DC Choppers

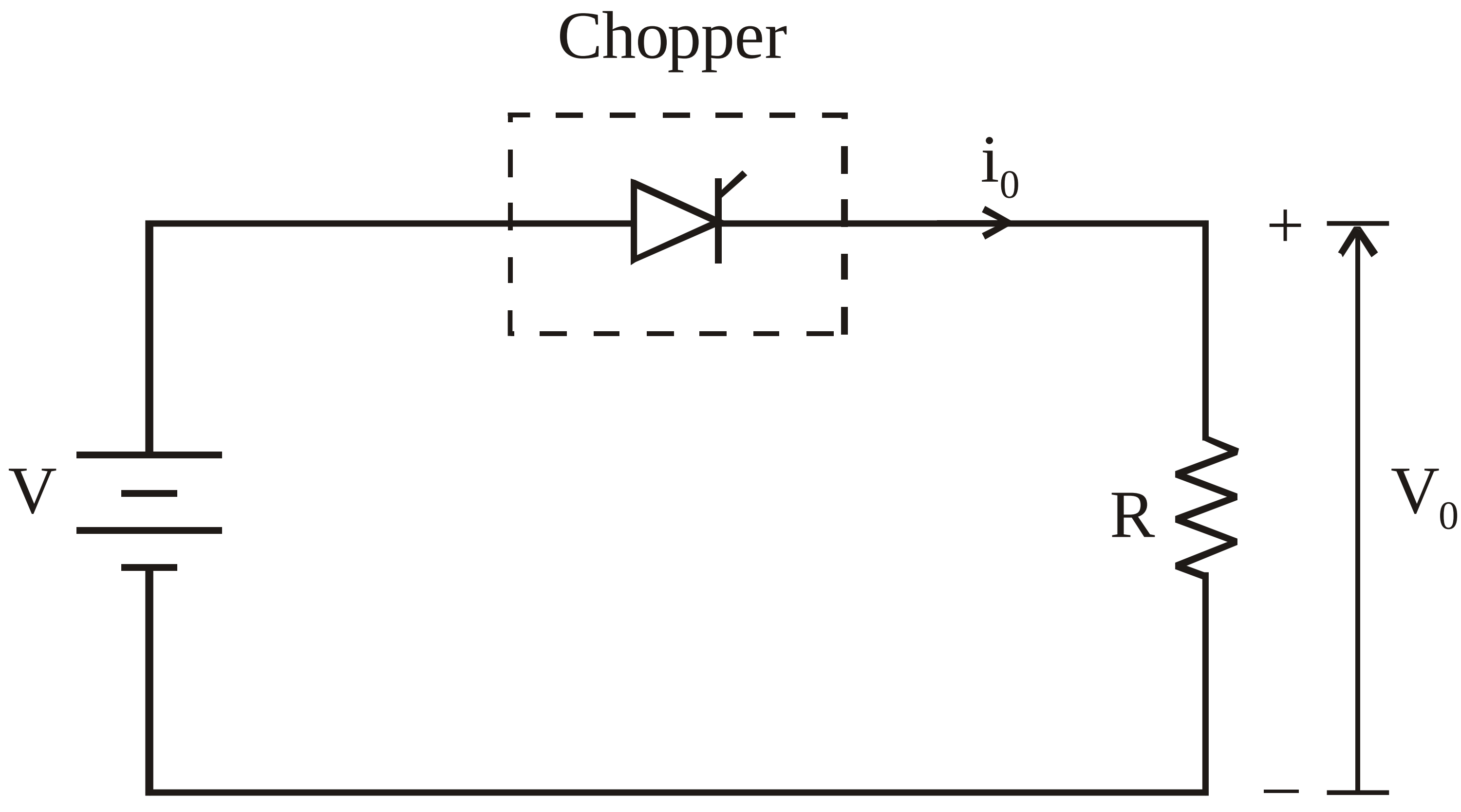
Introduction

- Chopper is a static device.
- A variable dc voltage is obtained from a constant dc voltage source.
- Also known as dc-to-dc converter.
- Widely used for motor control.
- Also used in regenerative braking.
- Thyristor converter offers greater efficiency, faster response, lower maintenance, smaller size and smooth control.

