In The Name Of God

Power Electronics

Chopper Converters

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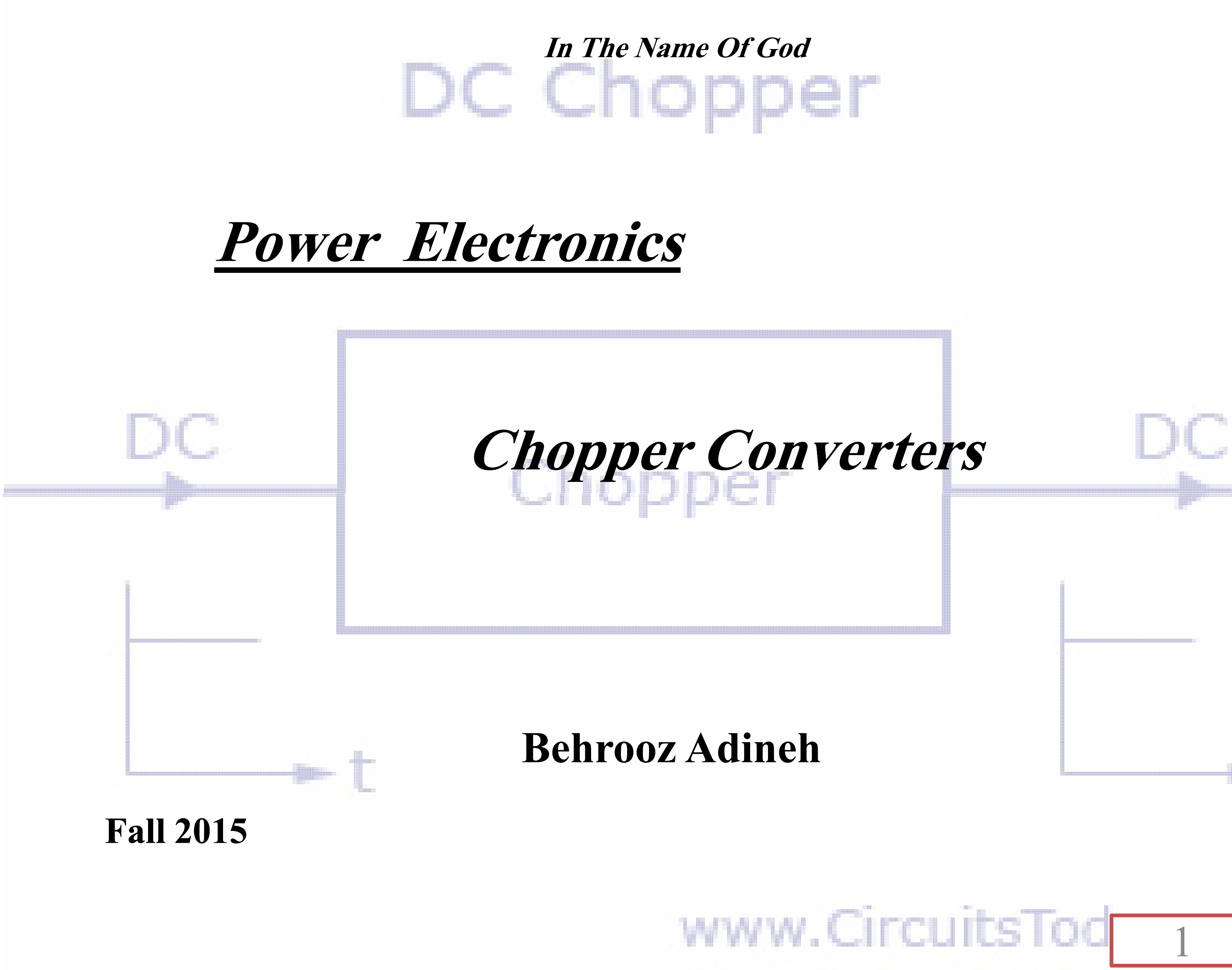
Fall 2015



PRINCIPLE OF STEP-UP OPERATION

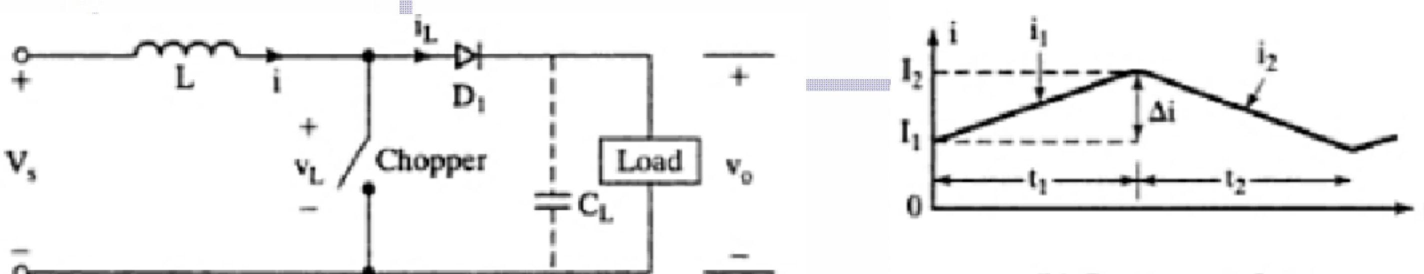
A converter can be used to step up a dc voltage and an arrangement for step-up operation is shown in Figure 5.6a. When switch SW is closed for time t_1, the inductor current rises and energy is stored in the inductor L. If the switch is opened for time t_2, the energy stored in the inductor is transferred to load through diode D_1 and the inductor current falls. Assuming a continuous current flow, the waveform for the inductor current is shown in Figure 5.6b.

