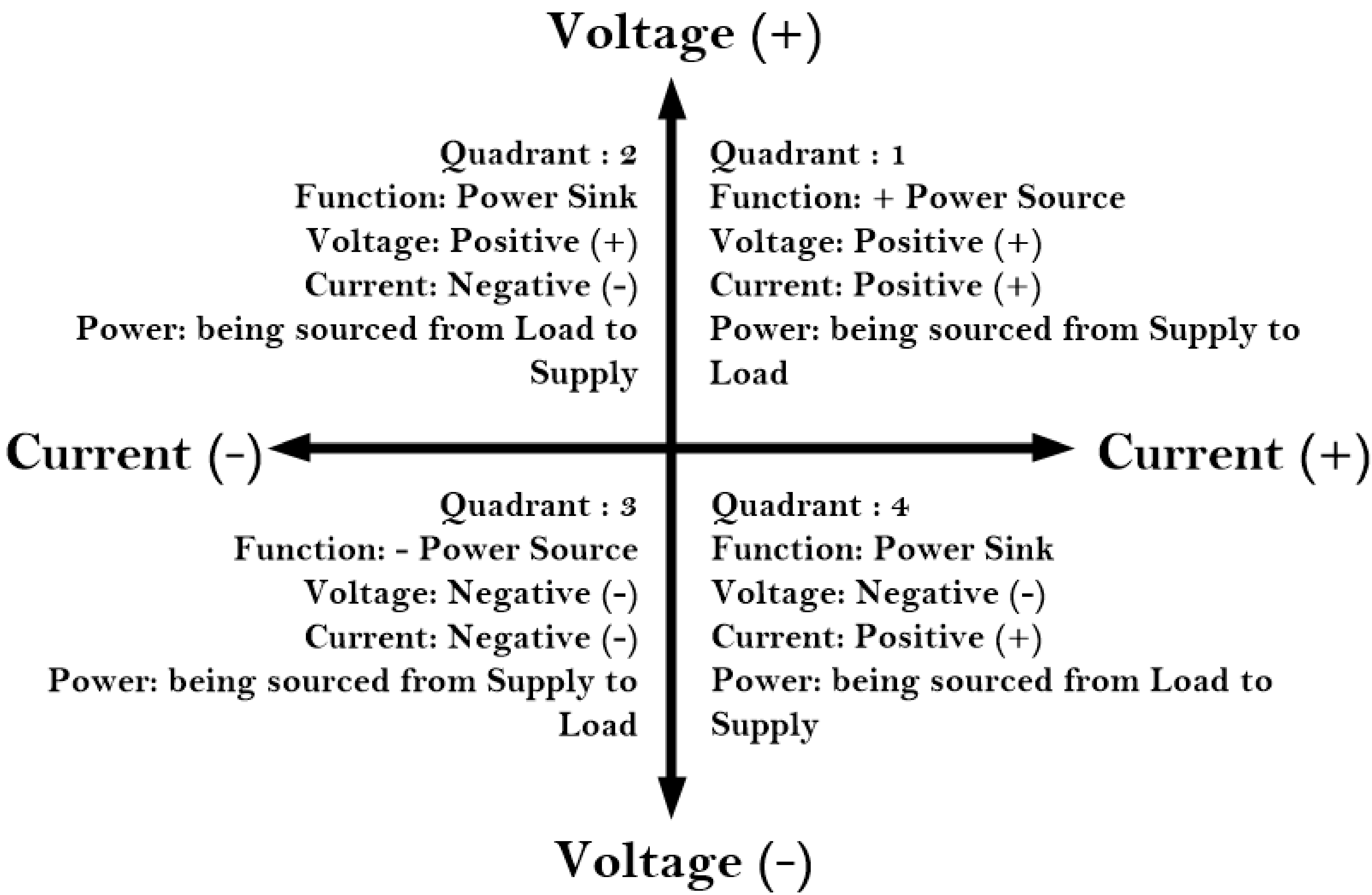


6.1 STATIC DC SWITCHES

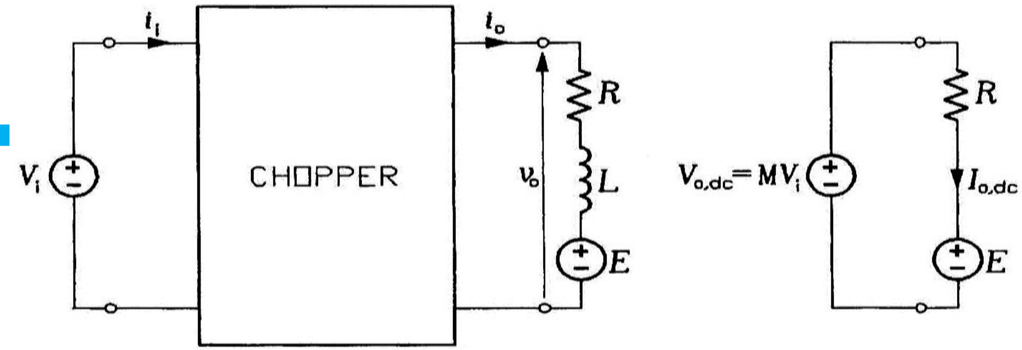
A commutating circuit increases the size, weight, and cost of a static dc switch and affects its reliability adversely. Moreover, the forced commutation reduces the maximum available operating frequency of the switch because of the definite duration of the transient conditions illustrated in Figure 6.5. The output voltage spike following turn-on of the auxiliary SCR constitutes an additional disadvantage, as it may damage the load.