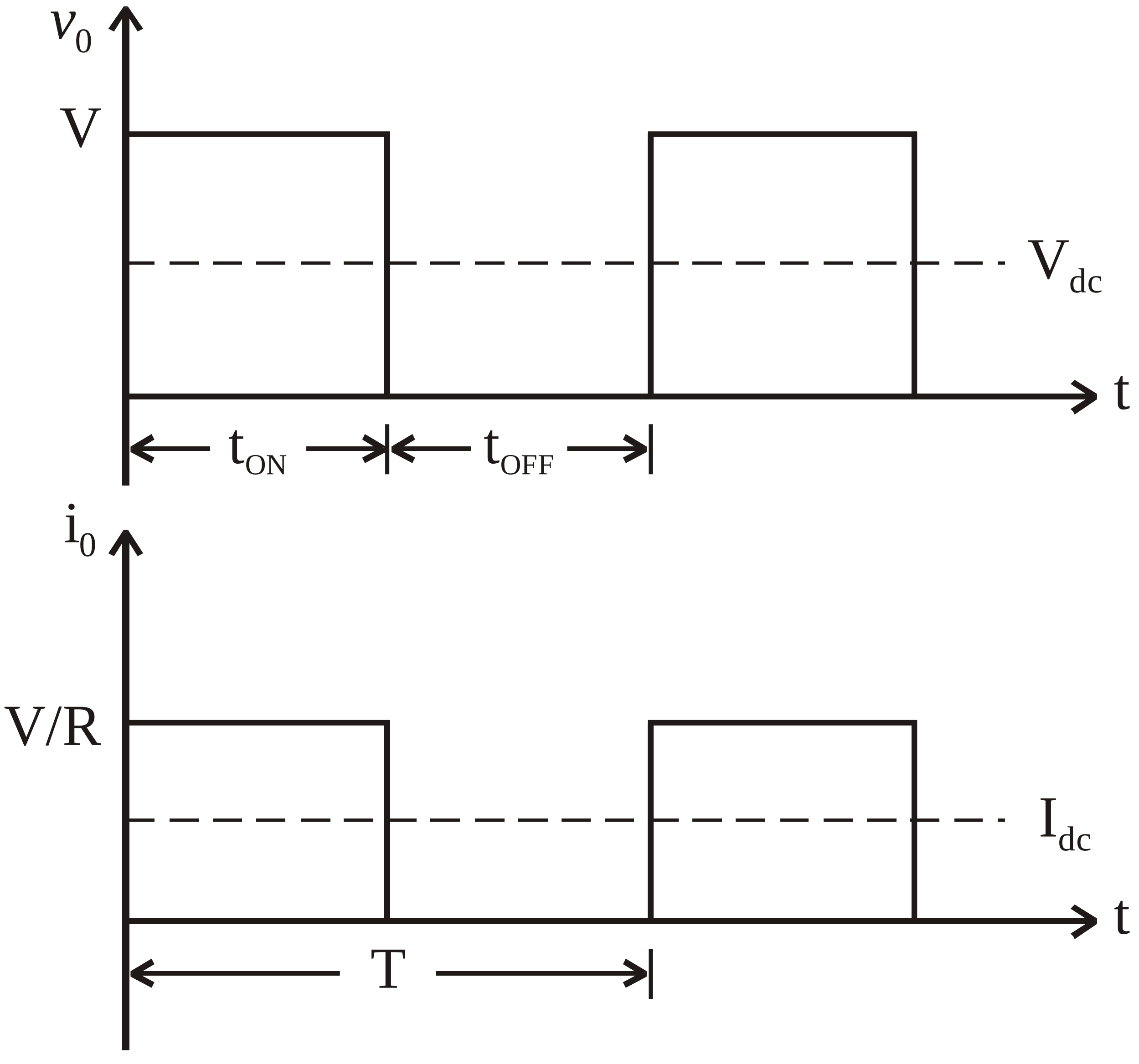
Choppers are of Two Types

- Step-down choppers.
- Step-up choppers.
  - In step down chopper output voltage is less than input voltage.
  - In step up chopper output voltage is more than input voltage.

Principle Of
Step-down Chopper



- A step-down chopper with resistive load.
- The thyristor in the circuit acts as a switch.
- When thyristor is ON, supply voltage appears across the load
- When thyristor is OFF, the voltage across the load will be zero.



v_0
V
V_{dc}
t
t_{ON}
t_{OFF}
i_0
V/R
I_{dc}
t
T

$V_{dc} = A$verage value of output or load voltage.

$I_{dc} = A$verage value of output or load current.

$t_{ON} =$ Time interval for which SCR conducts.

$t_{OFF} =$ Time interval for which SCR is OFF.

$T = t_{ON} + t_{OFF} =$ Period of switching or chopping period.

$f = \frac{1}{T} =$ Freq. of chopper switching or chopping freq.