When the converter is turned on, the voltage across the inductor is

$$v_L = L \frac{di}{dt}$$

and this gives the peak-to-peak ripple current in the inductor as

$$\Delta I = \frac{V_s}{L} t_1 \qquad (5.26)$$



(a) Step-up arrangement

(b) Current waveform

The average output voltage is

$$v_o = V_s + L\frac{\Delta I}{t_2} = V_s\left(1 + \frac{t_1}{t_2}\right) = V_s\frac{1}{1-k} \tag{5.27}$$

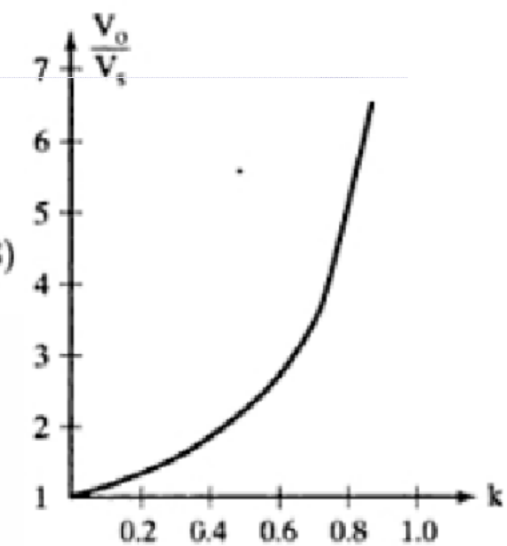
If a large capacitor C_L is connected across the load as shown by dashed lines in Figure 5.6a, the output voltage is continuous and v_o becomes the average value V_a. We can notice from Eq. (5.27) that the voltage across the load can be stepped up by varying the duty cycle k and the minimum output voltage is V_s when $k = 0$. However, the converter cannot be switched on continuously such that $k = 1$. For values of k tending to unity, the output voltage becomes very large and is very sensitive to changes in k, as shown in Figure 5.6c.

This principle can be applied to transfer energy from one voltage source to another as shown in Figure 5.7a. The equivalent circuits for the modes of operation are shown in Figure 5.7b and the current waveforms in Figure 5.7c. The inductor current for mode 1 is given by

$$V_s = L\frac{di_1}{dt}$$

and is expressed as

$$i_1(t) = \frac{V_s}{L}t + I_1 \tag{5.28}$$



(c) Output voltage

This principle can be applied to transfer energy from one voltage source to another as shown in Figure 5.7a. The equivalent circuits for the modes of operation are shown in Figure 5.7b and the current waveforms in Figure 5.7c. The inductor current for mode 1 is given by

$$V_s = L\frac{di_1}{dt}$$

and is expressed as

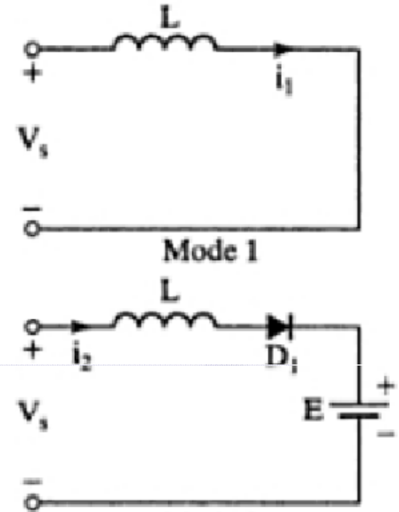
$$i_1(t) = \frac{V_s}{L}t + I_1 \quad (5.28)$$

where I_1 is the initial current for mode 1. During mode 1, the current must rise and the necessary condition,

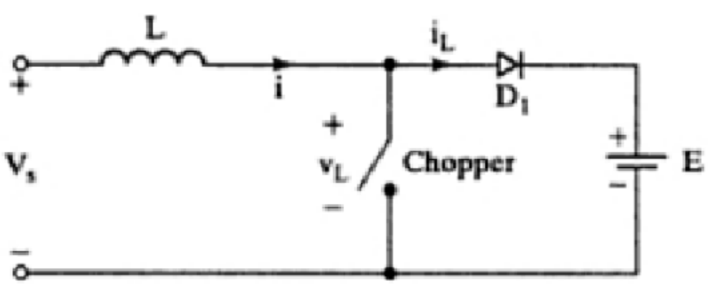
$$\frac{di_1}{dt} > 0 \quad \text{or} \quad V_s > 0$$

The current for mode 2 is given by

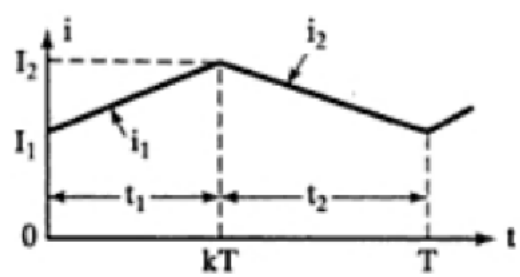
$$V_s = L\frac{di_2}{dt} + E$$



(b) Equivalent circuits



(a) Circuit diagram



(c) Current waveforms

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and is solved as

$$i_2(t) = \frac{V_s - E}{L} t + I_2 \tag{5.29}$$

where I_2 is initial current for mode 2. For a stable system, the current must fall and the condition is

$$\frac{di_2}{dt} < 0 \quad \text{or} \quad V_s < E$$

If this condition is not satisfied, the inductor current continues to rise and an unstable situation occurs. Therefore, the conditions for controllable power transfer are

$$0 < V_s < E \tag{5.30}$$

Equation (5.30) indicates that the source voltage V_s must be less than the voltage E to permit transfer of power from a fixed (or variable) source to a fixed dc voltage. In electric braking of dc motors, where the motors operate as dc generators, terminal voltage falls as the machine speed decreases. The converter permits transfer of power to a fixed dc source or a rheostat.