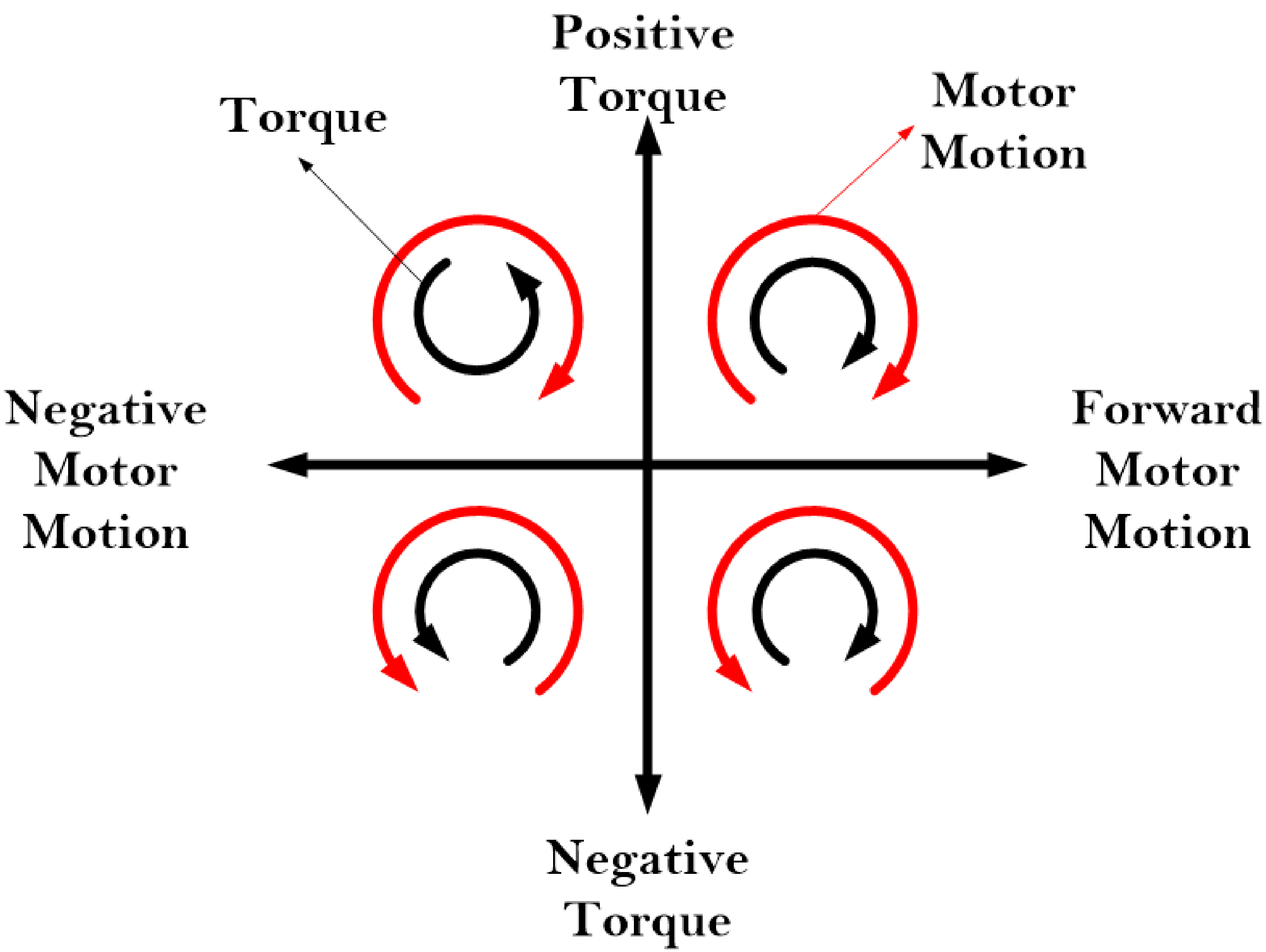
6.2 STEP-DOWN CHOPPERS



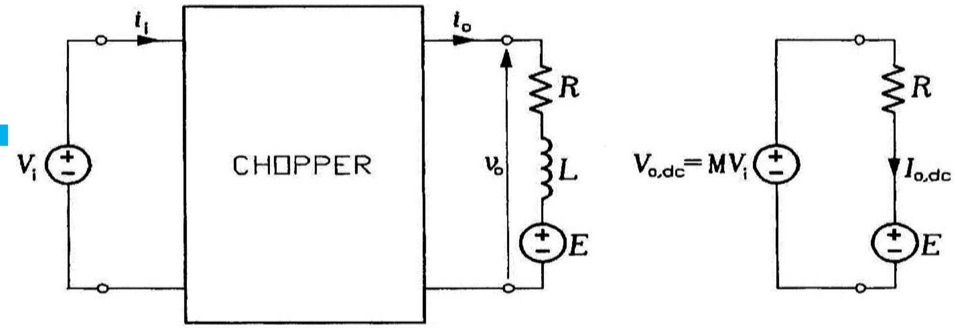


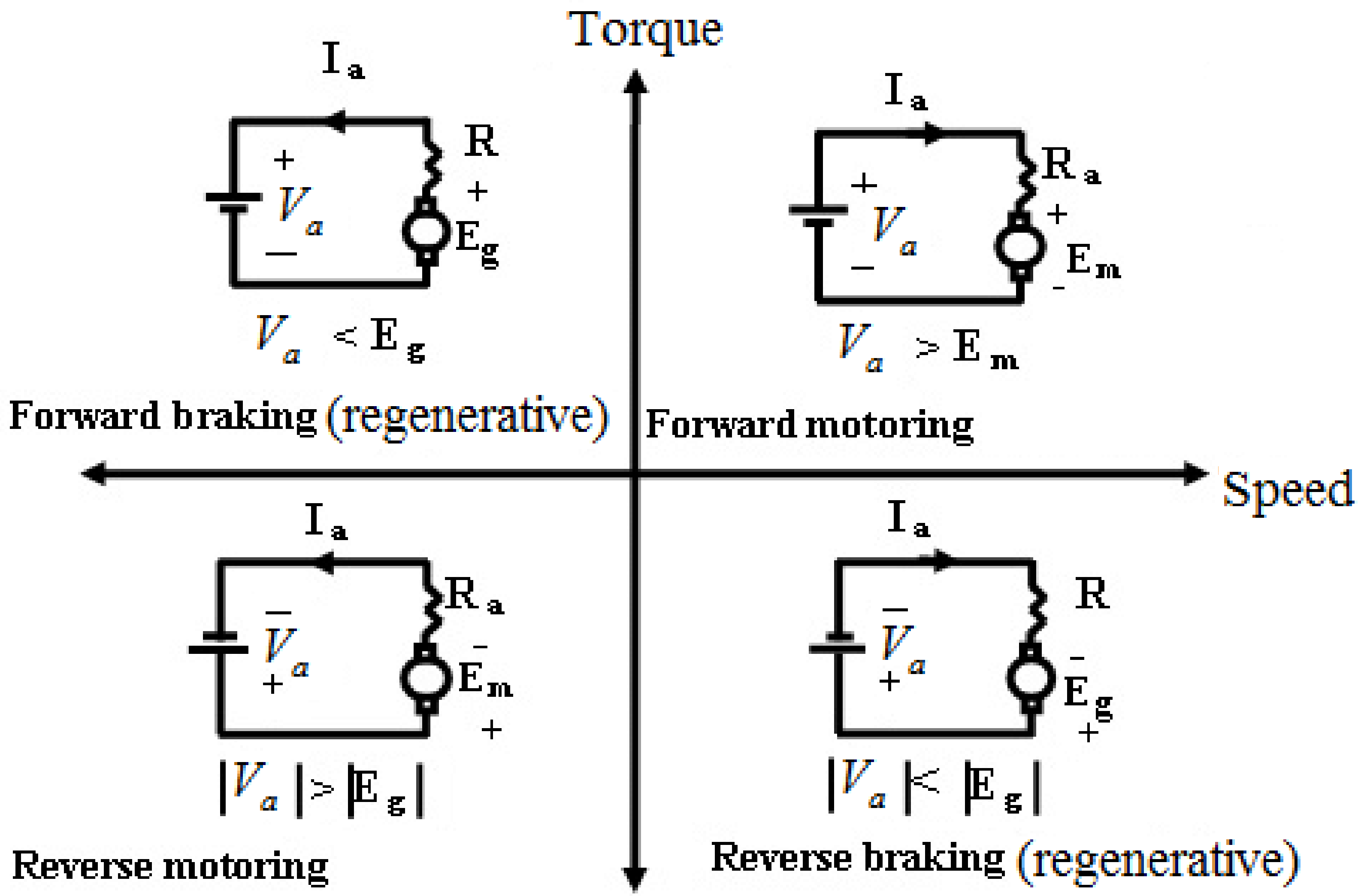
6.2 STEP-DOWN CHOPPERS





6.2 STEP-DOWN CHOPPERS





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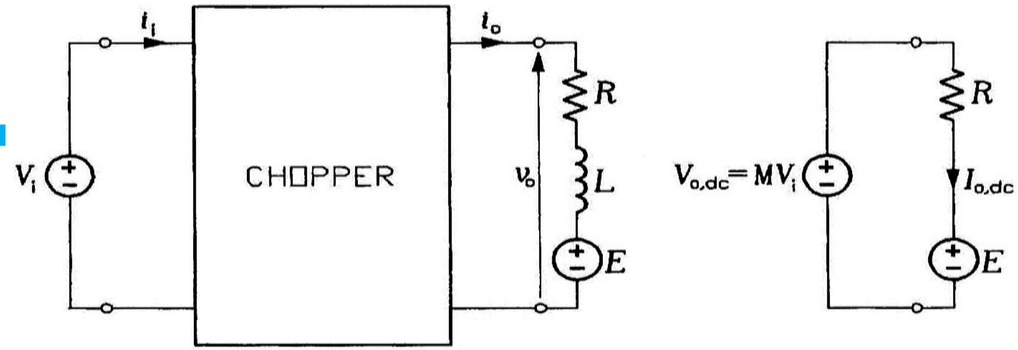


equals the input voltage, V_i . The average output voltage, $V_{o,\mathrm{dc}}$, depends linearly on the duty ratios of the chopper switches and, generally, can be controlled in the range $-V_i$ to $+V_i$. Consequently, the magnitude control ratio, M, of a chopper can be taken as

$$M = \frac{V_{o,\mathrm{dc}}}{V_i}. \tag{6.1}$$

The differential equation of the load is

$$L\frac{di_o}{dt} + Ri_o + E = v_o \tag{6.2}$$

$$i_o(t) = \frac{v_o - E}{R} + \left[\frac{E - v_o}{R} + i_o(t_0)\right] e^{-(R/L)(t-t_0)} \tag{6.3}$$

average output current, $I_{o,\mathrm{dc}}$, can be found from the circuit in Figure 6.6a as

$$I_{o,\mathrm{dc}} = \frac{V_{o,\mathrm{dc}} - E}{R} = \frac{MV_i - E}{R}. \tag{6.4}$$