Average Output Voltage

$$V_{dc} = V\left(\frac{t_{ON}}{t_{ON} + t_{OFF}}\right)$$

$$V_{dc} = V\left(\frac{t_{ON}}{T}\right) = V.d$$

$$but \ \left(\frac{t_{ON}}{t}\right) = d = \text{duty cycle}$$

Average Output Current

$$I_{dc} = \frac{V_{dc}}{R}$$

$$I_{dc} = \frac{V}{R}\left(\frac{t_{ON}}{T}\right) = \frac{V}{R}d$$

RMS value of output voltage

$$V_O = \sqrt{\frac{1}{T}\int_0^{t_{ON}} v_o^2 dt}$$

But during t_{ON}, $v_o = V$

Therefore RMS output voltage

$$V_O = \sqrt{\frac{1}{T}\int_0^{t_{ON}} V^2 dt}$$

$$V_O = \sqrt{\frac{V^2}{T} t_{ON}} = \sqrt{\frac{t_{ON}}{T}}.V$$

$$V_O = \sqrt{d}.V$$

Output power $P_O = V_O I_O$

But $I_O = \dfrac{V_O}{R}$

$\therefore$ Output power

$$P_O = \frac{V_O^2}{R}$$

$$P_O = \frac{dV^2}{R}$$

Effective input resistance of chopper

$$R_i = \frac{V}{I_{dc}}$$

$$R_i = \frac{R}{d}$$

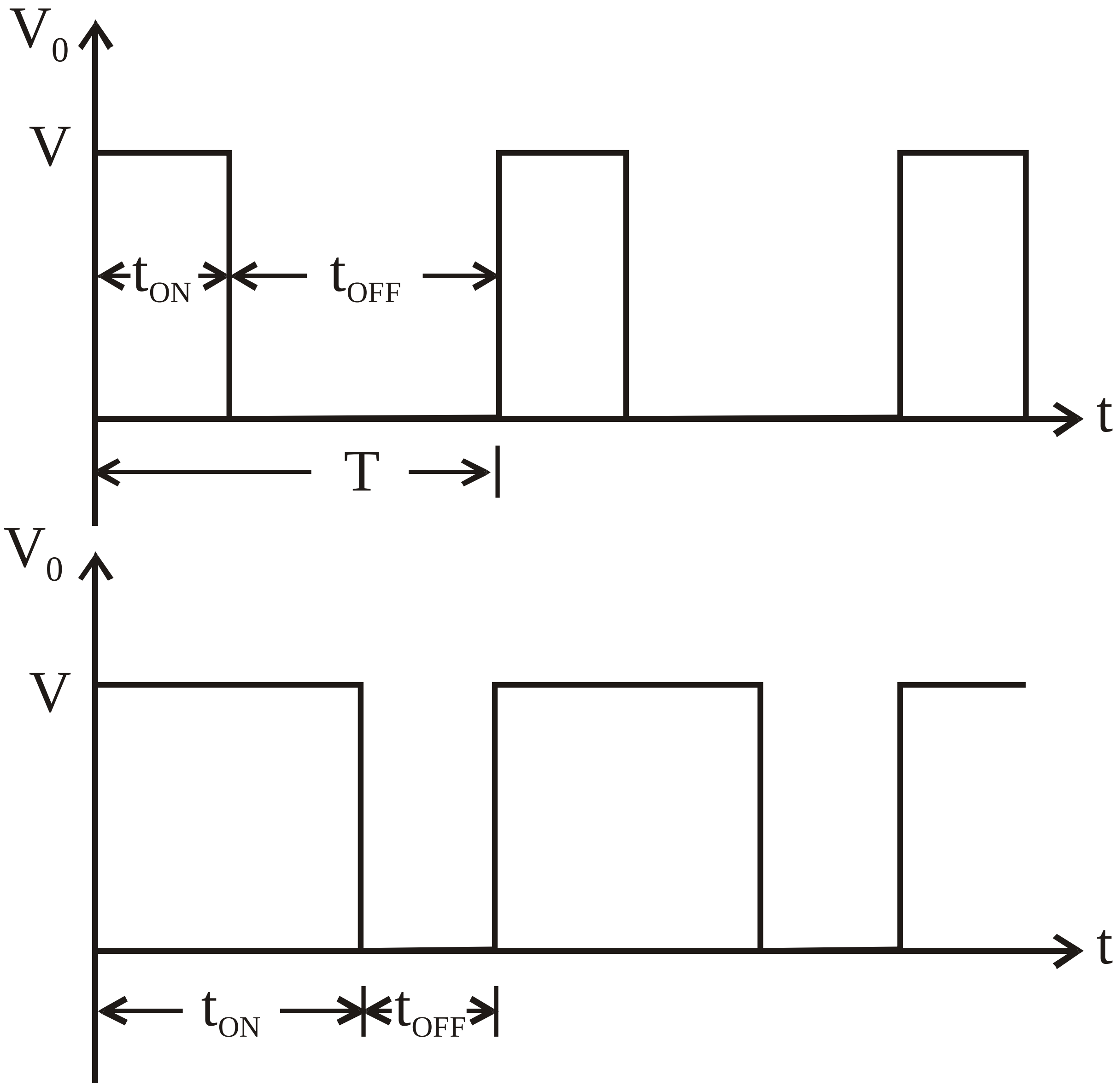
The output voltage can be varied by varying the duty cycle.

Methods Of Control

- The output dc voltage can be varied by the following methods.
  - Pulse width modulation control or constant frequency operation.
  - Variable frequency control.

