Study materials and Problems

of

Power Electronics

(ECE-S 501)

DC-DC Converters (Choppers)

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DC-DC Converters
(Choppers)

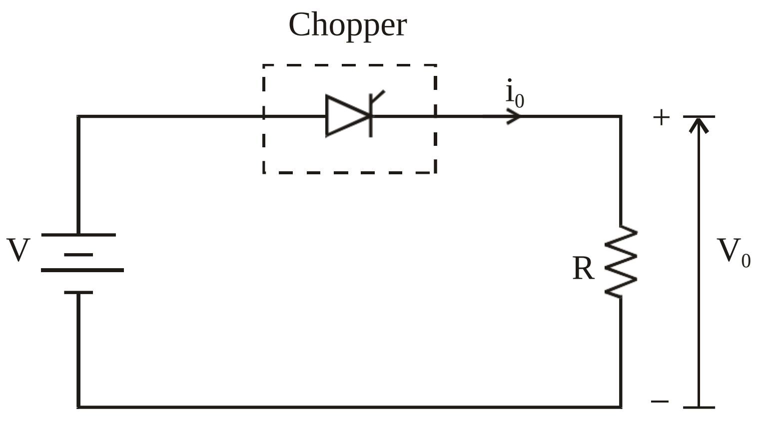
Introduction

- 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.

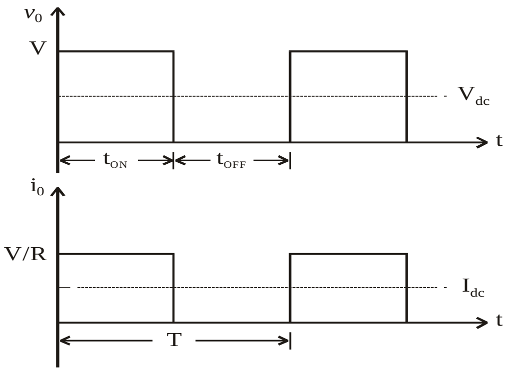
Choppers are of Two Types

- 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_{dc} = Average value of output or load voltage.
I_{dc} = Average 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 $I_O = \frac{V_O}{R}$

$\therefore$ Output power

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

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

Effective input resistance of chopper

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

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

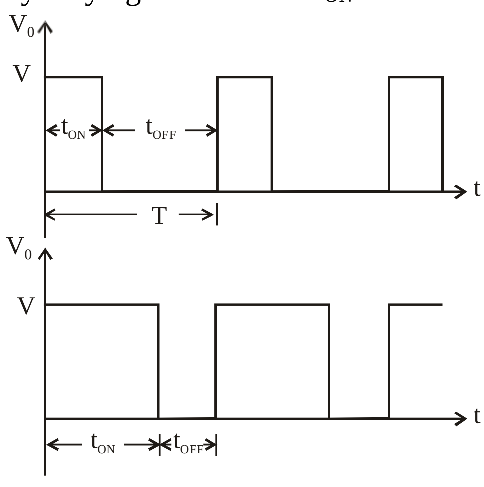
The output voltage can be varied by varying the duty cycle.