When the converter is turned on, the energy is transferred from the source V_s to inductor L. If the converter is then turned off, a magnitude of the energy stored in the inductor is forced to battery E.

Note: Without the chopping action, v_s must be greater than E for transferring power from V_s to E.

Key Points of Section 5.4

- A step-up dc converter can produce an output voltage that is higher than the input. The input current can be transferred to a voltage source higher than the input voltage.

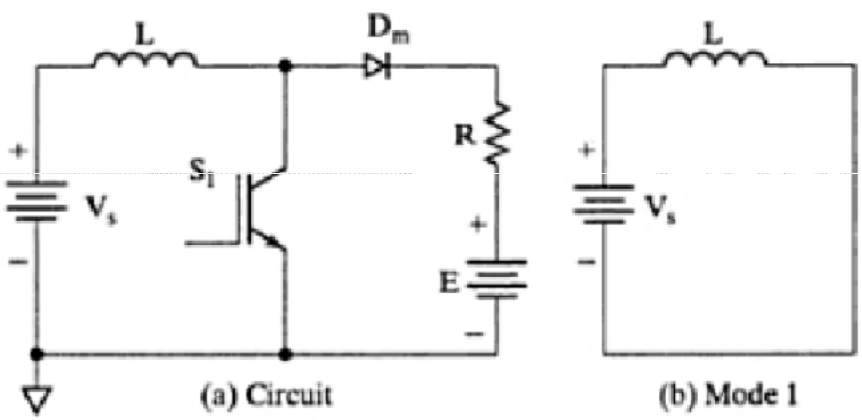
STEP-UP CONVERTER WITH A RESISTIVE LOAD

A step-up converter with a resistive load is shown in Figure 5.8a. When switch S_1 is closed, the current rises through L and the switch. The equivalent circuit during mode 1 is shown in Figure 5.8b and the current is described by

$$V_s = L\frac{d}{dt}i_1$$

which for an initial current of I_1 gives

$$i_1(t) = \frac{V_s}{L}t + I_1 \tag{5.31}$$



(a) Circuit (b) Mode 1

FIGURE 5.8

which is valid for $0 \le t \le kT$. At the end of mode 1 at $t = kT$,

$$I_2 = i_1(t = kT) = \frac{V_s}{L}kT + I_1 \tag{5.32}$$

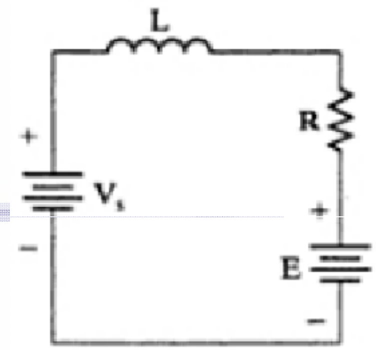
When switch S_1 is opened, the inductor current flows through the RL load.

The equivalent current is shown in Figure 5.8c and the current during mode 2 is described by

$$V_s = Ri_2 + \frac{d}{dt} i_2 + E$$

which for an initial current of I_2 gives

$$i_2(t) = \frac{V_s - E}{L}\left(1 - e^{\frac{-tR}{L}}\right) + I_2 e^{\frac{-tR}{L}} \qquad (5.33)$$



(c) Mode 2

which is valid for $0 \le t \le (1 - k)T$. At the end of mode 2 at $t = (1 - k)T$.

$$I_1 = i_2[t = (1 - k)T] = \frac{V_s - E}{L}\left[1 - e^{-(1-k)z}\right] + I_2 e^{-(1-k)z} \qquad (5.34)$$

where $z = TR/L$. Solving for I_1 and I_2 from Eqs. (5.32) and (5.34), we get

$$I_1 = \frac{V_s kz}{R} \frac{e^{-(1-k)z}}{1 - e^{-(1-k)z}} + \frac{V_s - E}{R} \qquad (5.35)$$

$$I_2 = \frac{V_s kz}{R} \frac{1}{1 - e^{-(1-k)z}} + \frac{V_s - E}{R} \qquad (5.36)$$

The ripple current is given by

$$\Delta I = I_2 - I_1 = \frac{V_s}{L} kT \qquad (5.37)$$

These equations are valid for $E \le V_s$. If $E \ge V_s$ and the converter switch S_1 is opened, the inductor transfers its stored energy through R to the source and the inductor current is discontinuous.