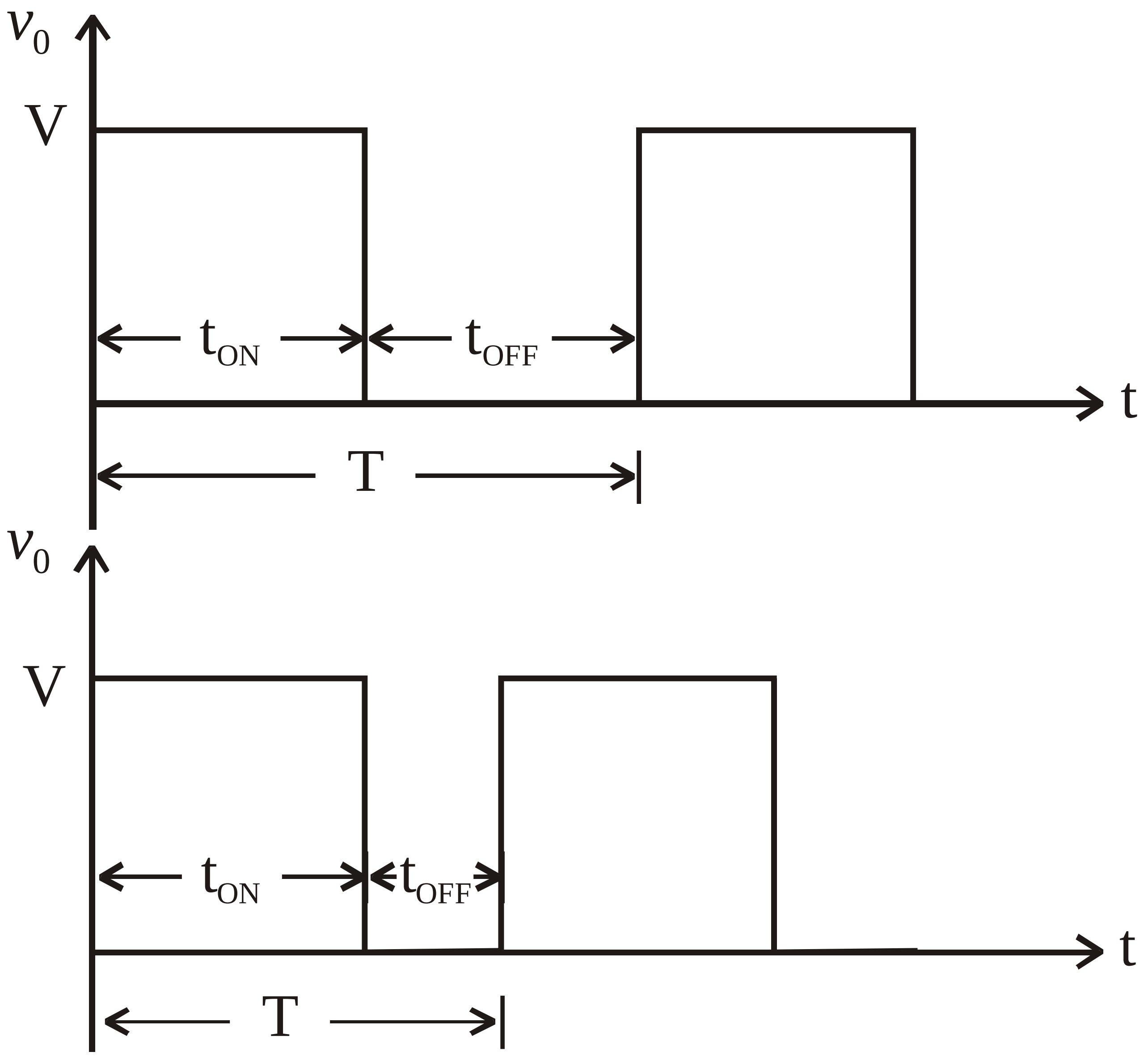
Pulse Width Modulation

- t_{ON} is varied keeping chopping frequency '*f*' & chopping period 'T' constant.
- Output voltage is varied by varying the ON time t_{ON}