6.2.1 First-Quadrant Chopper

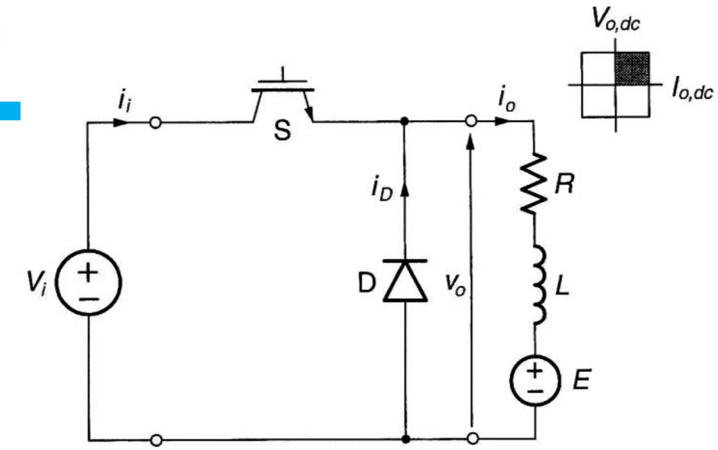


Figure 6.7 First-quadrant chopper.

The first-quadrant chopper can only produce positive dc output voltage and current, and the average power always flows from the source to the load. The circuit diagram of the chopper shown in Figure 6.7 is identical to that of the static dc switch in Figure 6.1. A switching variable, x, can be assigned to the fully controlled switch S, and the output voltage of the chopper can be expressed as

$$v_o = xV_i. \tag{6.5}$$

Figure 6.8. Specifically,

$$V_{o,\mathrm{dc}} = \frac{V_i \times t_{\mathrm{ON}} + 0 \times t_{\mathrm{OFF}}}{t_{\mathrm{ON}} + t_{\mathrm{OFF}}} = \frac{t_{\mathrm{ON}}}{t_{\mathrm{ON}} + t_{\mathrm{OFF}}} V_i = dV_i \tag{6.6}$$

6.2.1 First-Quadrant Chopper

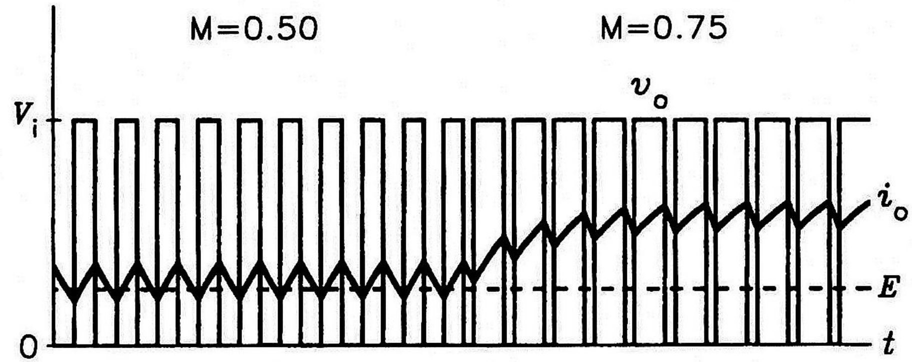


Figure 6.9 Waveforms of output voltage and current in a first-quadrant chopper.

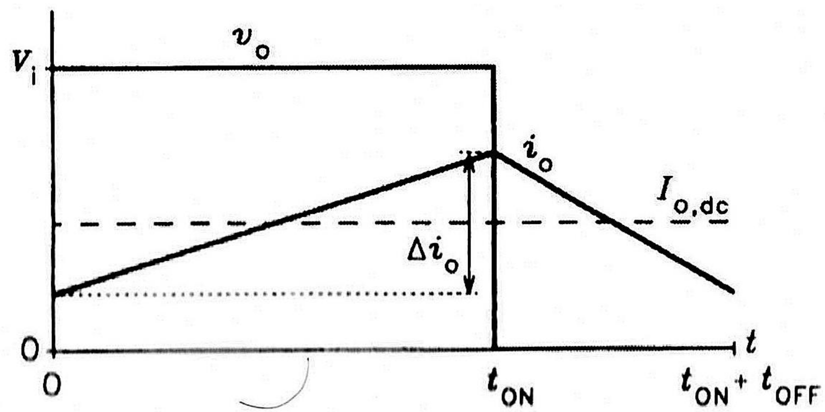


Figure 6.10 Single cycle of the output voltage and current in a first-quadrant chopper.

$$I_{o,\mathrm{ac}} = \frac{\Delta i_o}{2\sqrt{3}}. \tag{6.9}$$

From Eq. (6.2),

$$di_o = \frac{1}{L}(v_o - E - Ri_o)\,dt. \tag{6.10}$$

During the on-time, $di_o \approx \Delta i_o$, $v_o = V_i$, $i_o \approx I_{o,\mathrm{dc}}$, and $dt \approx t_{\mathrm{ON}}$. Consequently,

$$\Delta i_o = \frac{1}{L}(V_i - E - RI_{o,\mathrm{dc}})t_{\mathrm{ON}}. \tag{6.11}$$

Analogously, during the off-time, $di_o \approx -\Delta i_o$, $v_o = 0$, $i_o \approx I_{o,\mathrm{dc}}$, $dt \approx t_{\mathrm{OFF}}$, and

$$\Delta i_o = \frac{1}{L}(E - RI_{o,\mathrm{dc}})t_{\mathrm{OFF}}. \qquad (6.1$$