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.
  -

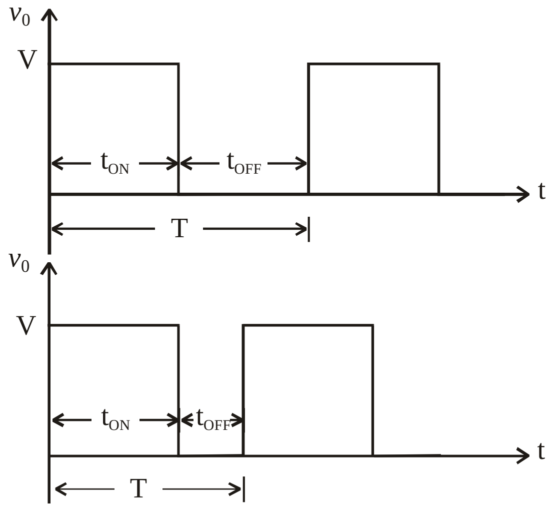
Pulse Width Modulation

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

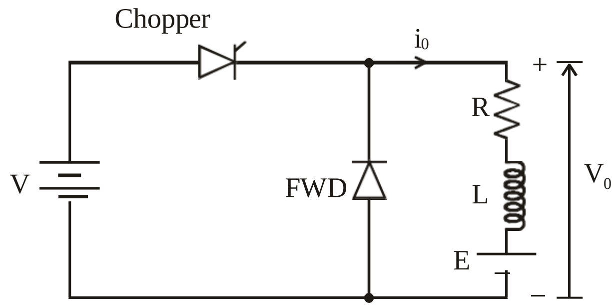


Variable Frequency Control

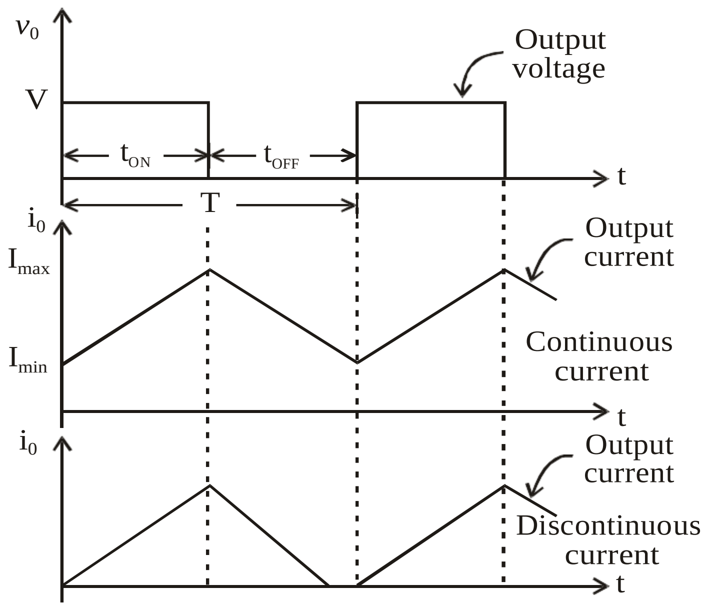
- Chopping frequency '*f*' is varied keeping either t_{ON} or t_{OFF} constant.
- To obtain full output voltage range, frequency has to be varied over a wide range.
- This method produces harmonics in the output and for large *tOFF* load current may become discontinuous



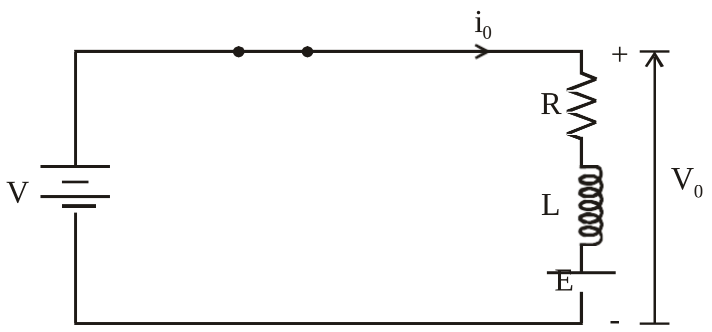
Step-down Chopper with R-L Load



- 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 *Imax* and *Imin*
- When current becomes equal to *Imax* the chopper is turned-off and it is turned-on when current reduces to *Imin.*



Expressions for Load Current *Io* for Continuous Current Operation When Chopper is ON *(0 ≤ T ≤ Ton)*



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

Taking Laplace Transform

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

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

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

Taking Inverse Laplace Transform

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

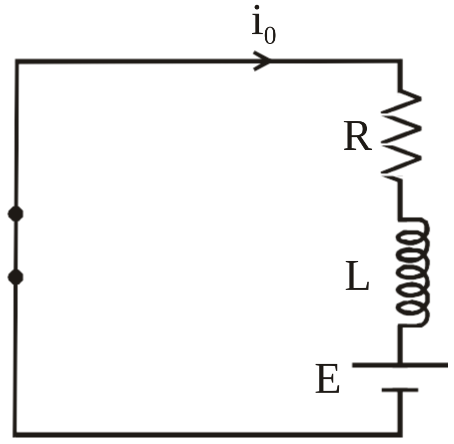
This expression is valid for $0 \le t \le t_{ON}$,