V0
V
tON
tOFF
t
T
V0
V
t
tON
tOFF

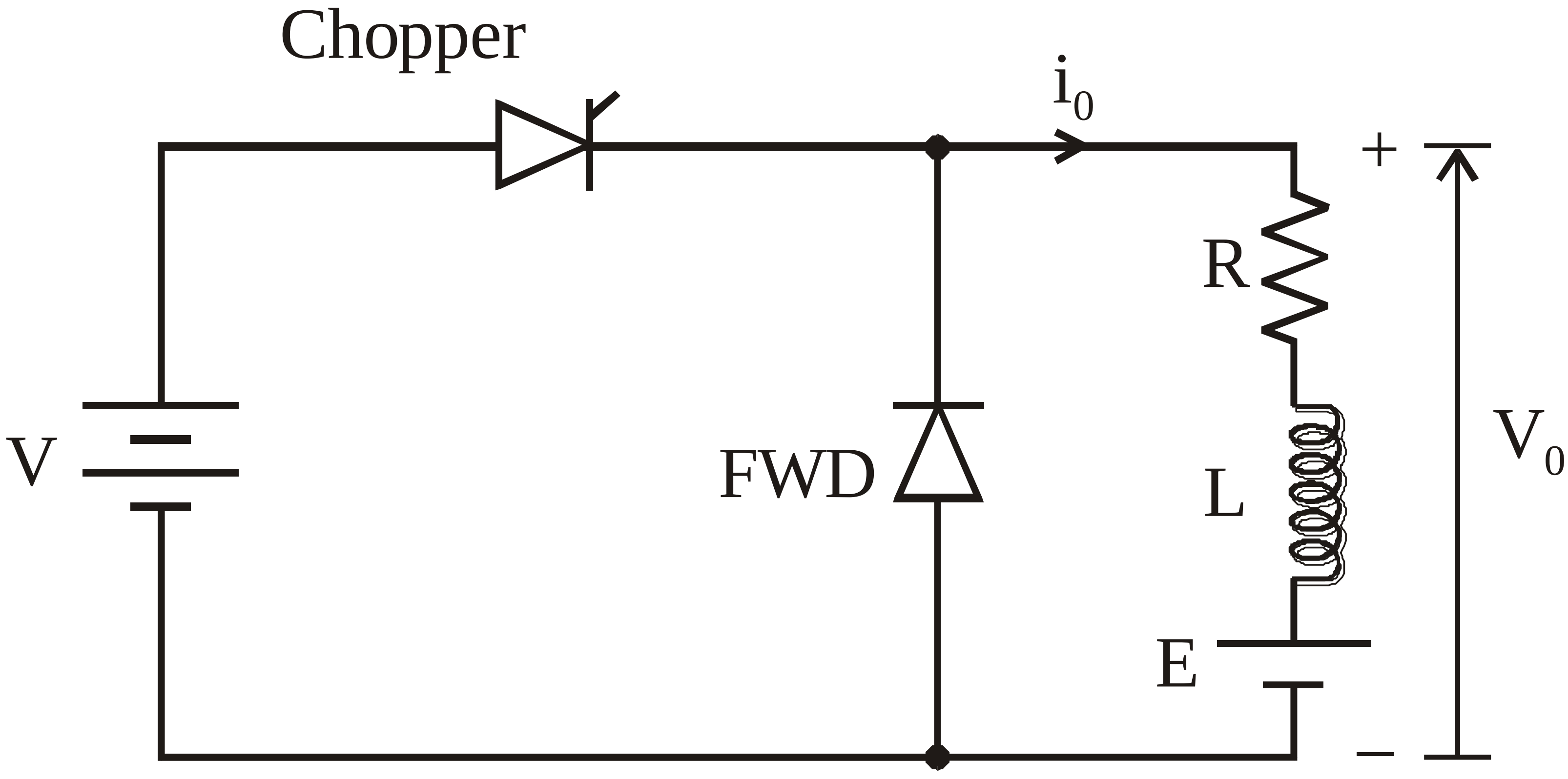
Variable Frequency Control

- Chopping frequency *'f'* is varied keeping either t_{ON} or t_{OFF} constant.
- To obtain full output voltage range, frequency has to be varied over a wide range.
- This method produces harmonics in the output and for large t_{OFF} load current may become discontinuous



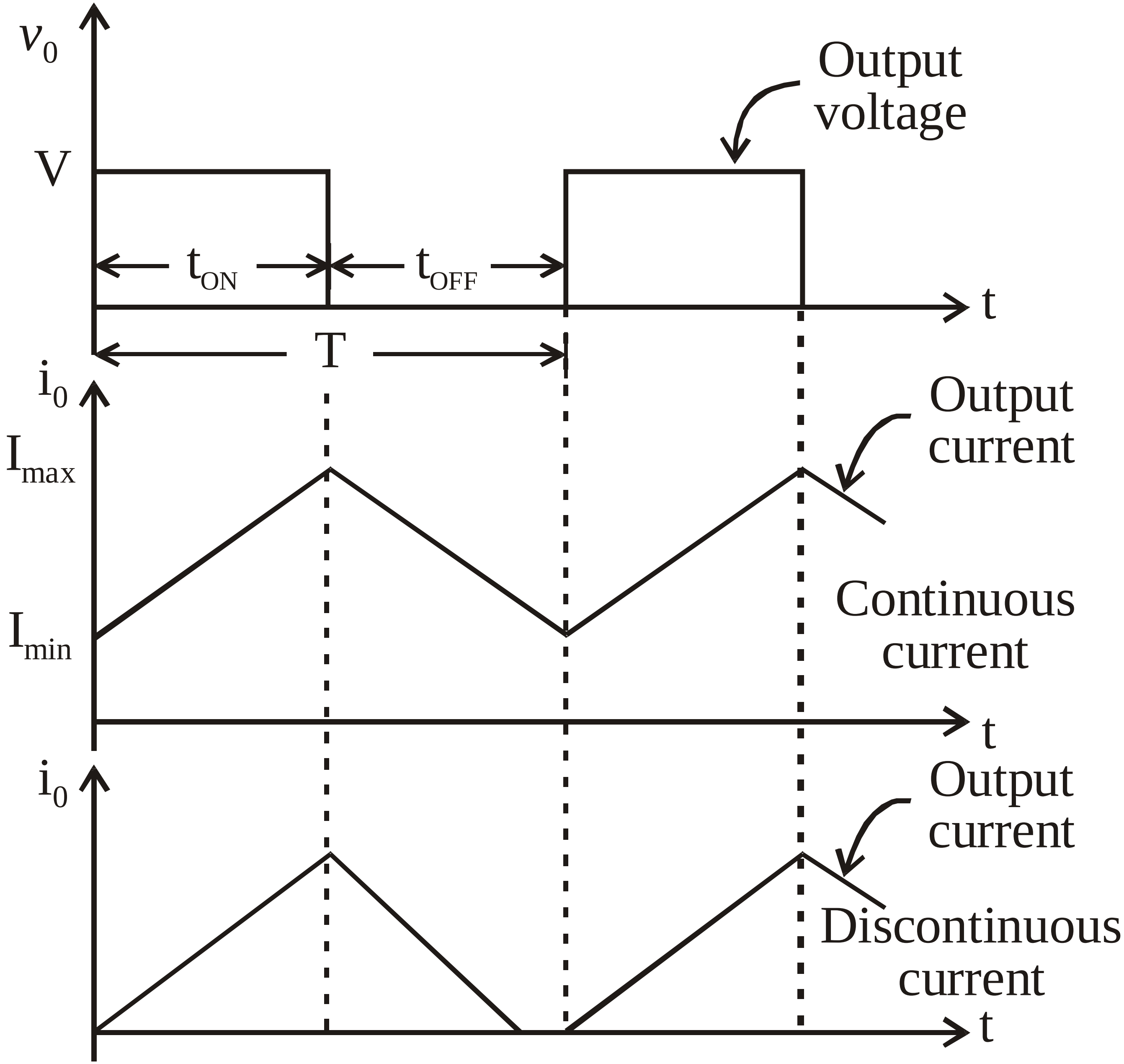
v_0
V
t_{ON}
t_{OFF}
t
T
v_0
V
t_{ON}
t_{OFF}
t
T