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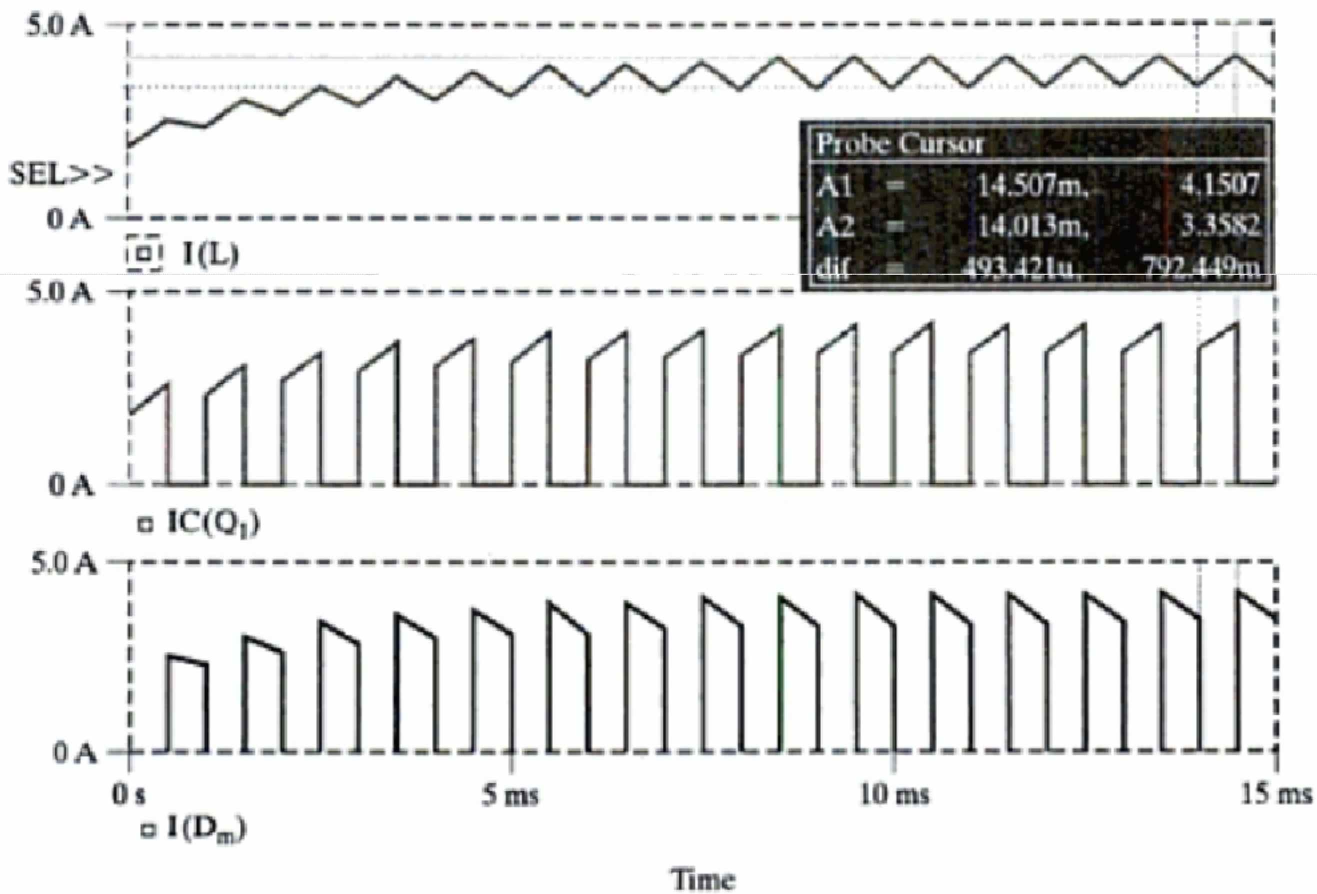
Example 5.4 Finding the Currents of a Step-up Dc Converter

The step-up converter in Figure 5.8a has $V_s = 10\ V$, $f = 1$ kHz, $R = 5\ \Omega$, $L = 6.5$ mH, E = 0 V, and $k = 0.5$. Find I_1, I_2, and ΔI. Use SPICE to find these values and plot the load, diode, and switch current.

Solution

Equations (5.35) and (5.36) give $I_1 = 3.64$ A (3.36 A from SPICE) and $I_2 = 4.4$ A (4.15 A from SPICE). The plots of the load current $I(L)$, the diode current $I(D_m)$ and the switch current $IC(Q_1)$ are shown in Figure 5.9.



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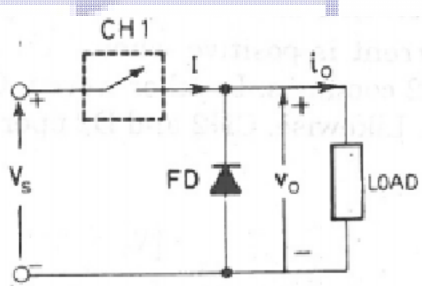
CONVERTER CLASSIFICATION

Depending on the directions of current and voltage flows, dc converters can be classified into five types:

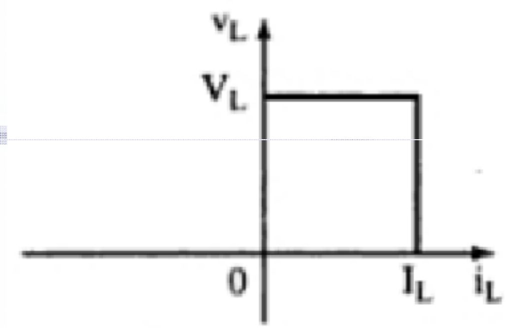
1. First quadrant converter
2. Second quadrant converter
3. First and second quadrant converter
4. Third and fourth quadrant converter
5. Four-quadrant converter

First-quadrant, or Type-A, Chopper

First quadrant converter. The load current flows into the load. Both the load voltage and the load current are positive This is a single-quadrant converter and is said to be operated as a rectifier.



(a)



(a) First quadrant converter

The power flow in type-*A* chopper is always from source to load. This chopper is also called *step-down chopper* as average output voltage V_0 is always less than the input dc voltage V_s.

