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Chapter 6

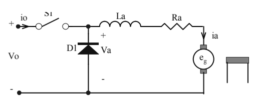
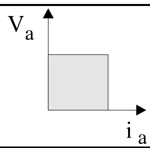
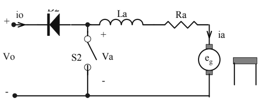
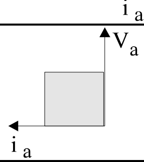
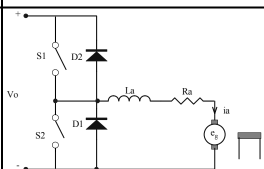
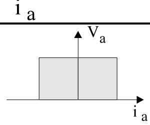
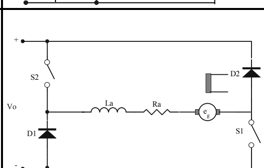
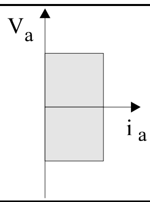
CHOPPER-CONTROLLED D.C. BRUSH MOTOR DRIVES

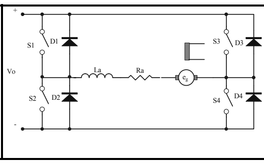
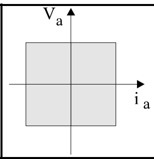
6.1. INTRODUCTION

The d.c. chopper is a d.c. to d.c. power electronic converter (PEC) with forced commutation. It is used for armature voltage control in d.c. brush motor drives. D.c. sources to supply d.c. choppers are batteries or diode rectifiers with output filters so typical for urban electric transportation systems or to low power d.c. brush motor drives. Thyristors, bipolar power transistors, MOSFETs or IGBTs are used in d.c. choppers.

The basic configurations are shown in Table 6.1 and they correspond to single, two- or four-quadrant operation.

Table 6.1. Single-phase chopper configurations for the d.c. brush motors

Type	Chopper configuration	ea-Ia characteristics	Function
First-quadrant (step-down) choppers			Va = V0 for S1 on Va = 0 for S1 off and D1 on
Second quadrant, regeneration (step-up) chopper			Va = 0 for S2 on Va = V0 for S2 off and D2 on
Two quadrant chopper			ea = e0 for S1 or D2 on ea = e0 for S2 or D1 on ia>0 for S1 or D1 on ia<0 for S2 or D2 on
Two quadrant chopper			Va = +V0 for S1 & S2 on Va = –V0 for S1 & S2 off and D1 & D2 on

Four quadrant chopper			S4 on & S3 off S1 & S2 operated Va>0 ia - reversible S2 on & S1 off S3 & S4 operated Va<0 ia - reversible

The first-quadrant chopper (Figure 6.1) is operated by turning on the PES for the interval t_{on}, when the supply voltage is connected to the load. During the interval t_{off}, when the main switch is off, the load current flows through the freewheeling diode D_1. The output voltage e_a is shown in Figure 6.1.

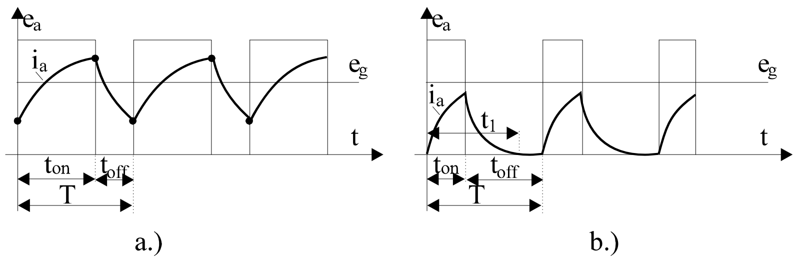


Figure 6.1. First-quadrant chopper operation

a.) continuous mode; b.) discontinuous mode

The average voltage V_{av} is

$$V_{av} = e_a \cdot \frac{t_{on}}{T} \leq V_0 \tag{6.1}$$

That is, a step-down chopper.

Constant frequency (constant T) control is preferred in order to improve the input filter operation and reduce the possibility of discontinuous current mode (Figure 6.1b) operation.

The voltage equation for constant speed is

$$V_0 = R_a \cdot i_a + L_a \cdot \frac{di_a}{dt} + e_g; \quad e_g = K_e \cdot \lambda_p \cdot n \quad \text{for} \quad 0 \leq t \leq t_{on} \tag{6.2}$$

$$0 = R_a \cdot i_a + L_a \cdot \frac{di_a}{dt} + e_g; \quad t_{on} \leq t \leq t_1; \quad i_a(t_1) = 0,$$
$$t_1 < T \text{ for discontiuous mode} \tag{6.3}$$

For continuous current mode $t_1 = T$ and $i_a(T) = i_a(0) \neq 0$ for steady state.

For the d.c. brush series motor

$$e_g = K_{ei} \cdot i_a \cdot n + K_{rem} \cdot n \tag{6.4}$$

In (6.4) K_{rem} refers to the remnant flux while the magnetization curve of the machine is considered linear.