Step-down Chopper
With R-L Load



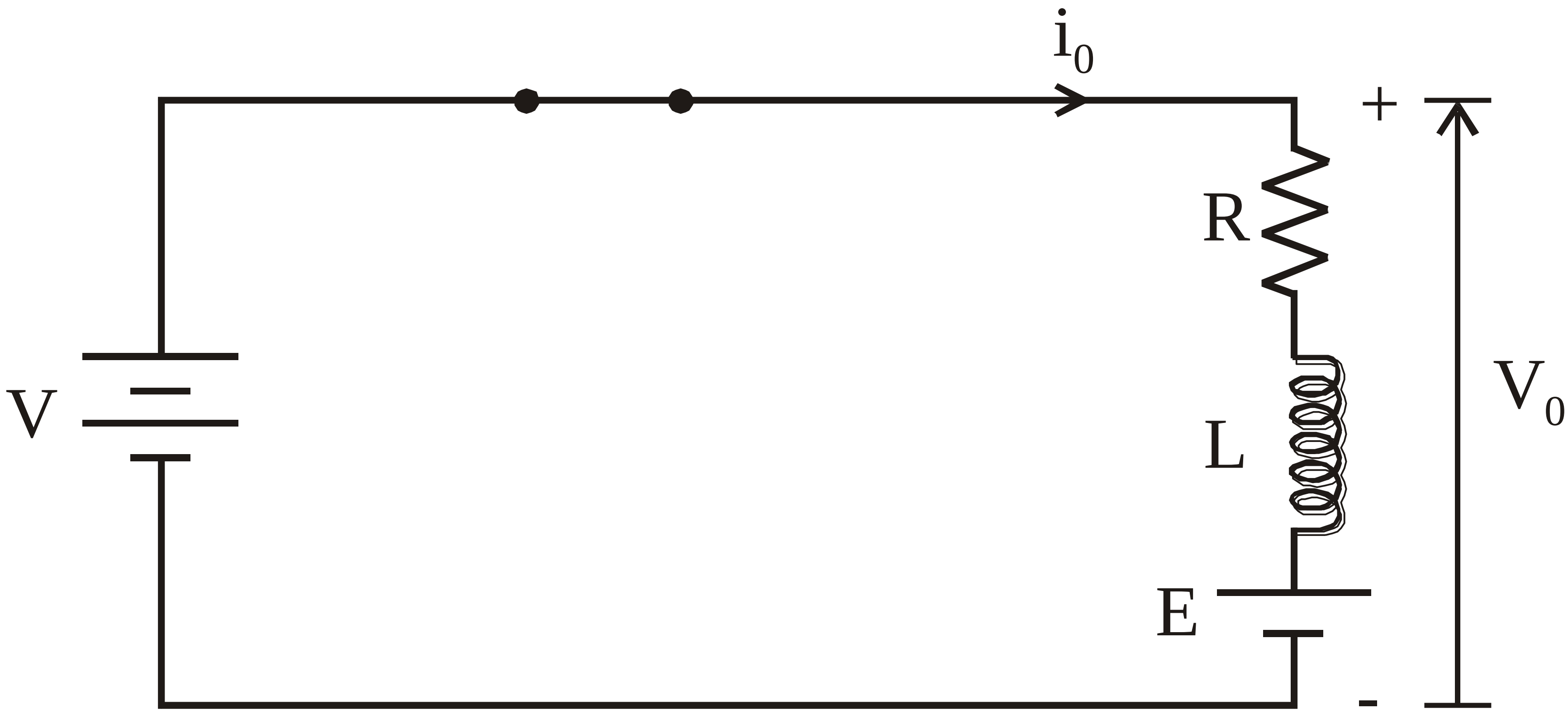
- When chopper is ON, supply is connected across load.
- Current flows from supply to load.
- When chopper is OFF, load current continues to flow in the same direction through FWD due to energy stored in inductor *'L'*.