Comparing Eqs. (6.11) and (6.12) and solving for $I_{o,\mathrm{dc}}$, yields

$$I_{o,\mathrm{dc}} = \frac{1}{R}\left(\frac{t_{\mathrm{ON}}}{t_{\mathrm{ON}} + t_{\mathrm{OFF}}}V_i - E\right) = \frac{d_1 V_i - E}{R} = \frac{MV_i - E}{R} \qquad (6.1$$

Substituting Eq. (6.13) in Eq. (6.12) gives

$$\Delta i_o = \frac{MV_i}{L} t_{\text{OFF}} \tag{6.14}$$

Note that t_{OFF} can be expressed as

$$t_{\text{OFF}} = (1 - d)(t_{\text{ON}} + t_{\text{OFF}}) = \frac{1 - M}{f_{\text{sw}}} \tag{6.15}$$

where $f_{\text{sw}} \equiv 1/(t_{\text{ON}} + t_{\text{OFF}})$ denotes the switching frequency of a chopper. Also, $L = \tau R$, where $\tau \equiv L/R$ is the time constant of the load. Thus, Eq. (6.14) can be rearranged to

$$\Delta i_o = \frac{V_i}{R} \frac{M(1 - M)}{\tau f_{\text{sw}}}. \tag{6.16}$$

For generality, to accommodate choppers operating in the third and fourth quadrants, that is, with negative magnitude control ratios, M in Eq. (6.16) can be replaced by $|M|$. Then, Eqs. (6.9) and (6.16) yield

$$I_{o,\text{ac(pu)}} = \frac{|M|(1 - |M|)}{2\sqrt{3}\, f_{\text{sw(pu)}}} \tag{6.17}$$

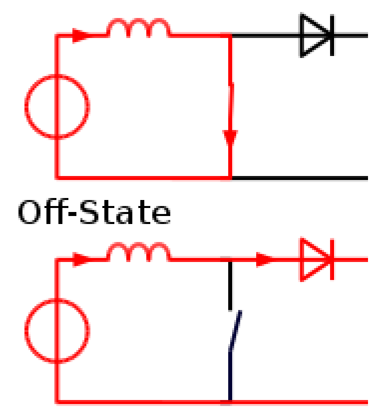
where $I_{o,\text{ac(pu)}}$ denotes a per-unit rms value of the output ripple current, defined as

$$I_{o,\text{ac(pu)}} \equiv \frac{I_{o,\text{ac}}}{V_i/R} \tag{6.18}$$

6.2.2 Second-Quadrant Chopper

In state 1, switch S shorts the load and the load EMF, E, supplies the resulting, circuit, which includes the load inductance, L. In state 0, the energy stored in this inductance maintains the current, which is now forced to flow through diode D to the supply source. The instantaneous output voltage is given by

$$v_o = (1 - x)V_i \tag{6.20}$$



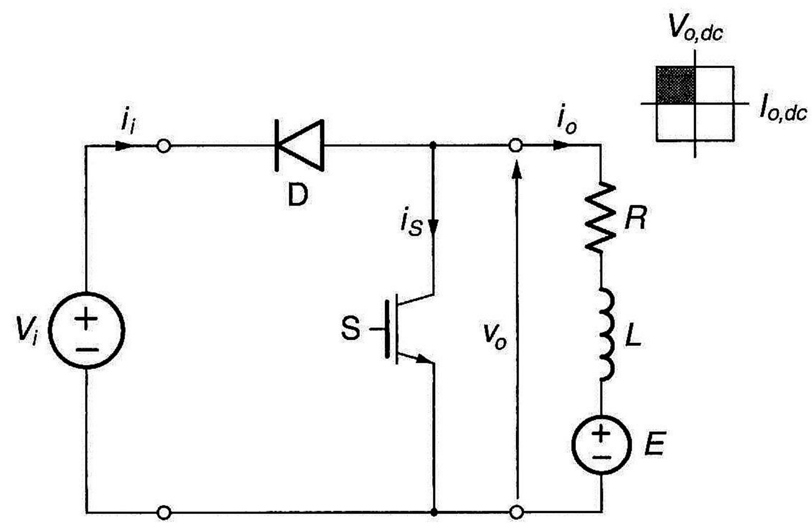


Figure 6.12 Second-quadrant chopper.

and the average output voltage can be determined as

$$V_{o,\mathrm{dc}} = \frac{0 \times t_{\mathrm{ON}} + V_i \times t_{\mathrm{OFF}}}{t_{\mathrm{ON}} + t_{\mathrm{OFF}}} = \frac{t_{\mathrm{OFF}}}{t_{\mathrm{ON}} + t_{\mathrm{OFF}}} V_i = (1 - d_2)V_i \tag{6.21}$$

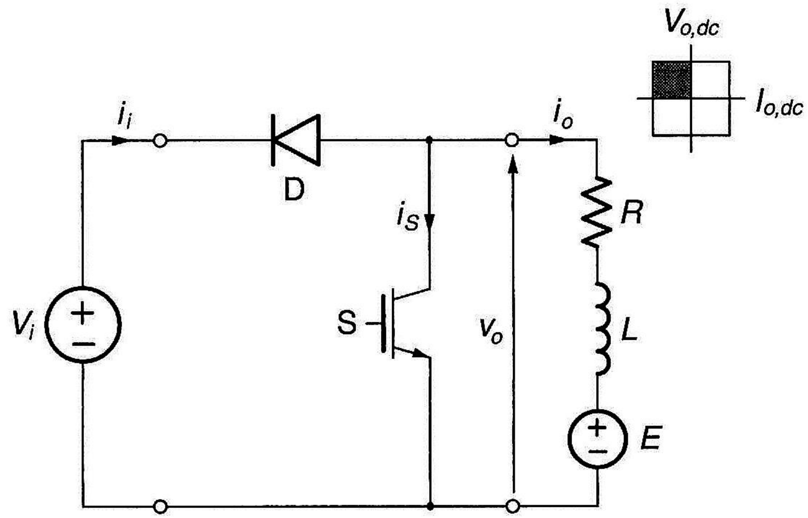


Figure 6.12 Second-quadrant chopper.