The average output voltage for the discontinuous mode may be determined noting that the motor voltage is then zero

$$V_{av} = V_0 \frac{t_{on}}{T} + e_g \cdot \frac{T - t_1}{T}; \qquad t_1 \le T \tag{6.5}$$

The output current expressions are obtained from (6.2)-(6.3)

$$i_a = A \cdot e^{-t \cdot \frac{R_a}{L_a}} + \frac{V_0 - e_g}{R_a}; \qquad \text{for } 0 \le t \le t_{on} \tag{6.6}$$

$$i_a' = A' \cdot e^{-(t - t_{on}) \cdot \frac{R_a}{L_a}} - \frac{e_g}{R_a}; \text{ for } 0 \le t \le t_1 \begin{cases} t_1 = T \text{ for continuous current} \\ t_1 < T \text{ for discontinuous current} \end{cases} \tag{6.7}$$

The continuity condition is

$$i_a(t_{on}) = i_a'(t_{on}) \tag{6.8}$$

The average output current i_{av} is

$$i_{av} = \frac{\int_0^{t_{on}} i_a dt + \int_{t_{on}}^{t_1} i_a' dt}{T} \tag{6.9}$$

For the second-quadrant chopper (Table 6.1b) the d.c. motor e.m.f. e_g with S_2 on produces a current rise in inductance L_a

$$R_a \cdot i_a + L_a \cdot \frac{di_a}{dt} = -e_g; \qquad \text{for } 0 \le t \le t_{on}; \quad i_a(0) = 0 \tag{6.10}$$

When S_2 is turned off, the energy stored in the inductor is sent back to the source as long as $V_0 > V_a$

$$V_0 - e_g = -R_a \cdot i_a' - L_a \cdot \frac{di_a'}{dt}; \quad t_{on} \le t \le T \tag{6.11}$$

with the solution

$$i_a = -\frac{e_g}{R_a} + B \cdot e^{-t \cdot \frac{R_a}{L_a}} + i_{a0} \tag{6.12}$$

$$i_a' = +\frac{V_0 - e_g}{R_a} + B' \cdot e^{-(t-t_{on})\cdot\frac{R_a}{L_a}} \tag{6.13}$$

The boundary conditions are

$$i_a(t_{on}) = i_a'(t_{on}), i_a(0) = i_{a0} \text{ and } i_a'(T) = i_{a0} \tag{6.14}$$

It is thus possible with $e_g < V_0$ to retrieve the energy back from the d.c. brush motor by using the inductor L_a as an energy sink (Figure 6.2).

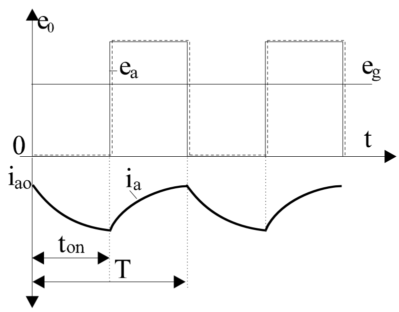


Figure 6.2. Second-quadrant chopper operation

The two-quadrant chopper (Table 6.1c,d) is a combination of one first and one second-quadrant chopper. Finally two-quadrant choppers are combined to obtain a four-quadrant chopper.

As the chopper is an on-off switch, the source current is chopped (Figure 6.3). This makes the peak input power demand high. Also, the supply current (Figure 6.3) has harmonics which produce voltage fluctuations, signal interference, etc.

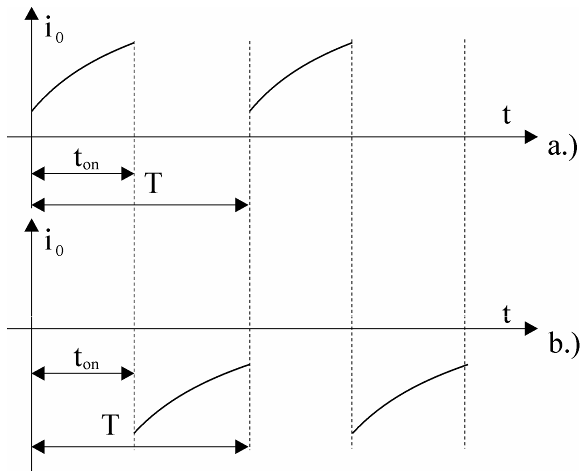


Figure 6.3. Source current waveforms

a.) first-quadrant operation, b.) second-quadrant operation.

An LC input filter (Figure 6.4) will provide a path for the ripple current such that only (approximately) the average current is drawn from the supply.

The n^{th} harmonic current i_n in the supply (Figure 6.4b) is

$$i_n = \frac{X_c / n}{(nX_L - X_C / n)} I_{sn} = \frac{I_{sn}}{(nf_{ch} / f_r)^2 - 1} \tag{6.15}$$

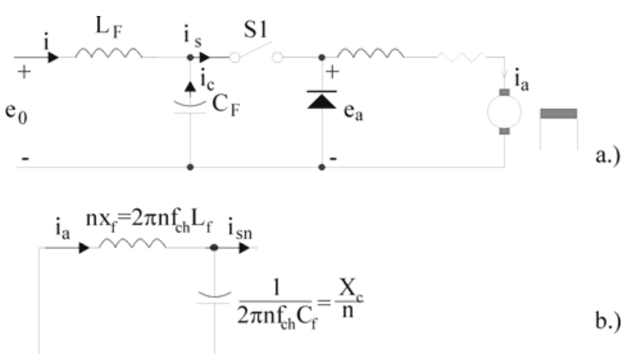


Figure 6.4. First-quadrant chopper with LC input filter

a.) basic circuit, b.) equivalent circuit for nth harmonic

where f_{ch} is the chopping frequency (f_{ch} = 1 / T) and f_r is the resonance frequency of the filter $f_r = 1/2\pi\sqrt{LC}$. To avoid resonance $f_{ch} \geq (2-3)f_r$.