- Load current can be continuous or discontinuous depending on the values of *'L'* and duty cycle *'d'*
- For a continuous current operation, load current varies between two limits I_{max} and I_{min}
- When current becomes equal to I_{max} the chopper is turned-off and it is turned-on when current reduces to I_{min}.



v_0
Output voltage
V
t_{ON}
t_{OFF}
t
T
i_0
Output current
I_{max}
I_{min}
Continuous current
t
i_0
Output current
Discontinuous current
t

Expressions For
Load Current
i_O For Continuous Current Operation
When
Chopper Is ON $(0 \leq t \leq t_{ON})$


i0
+
R
V
L
V0
E
-

$$V = i_O R + L\frac{di_O}{dt} + E$$

Taking Laplace Transform

$$\frac{V}{S} = RI_O(S) + L\left[S.I_O(S) - i_O\left(0^-\right)\right] + \frac{E}{S}$$

At $t = 0$, initial current $i_O\left(0^-\right) = I_{\min}$

$$I_O(S) = \frac{V - E}{LS\left(S + \frac{R}{L}\right)} + \frac{I_{\min}}{S + \frac{R}{L}}$$

Taking Inverse Laplace Transform

$$i_O(t) = \frac{V-E}{R}\left[1 - e^{-\left(\frac{R}{L}\right)t}\right] + I_{\min} e^{-\left(\frac{R}{L}\right)t}$$

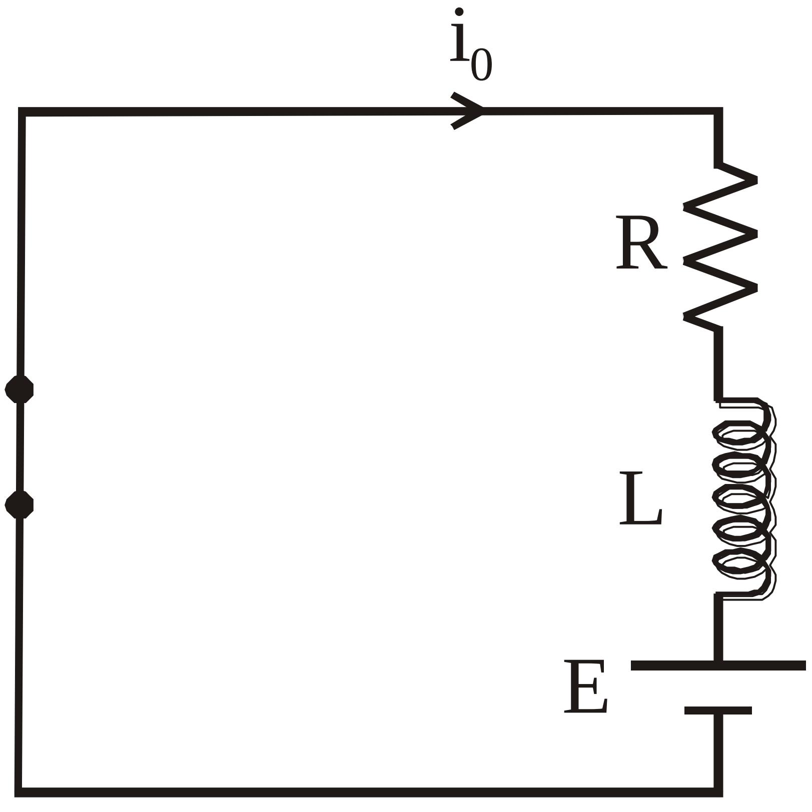
This expression is valid for $0 \le t \le t_{ON}$,

i.e., during the period chopper is ON.