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 $(0 \le t \le t_{OFF})$

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

Talking Laplace transform

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

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

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

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

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

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

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

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

From equation

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

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

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

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

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,

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

$(I_{\max} - I_{\min})$ 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

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

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

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

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

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

Effective input resistance is

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

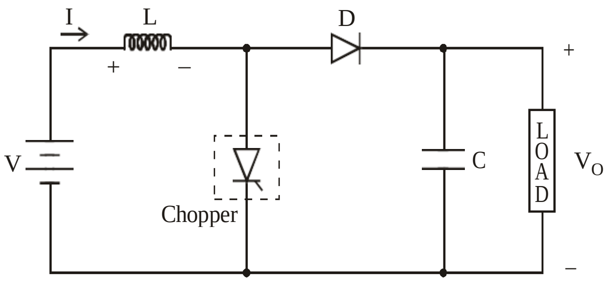
Where

I_S = Average source current

$I_S = dI_{dc}$

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

Principle of Step-up Chopper



- Step-up chopper is used to obtain a load voltage higher than the input voltage *V*.
- The values of *L* and *C* are chosen depending upon the requirement of output voltage and current.
- When the chopper is *ON*, the inductor *L* is connected across the supply.
- The inductor current *'I'* rises and the inductor stores energy during the *ON* time of the chopper, *tON*.
- When the chopper is off, the inductor current *I* is forced to flow through the diode *D* and load for a period, *tOFF*.
- The current tends to decrease resulting in reversing the polarity of induced EMF in *L*.
- Therefore voltage across load is given by

$$V_O = V + L\frac{dI}{dt} \quad i.e., \quad V_O > V$$

- A large capacitor 'C' connected across the load, will provide a continuous output voltage .
- Diode *D* prevents any current flow from capacitor to the source.
- Step up choppers are used for regenerative braking of dc motors.

(i) Expression For Output Voltage

Assume the average inductor current to be I during ON and OFF time of Chopper.

When Chopper is ON

Voltage across inductor $L = V$

Therefore energy stored in inductor

$$= V.I.t_{ON}$$

Where $t_{ON} = ON$ period of chopper.

When Chopper is OFF

(energy is supplied by inductor to load)

Voltage across $L = V_O - V$

Energy supplied by inductor $L = (V_O - V)\, It_{OFF}$

where $t_{OFF} = OFF$ period of Chopper.

Neglecting losses, energy stored in inductor L = energy supplied by inductor L

$$\therefore \quad VIt_{ON} = (V_O - V)\, It_{OFF}$$

$$V_O = \frac{V\left[t_{ON} + t_{OFF}\right]}{t_{OFF}}$$

$$V_O = V\left(\frac{T}{T - t_{ON}}\right)$$

Where

T = Chopping period or period of switching.

$$T = t_{ON} + t_{OFF}$$

$$V_O = V\left(\frac{1}{1 - \frac{t_{ON}}{T}}\right)$$

$$\therefore \quad V_O = V\left(\frac{1}{1}\right)$$

Where $d = \frac{t_{ON}}{T} =$ duty cyle

Performance Parameters

- The thyristor requires a certain minimum time to turn *ON* and turn *OFF*.
- Duty cycle *d* can be varied only between a min. & max. value, limiting the min. and max. value of the output voltage.
- Ripple in the load current depends inversely on the chopping frequency, *f*.
- To reduce the load ripple current, frequency should be as high as possible.

Problem

1. A Chopper circuit is operating on TRC at a frequency of 2 kHz on a 460 V supply. If the load voltage is 350 volts, calculate the conduction period of the thyristor in each cycle.

Solution:

$V = 460$ V, $V_{dc} = 350$ V, f = 2 kHz

Chopping period $T = \frac{1}{f}$

$$T = \frac{1}{2\times10^{-3}} = 0.5\ m\text{sec}$$

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

Conduction period of thyristor

$$t_{ON} = \frac{T\times V_{dc}}{V}$$

$$t_{ON} = \frac{0.5\times10^{-3}\times350}{460}$$

$$t_{ON} = 0.38\ \text{msec}$$

Problem

2. Input to the step up chopper is 200 V. The output required is 600 V. If the conducting time of thyristor is 200 μsec. Compute

   - Chopping frequency,
   - If the pulse width is halved for constant frequency of operation, find the new output voltage.