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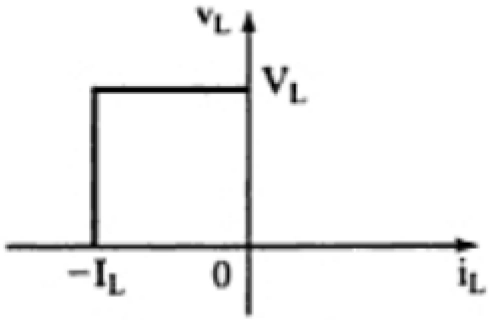
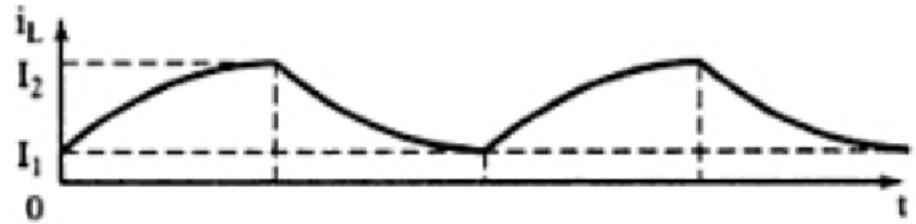
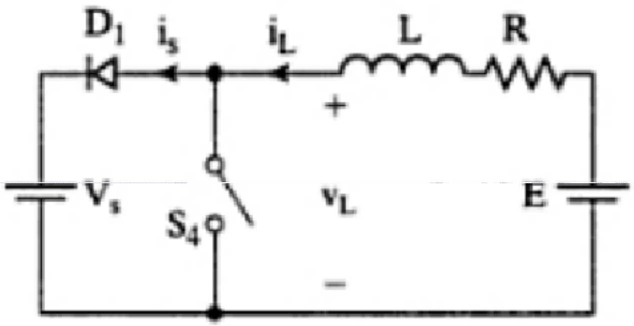
Second-quadrant, or Type-B, Chopper



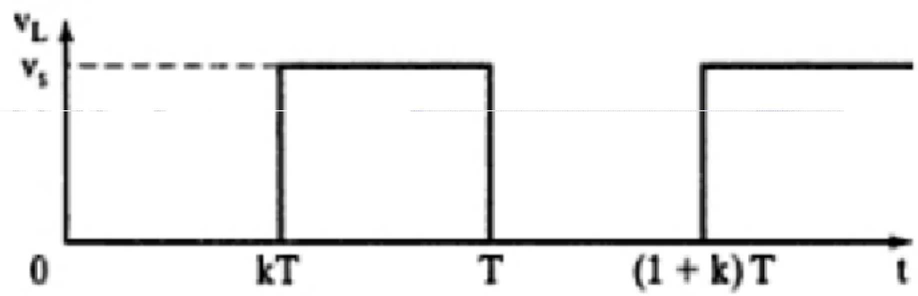
(b) Second quadrant converter



(b) Load current



(a) Circuit



(c) Load voltage

Second quadrant converter. The load current flows out of the load. The load voltage is positive, but the load current is negative, This is also a single-quadrant converter, but operates in the second quadrant and is said to be operated as an inverter. A second quadrant converter is shown in Figure 5.11a, where the battery *E* is a part of the load and may be the back emf of a dc motor.

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When switch S_4 is turned on, the voltage E drives current through inductor L and load voltage v_L becomes zero. The instantaneous load voltage v_L and load current i_L are shown in Figure 5.11b and 5.11c, respectively. The current i_L, which rises, is described by

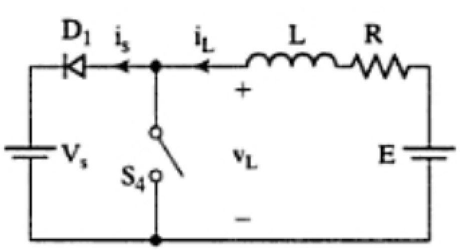
$$0 = L\frac{di_L}{dt} + Ri_L + E$$

which, with initial condition $i_L(t = 0) = I_1$, gives

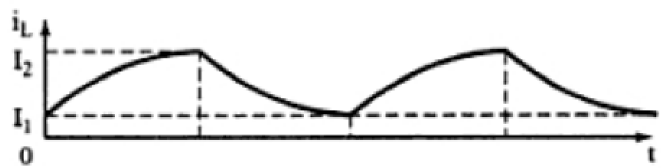
$$i_L = I_1 e^{-(R/L)t} - \frac{E}{R}\left(1 - e^{-(R/L)t}\right) \qquad \text{for } 0 \le t \le kT \tag{5.38}$$

At $t = t_1$,

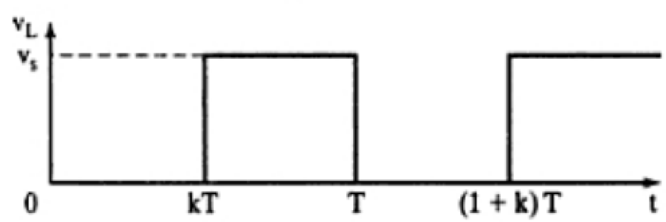
$$i_L(t = t_1 = kT) = I_2 \tag{5.39}$$



(a) Circuit



(b) Load current



(c) Load voltage

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When switch S_4 is turned off, a magnitude of the energy stored in inductor L is returned to the supply V_s via diode D_1. The load current i_L falls. Redefining the time origin $t = 0$, the load current i_L is described by

$$V_s = L\frac{di_L}{dt} + Ri_L + E$$

which, with initial condition $i(t = t_2) = I_2$, gives

$$i_L = I_2 e^{-(R/L)t} + \frac{V_s - E}{R}\left(1 - e^{-(R/L)t}\right) \qquad \text{for } 0 \le t \le t_2 \tag{5.40}$$