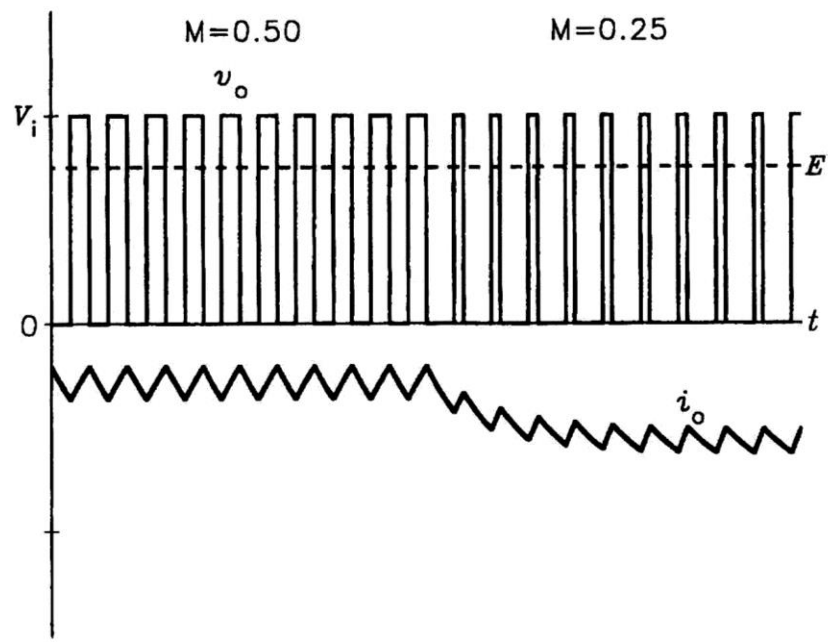
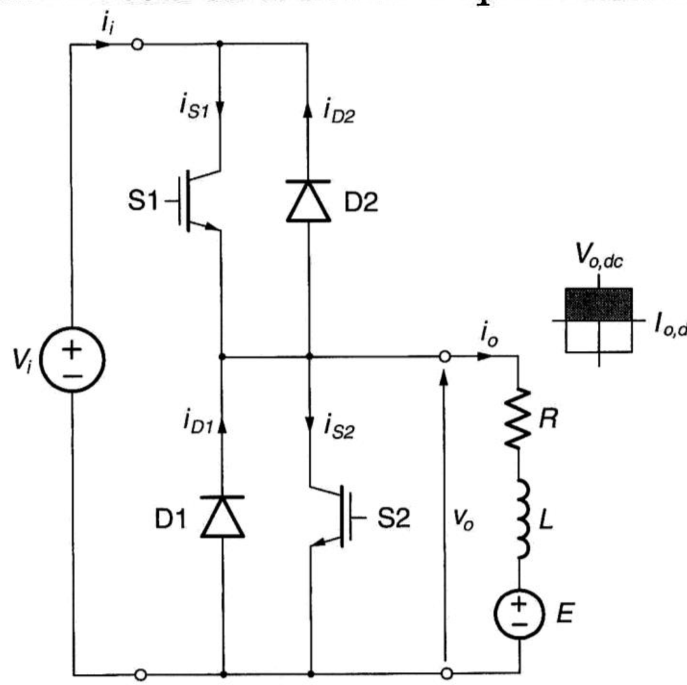
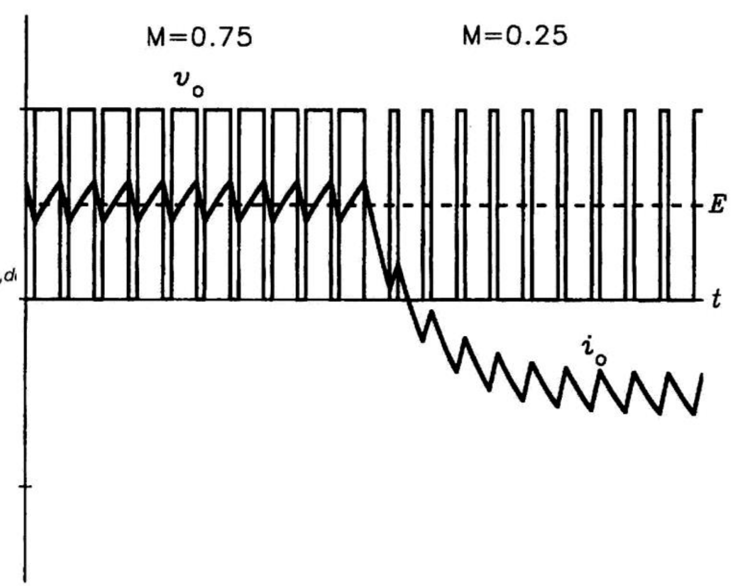


Figure 6.14 Waveforms of output voltage and current in a second-quadrant chopper.