Solution:

$$V = 200\ V,\quad t_{ON} = 200\mu s,\quad V_{dc} = 600V$$

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

$$600 = 200\left(\frac{T}{T-200\times10^{-6}}\right)$$

Solving for T

$$T = 300\mu s$$

Chopping frequency

$$f = \frac{1}{T}$$

$$f = \frac{1}{300\times10^{-6}} = 3.33KHz$$

Pulse width is halved

$$\therefore \qquad t_{ON} = \frac{200\times10^{-6}}{2} = 100 \quad s$$

Frequency is constant

$$\therefore \qquad f = 3.33KHz$$

$$T = \frac{1}{f} = 300\mu s$$

$$\therefore \text{Output voltage} = V\left(\frac{T}{T - t_{ON}}\right)$$

$$= 200\left(\frac{300\times10^{-6}}{(300-100)10^{-6}}\right) = 300 \text{ Volts}$$

Problem

3. A dc chopper has a resistive load of 20Λ and input voltage VS = 220V. When chopper is ON, its voltage drop is 1.5 volts and chopping frequency is 10 kHz. If the duty cycle is 80%, determine the average output voltage and the chopper on time.

Solution:

$$V_S = 220V,\ R = 20\Lambda, \quad f = 10\ kHz$$

$$d = \frac{t_{ON}}{T} = 0.80$$

V_{ch} = Voltage drop across chopper = 1.5 volts

Average output voltage

$$V_{dc} = \left(\frac{t_{ON}}{T}\right)(V_S - V_{ch})$$

$$V_{dc} = 0.80(220 - 1.5) = 174.8 \text{ Volts}$$

Chopper ON time, $t_{ON} = dT$

Chopping period, $T = \frac{1}{f}$

$$T = \frac{1}{10\times10^{3}} = 0.1\times10^{-3} \text{ secs} = 100 \text{ µsecs}$$

Chopper ON time,

$$t_{ON} = dT$$

$$t_{ON} = 0.80\times0.1\times10^{-3}$$

$$t_{ON} = 0.08\times10^{-3} = 80 \text{ µsecs}$$

Problem

4. In a dc chopper, the average load current is 30 Amps, chopping frequency is 250 Hz, supply voltage is 110 volts. Calculate the ON and OFF periods of the chopper if the load resistance is 2 ohms.

Solution:

$$I_{dc} = 30 \; Amps, \;\; f = 250 \; Hz, \;\; V = 110 \; V, \;\; R = 2\Lambda$$

Chopping period, $T = \frac{1}{f} = \frac{1}{250} = 4\times10^{-3} = 4 \text{ msecs}$

$$I_{dc} = \frac{V_{dc}}{R} \;\; \& \; V_{dc} = dV$$

$$\therefore \quad I_{dc} = \frac{dV}{R}$$

$$d = \frac{I_{dc}R}{V} = \frac{30\times2}{110} = 0.545$$

Chopper ON period,

$$t_{ON} = dT = 0.545\times4\times10^{-3} = 2.18 \text{ msecs}$$

Chopper OFF period,

$$t_{OFF} = T - t_{ON}$$

$$t_{OFF} = 4\times10^{-3} - 2.18\times10^{-3}$$

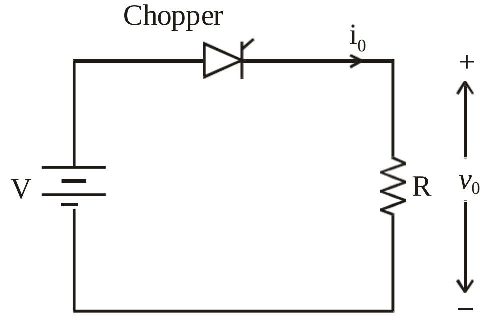
$$t_{OFF} = 1.82\times10^{-3} = 1.82 \text{ msec}$$

Problem

5. A dc chopper in figure has a resistive load of R = 10Λ and input voltage of V = 200 V. When chopper is ON, its voltage drop is 2 V and the chopping frequency is 1 kHz. If the duty cycle is 60%, determine

– Average output voltage

– RMS value of output voltage
– Effective input resistance of chopper
– Chopper efficiency.



Solution:

$V = 200\ V$, $R = 10\Omega$, *Chopper voltage drop* $V_{ch} = 2V$

$d = 0.60$, $f = 1\ kHz$.