where $t_2 = (1 - k)T$. At $t = t_2$,

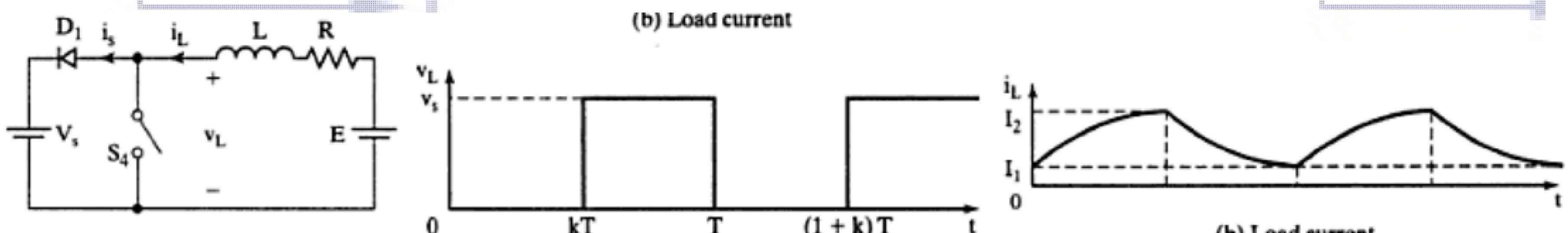
$$\begin{aligned} i_L(t = t_2) &= I_1 \quad \text{for steady-state continuous current} \\ &= 0 \quad \text{for steady-state discontinuous current} \end{aligned} \tag{5.41}$$

Using the boundary conditions in Eqs. (5.39) and (5.41), we can solve for I_1 and I_2 as

$$I_1 = \frac{V_S}{R}\left[\frac{1 - e^{-(1-k)z}}{1 - e^{-z}}\right] - \frac{E}{R} \tag{5.42}$$

$$I_2 = \frac{V_S}{R}\left(\frac{e^{-kz} - e^{-z}}{1 - e^{-z}}\right) - \frac{E}{R} \tag{5.43}$$

(b) Load current



(a) Circuit

(c) Load voltage

(b) Load current

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Two-quadrant type-A chopper, or Type-C Chopper

This type of chopper is obtained by connecting type-*A* and type-*B* choppers in parallel as shown in Fig. 7.8 (*a*). The output voltage V_0 is always positive because of the presence of freewheeling diode FD across the load. When chopper CH2 is on, or freewheeling diode FD conducts, output voltage $v_0 = 0$ and in case chopper CH1 is on or diode D2 conducts, output voltage $v_0 = V_s$. The load current i_0 can, however, reverse its direction. Current i_0 flows in the arrow direction marked in Fig. 7.8 (*a*), *i.e.* load current is positive when CH1 is on or FD conducts. Load current is negative if CH2 is on or D2 conducts. In other words, CH1 and FD operate together as type-*A* chopper in first quadrant. Likewise, CH2 and D2 operate together as type-*B* chopper in second quadrant.

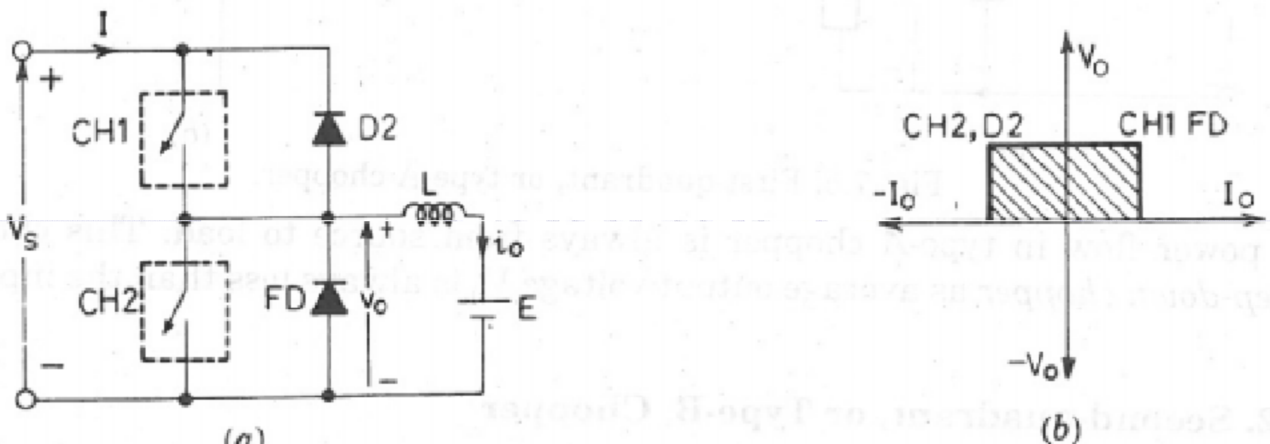

Fig. 7.8. Two-quadrant type-A chopper, or type-C chopper.

Average load voltage is always positive but average load current may be positive or negative as explained above. Therefore, power flow may be from source to load (first-quadrant operation) or from load to source (second-quadrant operation). Choppers CH1 and CH2 should not be on simultaneously as this would lead to a direct short circuit on the supply lines. This type of chopper configuration is used for motoring and regenerative braking of dc motors. The operating region of this type of chopper is shown in Fig. 7.8 (*b*) by hatched area in first and second quadrants.