6.2.3 First-and-Second-Quadrant Chopper

While the single-quadrant choppers described in Sections 6.2.1 and 6.2.2 can transmit energy in only one direction, two-quadrant choppers are capable of bidirectional power flow. Figure 6.15 is a circuit diagram of a first-and-second-quadrant chopper, that is, one operating with a positive output voltage and an output current of either polarity. Topologically, the chopper is a combination of first- and second-quadrant choppers. Indeed, if branch S2–D2 were removed, the remaining circuit would be identical with that of a first-quadrant chopper; and vice versa, removal of branch S1–D1 would result in a second-quadrant chopper.





aveforms of output voltage and current in a first-and-second-quadrant

Figure 6.15 First-and-second-quadrant chopper.

6.2.4 First-and-Fourth-Quadrant Chopper

The first-and-fourth-quadrant chopper shown in Figure 6.17 allows bidirectional power flow with a positive output current. The load EMF must be positive for first-quadrant operation and negative when the chopper is to operate in the fourth quadrant. The state of the chopper is designated as $(x_1x_4)_2$, where x_1 and x_4 denote switching variables of switches S1 and S4, respectively.

For first-quadrant operation, switch S4 must be turned on permanently to provide a path for the output current. Switch S1 performs the chopping, with the duty ratio d_1, so the chopper operates alternately in states 2 and 3. In the fourth quadrant, switch S1 is off, S4 operates with the duty ratio d_4, and the chopper alternates between states 0 and 1.

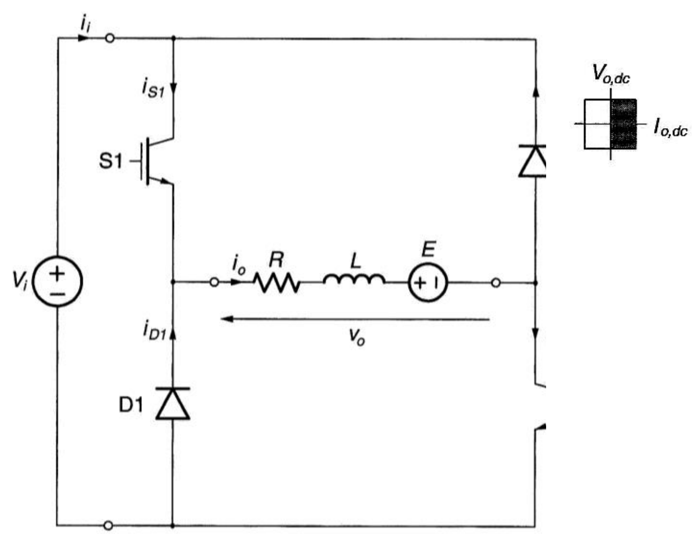


Figure 6.17 First-and-fourth-quadrant chopper.

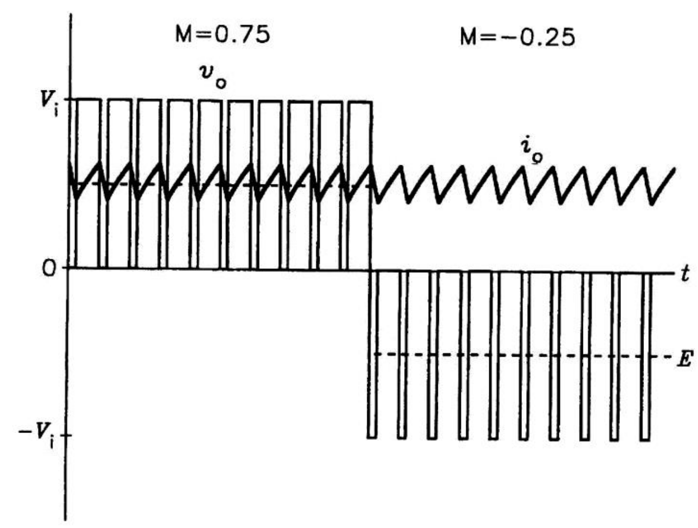


Figure 6.19 Waveforms of output voltage and current in a first-and-fourth-quadrant chopper.