Average output voltage

$$V_{dc} = d\left(V - V_{ch}\right)$$

$$V_{dc} = 0.60\left[200 - 2\right] = 118.8 \text{ Volts}$$

RMS value of output voltage

$$V_O = \sqrt{d}\left(V - V_{ch}\right)$$

$$V_O = \sqrt{0.6}\left(200 - 2\right) = 153.37 \text{ Volts}$$

Effective input resistance of chopper is

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

$$I_{dc} = \frac{V_{dc}}{R} = \frac{118.8}{10} = 11.88 \text{ Amps}$$

$$R_i = \frac{V}{I_S} = \frac{V}{I_{dc}} = \frac{200}{11.88} = 16.83\Lambda$$

Output power is

$$P_O = \frac{1}{T}\int_0^{dT} \frac{v_0^2}{R}\,dt = \frac{1}{T}\int_0^{dT} \frac{\left(V - V_{ch}\right)^2}{R}\,dt$$

$$P_O = \frac{d\left(V - V_{ch}\right)^2}{R}$$

$$P_O = \frac{0.6\left[200 - 2\right]^2}{10} = 2352.24 \text{ watts}$$

Input power,

$$P_i = \frac{1}{T}\int_0^{dT} V i_O\,dt$$

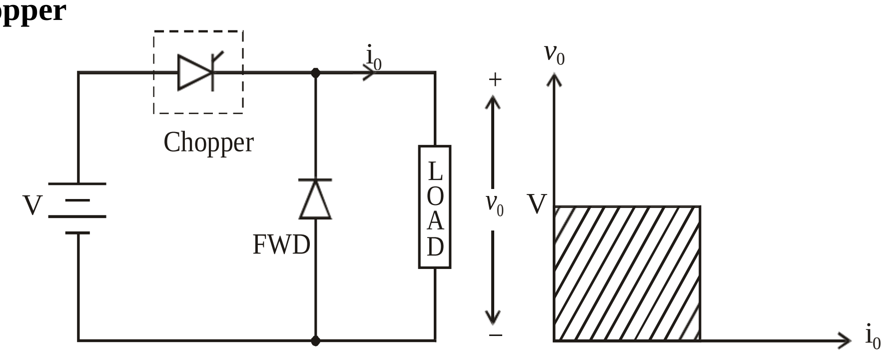
$$P_O = \frac{1}{T}\int_0^{dT} \frac{V\left(V - V_{ch}\right)}{R}\,dt$$

Classification of Choppers

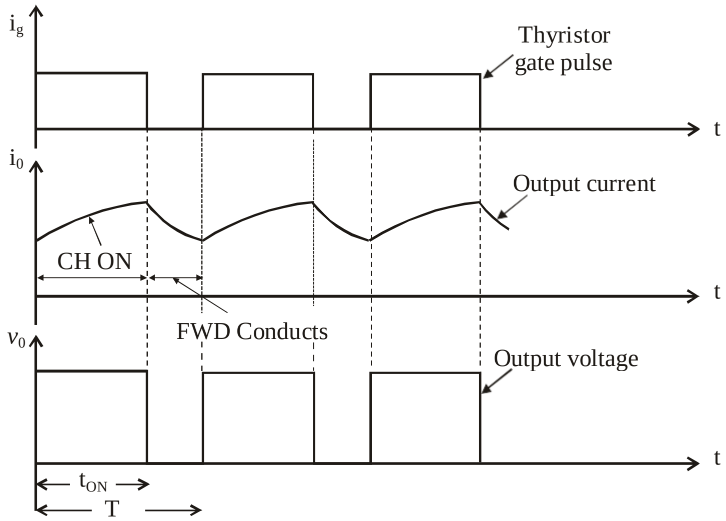
Choppers are classified as

- **Class A Chopper**
- **Class B Chopper**
- **Class C Chopper**
- **Class D Chopper**
- **Class E Chopper**