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Two-quadrant Type-B Chopper, or Type-D Chopper

The power circuit diagram for two-quadrant type-*B* chopper, or type-*D* chopper, is shown in Fig. 7.9 (*a*). The output voltage $v_0 = V_s$ when both CH1 and CH2 are on and $v_0 = -V_s$ when both choppers are off but both diodes *D*1 and *D*2 conduct. Average output voltage V_0 is positive when choppers turn-on time T_{on} is more than their turn-off time T_{off} as shown in Fig. 7.9 (*c*). Average output voltage V_0 is negative when their $T_{on} < T_{off}$, Fig. 7.9 (*d*). The direction of load current is always positive because choppers and diodes can conduct current only in the

direction of arrows shown in Fig. 7.9 (*a*). As V_0 is reversible, power flow is reversible. The operation of this type of chopper is shown by the hatched area in first and fourth quadrants in Fig. 7.9 (*b*).

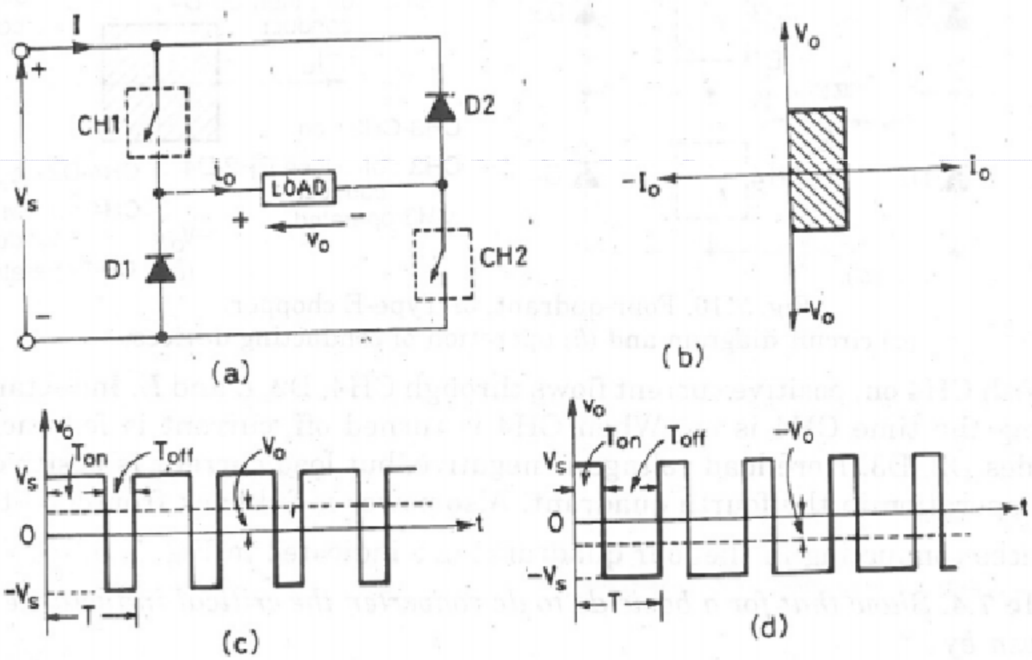

Fig. 7.9 (*a*) and (*b*) Two-quadrant type-B chopper, or type-D chopper (*c*) V_0 is positive, $T_{on} > T_{off}$ and (*d*) V_0 is negative, $T_{on} < T_{off}$

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Four-quadrant Chopper, or Type-E Chopper

7.4.5. Four-quadrant Chopper, or Type-E Chopper

The power circuit diagram for a four-quadrant chopper is shown in Fig. 7.10 (*a*). It consists of four semiconductor switches CH1 to CH4 and four diodes D1 to D4 in antiparallel. Working of this chopper in the four quadrants is explained as under :

First quadrant : For first-quadrant operation of Fig. 7.10 (*a*), CH4 is kept on, CH3 is kept off and *CH1 is operated*. With CH1, CH4 on, load voltage $v_0 = V_s$ (source voltage) and load current i_0 begins to flow. Here both v_0 and i_0 are positive giving first quadrant operation. When CH1 is turned off, positive current freewheels through CH4, D2. In this manner, both V_0, I_0 can be controlled in the first quadrant.

Second quadrant : *Here CH2 is operated* and CH1, CH3 and CH4 are kept off. With CH2 on, reverse (or negative) current flows through L, CH2, D4 and E. Inductance L stores energy during the time CH2 is on. When CH2 is turned off, current is fed back to source through diodes D1, D4. Note that here $\left(E + L\frac{di}{dt}\right)$ is more than the source voltage V_s. As load voltage V_0 is positive and I_0 is negative, it is second quadrant operation of chopper. Also, power is fed back from load to source.

Third quadrant : For third-quadrant operation of Fig. 7.10 (*a*), CH1 is kept off, CH2 is kept on and *CH3 is operated*. Polarity of load emf E must be reversed for this quadrant working. With CH3 on, load gets connected to source V_s so that both v_0, i_0 are negative leading to third quadrant operation. When CH3 is turned off, negative current freewheels through CH2, D4. In this manner, v_0 and i_0 can be controlled in the third quadrant.