6.2.5. Four-Quadrant Chopper

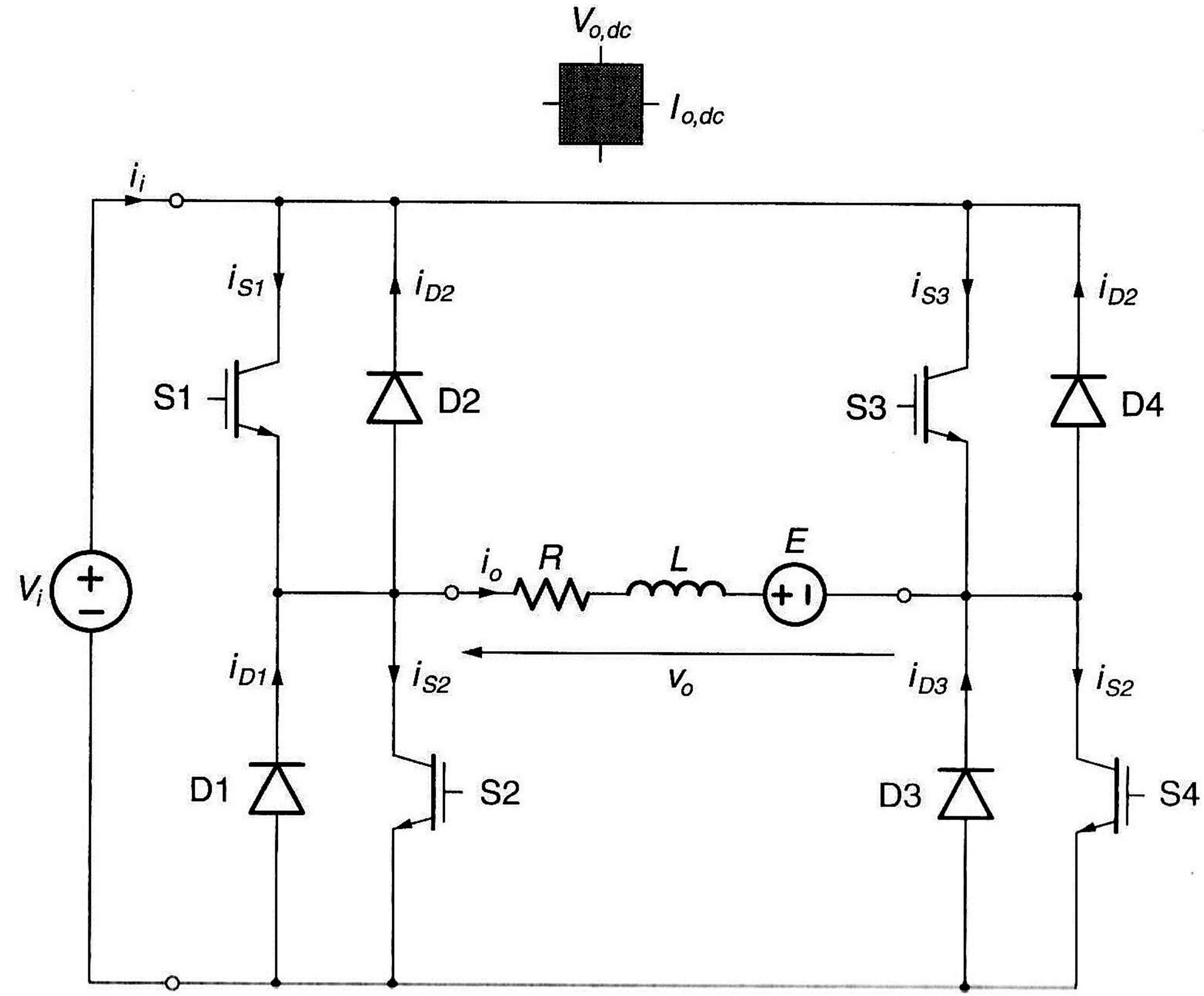


Figure 6.20 Four-quadrant chopper.

6.3 STEP-UP CHOPPER

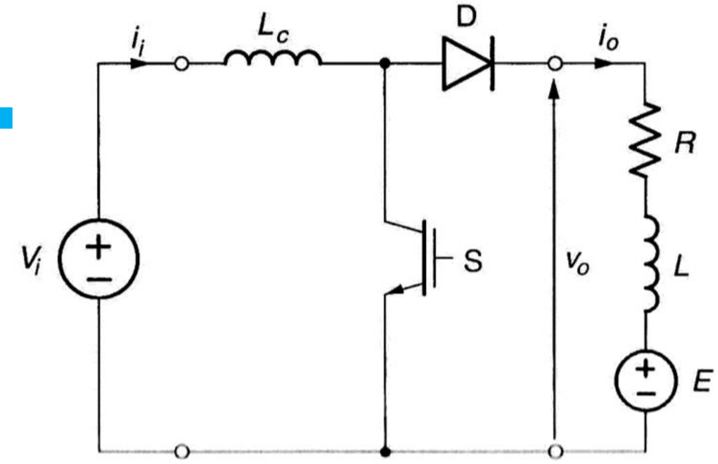


Figure 6.22 Step-up chopper.

$$\Delta i_i = \frac{V_i}{L_c} t_{\mathrm{ON}}. \tag{6.35}$$

interval, t_{ON}. Assuming that the current changes linearly in time, its derivative can be expressed as

$$\frac{di_i}{dt} = -\frac{\Delta i_i}{t_{\mathrm{OFF}}} = -\frac{V_i}{L_c}\frac{t_{\mathrm{ON}}}{t_{\mathrm{OFF}}}. \tag{6.36}$$

Consequently, the output voltage during the off-time of the switch is given by

$$v_o = V_i - v_{\mathrm{L}} = V_i - L_c\frac{di_i}{dt} = V_i + L_c\frac{V_i}{L_c}\frac{t_{\mathrm{ON}}}{t_{\mathrm{OFF}}} = V_i\left(1 + \frac{t_{\mathrm{ON}}}{t_{\mathrm{OFF}}}\right). \tag{6.37}$$

According to Eq. (6.37), the output voltage is constant and equal to its peak value, $V_{o,p}$, so

$$V_{o,p} = V_i \left(1 + \frac{t_{\mathrm{ON}}}{t_{\mathrm{OFF}}}\right) = \frac{V_i}{1-d} \tag{6.38}$$

where d denotes the duty ratio of switch S.

The average output voltage, $V_{o,\mathrm{dc}}$, can be determined as

$$V_{o,\mathrm{dc}} = \frac{0 \times t_{\mathrm{ON}} + V_i/(1-d) \times t_{\mathrm{OFF}}}{t_{\mathrm{ON}} + t_{\mathrm{OFF}}} = \frac{V_i}{1-d} \frac{t_{\mathrm{OFF}}}{t_{\mathrm{ON}} + t_{\mathrm{OFF}}} = \frac{V_i}{1-d}(1-d) = V_i \tag{6.39}$$

6.5 DEVICE SELECTION FOR CHOPPERS