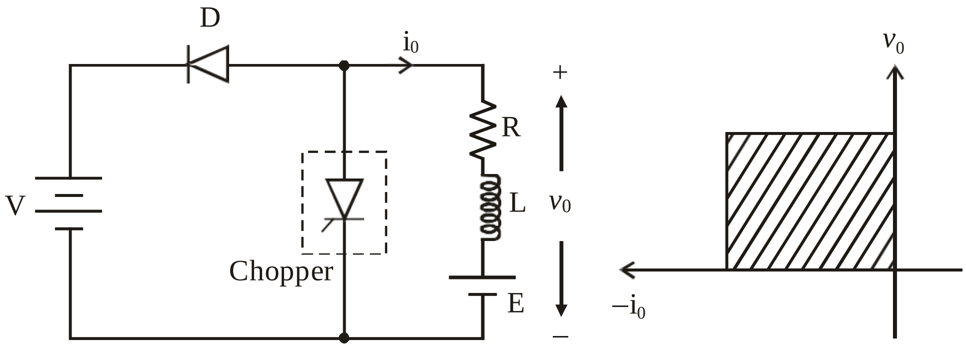
1. Class A Chopper



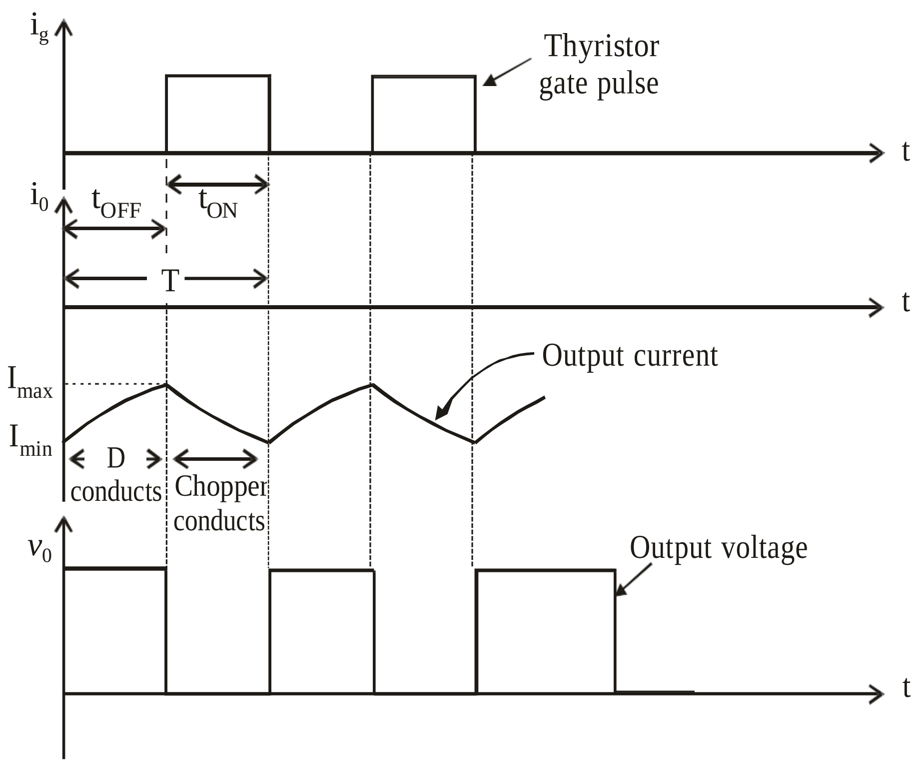
- When chopper is *ON*, supply voltage *V* is connected across the load.
- When chopper is OFF, *v*O = 0 and the load current continues to flow in the same direction through the FWD.
- The average values of output voltage and current are always positive.
- *Class A Chopper* is a first quadrant chopper .
- *Class A Chopper* is a step-down chopper in which power always flows form source to load.
- It is used to control the speed of dc motor.
- The output current equations obtained in step down chopper with *R-L* load can be used to study the performance of *Class A Chopper.*



2. Class B Chopper



- When chopper is ON, *E* drives a current through *L* and R in a direction opposite to that shown in figure.
- During the ON period of the chopper, the inductance *L* stores energy.
- When Chopper is OFF, diode *D* conducts, and part of the energy stored in inductor *L* is returned to the supply.
- Average output voltage is positive.
- Average output current is negative.
- Therefore C*lass B Chopper* operates in second quadrant.
- In this chopper, power flows from load to source.
- *Class B Chopper* is used for regenerative braking of dc motor.
- *Class B Chopper* is a step-up chopper.



(i) Expression for Output Current

During the interval diode 'D' conducts voltage equation is given by

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

For the initial condition i.e.,

$$i_O(t) = I_{min} \quad \text{at } t = 0$$

The solution of the above equation is obtained along similar lines as in step-down chopper with R-L load

$$\therefore \quad i_O(t) = \frac{V-E}{R}\left(1 - e^{-\frac{R}{L}t}\right) + I_{min} e^{-\frac{R}{L}t} \quad 0 < t < t_{OFF}$$

At $t = t_{OFF}$ $\quad i_{(O)}(t) = I_{max}$

$$I_{max} = \frac{V-E}{R}\left(1 - e^{-\frac{R}{L}t_{OFF}}\right) + I_{min} e^{-\frac{R}{L}t_{OFF}}$$