Fourth quadrant : *Here CH4 is operated* and other devices are kept off. Load emf E must have its polarity reversed to that shown in Fig. 7.10 (*a*) for operation in the fourth

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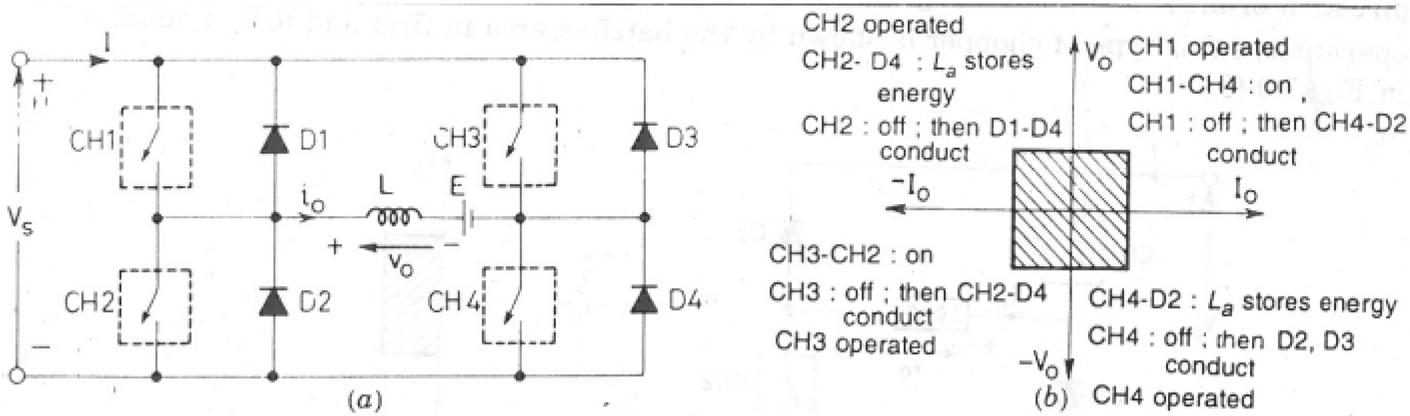

Fig. 7.10. Four-qudrant, or Type-E chopper
(*a*) circuit diagram and (*b*) operation of conducting devices.

quadrant. With CH4 on, positive current flows through CH4, D2, L and E. Inductance L stores energy during the time CH4 is on. When CH4 is turned off, current is fed back to source through diodes D2, D3. Here load voltage is negative, but load current is positive leading to the chopper operation in the fourth quadrant. Also power is fed back from load to source.

The devices conducting in the four quadrants are indicated in Fig. 7.10 (*b*).

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Example 7.4. *Show that for a basic dc to dc converter, the critical inductance of the filter circuit is given by*

$$L = \frac{V_0^2 (V_s - V_0)}{2f\, V_s\, P_0}$$

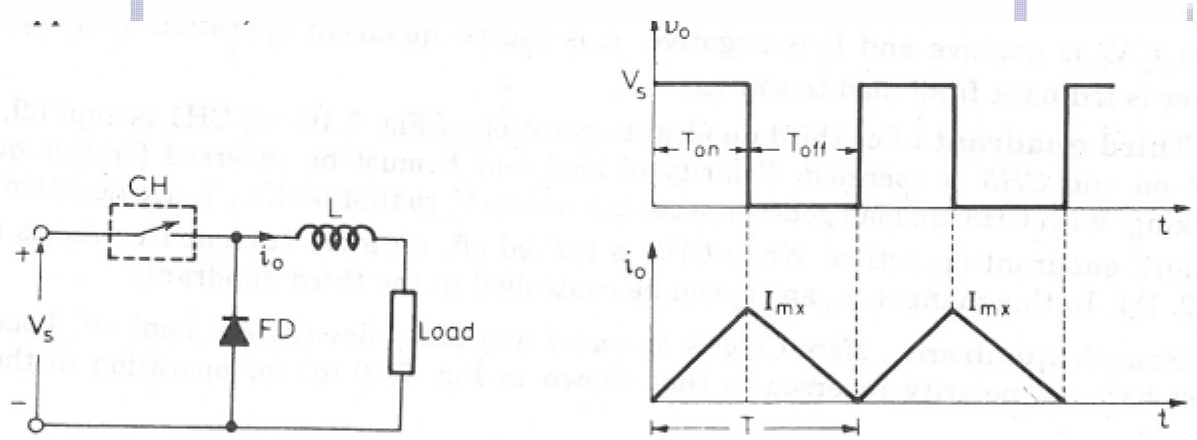
where V_0, V_s, P_0 and f are load voltage, source voltage, load power and chopping frequency respectively.

Solution. The critical inductance L is that value of inductance for which the output current falls to zero at $t = T$ during the turn-off period of the chopper. A typical waveform of output current, with critical inductance in the load circuit, is shown in Fig. 7.11 (*b*). If current variation, from zero to I_{mx} during T_{on} and from I_{mx} to zero during T_{off}, is assumed linear, then average value of output current I_0 is given by

$$I_0 \cdot T = \frac{1}{2} I_{mx}\, T_{on} + \frac{1}{2} I_{mx}\, T_{off}$$

$$= \frac{1}{2} I_{mx} \left(T_{on} + T_{off}\right) = \frac{1}{2} I_{mx}\, T$$

or $I_{mx} = 2\, I_0$ = maximum value of chopper current at $t = T_{on}$. It is seen from Fig. 7.11 (*a*) that when chopper CH is on,



(*a*) (*b*)

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$$V_0 + L\frac{di}{dt} = V_s \quad \text{or} \quad V_0 + L\frac{I_{mx}}{T_{on}} = V_s$$

or

$$L\frac{2I_0}{T_{on}} = V_s - V_0$$

$\therefore$

$$L = \frac{(V_s - V_0)\,T_{on}}{2I_0} \qquad \ldots(i)$$

But average value of output voltage $V_0 = f\,T_{on}\,V_s$ and output, or load, power $P_0 = V_0 I_0$. This gives

$$T_{on} = \frac{V_0}{f \cdot V_s} \quad \text{and} \quad I_0 = \frac{P_0}{V_0}$$

Substituting these values of T_{on} and I_0 in Eq (i), we get

$$L = \frac{(V_s - V_0)\,V_0^2}{2f\,V_s\,P_0}$$

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