At the instant the chopper is turned off,

load current is $i_O(t_{ON}) = I_{\max}$

When Chopper is OFF



When Chopper is OFF $\left(0 \le t \le t_{OFF}\right)$

$$0 = Ri_O + L\frac{di_O}{dt} + E$$

Talking Laplace transform

$$0 = RI_O\left(S\right) + L\left[SI_O\left(S\right) - i_O\left(0^-\right)\right] + \frac{E}{S}$$

Redefining time origin we have at $t = 0$,

initial current $i_O\left(0^-\right) = I_{\max}$

$$\therefore I_O(S)=\frac{I_{\max}}{S+\frac{R}{L}}-\frac{E}{LS\left(S+\frac{R}{L}\right)}$$

Taking Inverse Laplace Transform

$$i_O(t)=I_{\max}e^{-\frac{R}{L}t}-\frac{E}{R}\left[1-e^{-\frac{R}{L}t}\right]$$

The expression is valid for $0 \le t \le t_{OFF}$,

i.e., during the period chopper is OFF

At the instant the chopper is turned ON or at the end of the off period, the load current is

$$i_O\left(t_{OFF}\right) = I_{\min}$$

To Find $I_{\max}$ & $I_{\min}$

From equation

$$i_O(t) = \frac{V-E}{R}\left[1 - e^{-\left(\frac{R}{L}\right)t}\right] + I_{\min} e^{-\left(\frac{R}{L}\right)t}$$

At $\quad t = t_{ON} = dT, \quad i_O(t) = I_{\max}$

$$\therefore \quad I_{\max} = \frac{V-E}{R}\left[1 - e^{-\frac{dRT}{L}}\right] + I_{\min} e^{-\frac{dRT}{L}}$$

From equation

$$i_O(t) = I_{\max} e^{-\frac{R}{L}t} - \frac{E}{R}\left[1 - e^{-\frac{R}{L}t}\right]$$

At $$t = t_{OFF} = T - t_{ON}, \quad i_O(t) = I_{\min}$$

$$t = t_{OFF} = (1-d)T$$

$$\therefore \qquad I_{\min} = I_{\max} e^{-\frac{(1-d)RT}{L}} - \frac{E}{R}\left[1 - e^{-\frac{(1-d)RT}{L}}\right]$$

Substituting for $I_{\min}$ in equation

$$I_{\max} = \frac{V-E}{R}\left[1 - e^{-\frac{dRT}{L}}\right] + I_{\min} e^{-\frac{dRT}{L}}$$

we get,

$$I_{\max} = \frac{V}{R}\left[\frac{1 - e^{-\frac{dRT}{L}}}{1 - e^{-\frac{RT}{L}}}\right] - \frac{E}{R}$$

Substituting for $I_{\max}$ in equation

$$I_{\min} = I_{\max} e^{-\frac{(1-d)RT}{L}} - \frac{E}{R}\left[1 - e^{-\frac{(1-d)RT}{L}}\right]$$

we get,

$$I_{\min} = \frac{V}{R}\left[\frac{e^{\frac{dRT}{L}} - 1}{e^{\frac{RT}{L}} - 1}\right] - \frac{E}{R}$$

$\left(I_{\max} - I_{\min}\right)$ is known as the steady state ripple.

Therefore peak-to-peak ripple current

$$\Delta I = I_{\max} - I_{\min}$$

Average output voltage

$$V_{dc} = d.V$$

Average output current

$$I_{dc(approx)} = \frac{I_{\max} + I_{\min}}{2}$$

Assuming load current varies linearly from $I_{\min}$ to $I_{\max}$ instantaneous load current is given by

$$i_O = I_{\min} + \frac{(\Delta I).t}{dT} \quad for \; 0 \le t \le t_{ON}\,(dT)$$

$$i_O = I_{\min} + \left(\frac{I_{\max} - I_{\min}}{dT}\right)t$$

RMS value of load current

$$I_{O(RMS)} = \sqrt{\frac{1}{dT}\int_0^{dT} i_0^2 dt}$$

$$I_{O(RMS)} = \sqrt{\frac{1}{dT}\int_0^{dT} \left[I_{\min} + \frac{(I_{\max} - I_{\min})t}{dT}\right]^2 dt}$$

$$I_{O(RMS)} = \sqrt{\frac{1}{dT}\int_0^{dT} \left[I_{\min}^2 + \left(\frac{I_{\max} - I_{\min}}{dT}\right)^2 t^2 + \frac{2I_{\min}(I_{\max} - I_{\min})t}{dT}\right] dt}$$

RMS value of output current

$$I_{O(RMS)} = \left[I_{\min}^2 + \frac{\left(I_{\max} - I_{\min}\right)^2}{3} + I_{\min}\left(I_{\max} - I_{\min}\right) \right]^{\frac{1}{2}}$$

RMS chopper current

$$I_{CH} = \sqrt{\frac{1}{T}\int_0^{dT} i_0^2 \, dt}$$

$$I_{CH} = \sqrt{\frac{1}{T}\int_0^{dT} \left[I_{\min} + \left(\frac{I_{\max} - I_{\min}}{dT} \right) t \right]^2 dt}$$

$$I_{CH} = \sqrt{d}\left[I_{\min}^2 + \frac{\left(I_{\max} - I_{\min}\right)^2}{3} + I_{\min}\left(I_{\max} - I_{\min}\right)\right]^{\frac{1}{2}}$$

$$I_{CH} = \sqrt{d}\, I_{O(RMS)}$$

Effective input resistance is

$$R_i = \frac{V}{I_S}$$

Where

$$I_S = \text{Average source current}$$

$$I_S = dI_{dc}$$

$$\therefore \qquad R_i = \frac{V}{dI_{dc}}$$