During the interval chopper is ON voltage equation is given by

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

Redefining the time origin, at $t = 0 \quad i_O(t) = I_{max}$

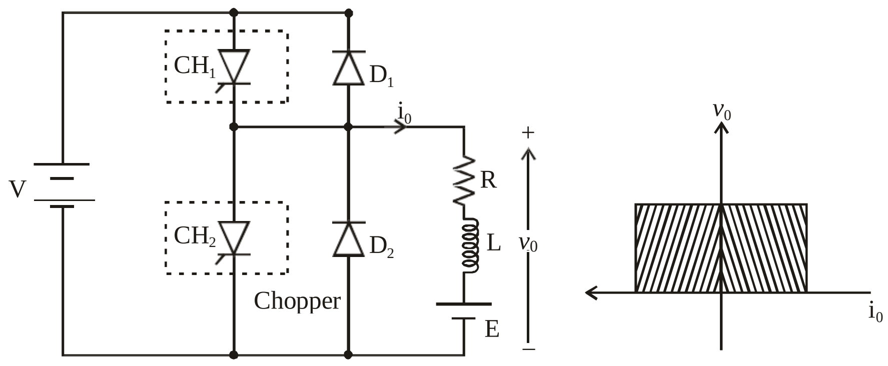
The solution for the stated initial condition is

$$i_O(t) = I_{max} e^{-\frac{R}{L}t} - \frac{E}{R}\left(1 - e^{-\frac{R}{L}t}\right) \qquad 0 < t < t_{ON}$$

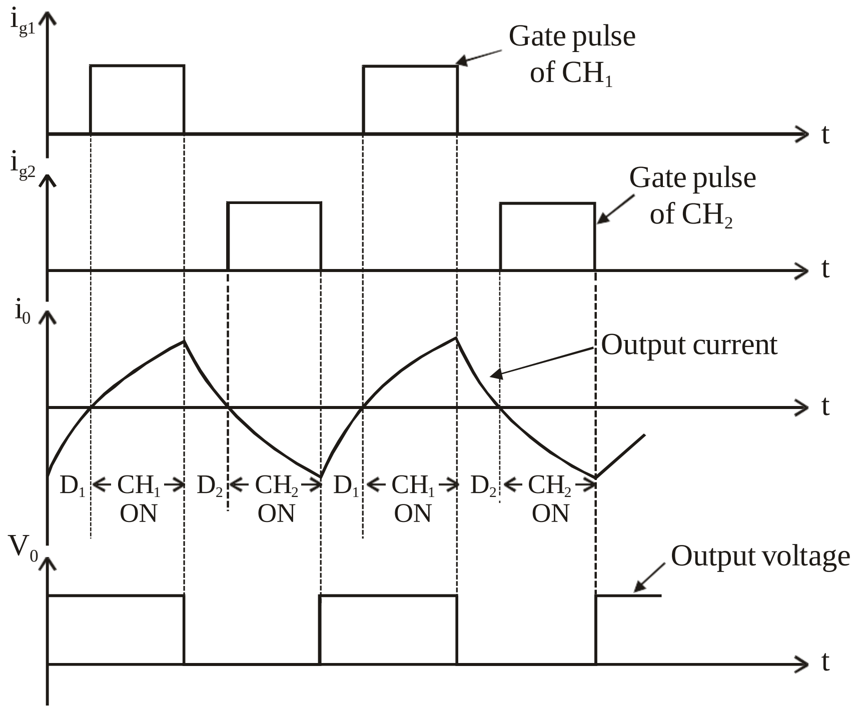
At $t = t_{ON}$ $\quad i_O(t) = I_{min}$

$$\therefore \quad I_{min} = I_{max} e^{-\frac{R}{L}t_{ON}} - \frac{E}{R}\left(1 - e^{-\frac{R}{L}t_{ON}}\right)$$

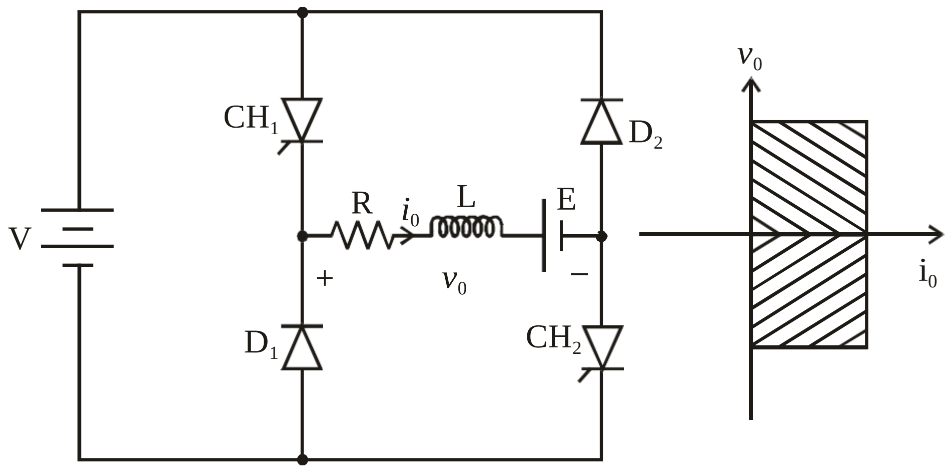
3. Class C Chopper



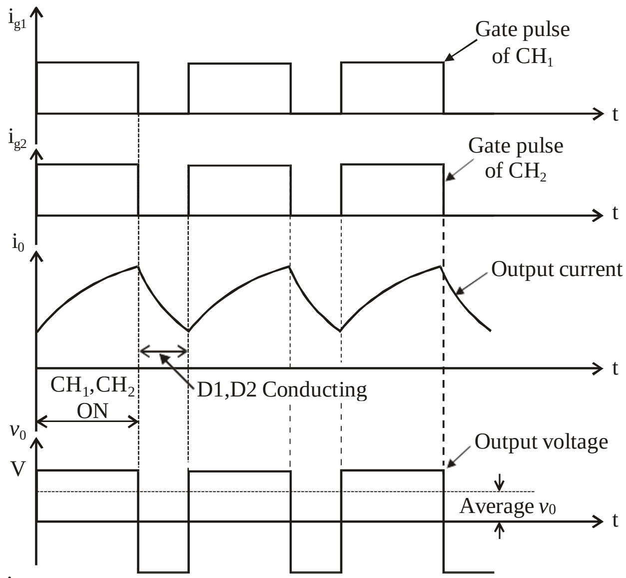
- *Class C Chopper* is a combination of *Class A* and *Class B Choppers*.
- For first quadrant operation, *CH1* is ON or *D2* conducts.
- For second quadrant operation, *CH2* is ON or *D1* conducts.
- When *CH1* is ON, the load current is positive.
- The output voltage is equal to *'V'* & the load receives power from the source.
- When *CH1* is turned OFF, energy stored in inductance *L* forces current to flow through the diode *D2* and the output voltage is zero.
- Current continues to flow in positive direction.
- When *CH2* is triggered, the voltage *E* forces current to flow in opposite direction through L and *CH2* .
- The output voltage is zero.
- On turning OFF *CH2* , the energy stored in the inductance drives current through diode *D1* and the supply
- Output voltage is *V*, the input current becomes negative and power flows from load to source.
- Average output voltage is positive
- Average output current can take both positive and negative values.
- Choppers *CH1 & CH2* should not be turned ON simultaneously as it would result in short circuiting the supply.
- *Class C Chopper* can be used both for dc motor control and regenerative braking of dc motor.
- *Class C Chopper* can be used as a step-up or step-down chopper.

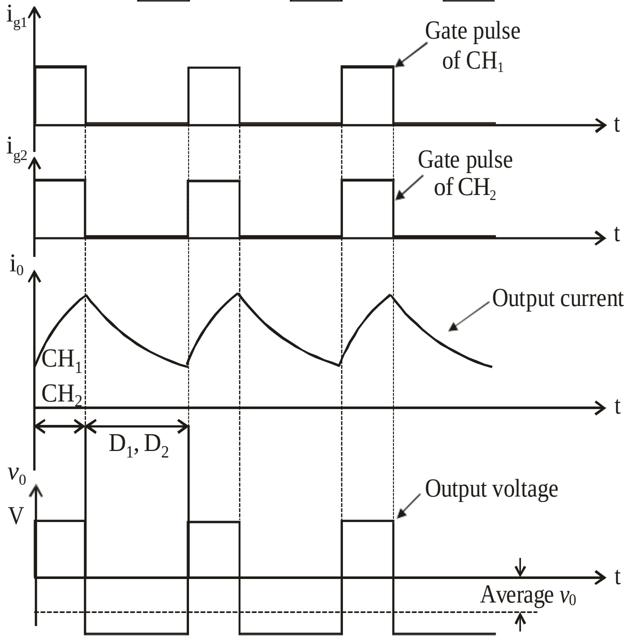


4. Class D Chopper

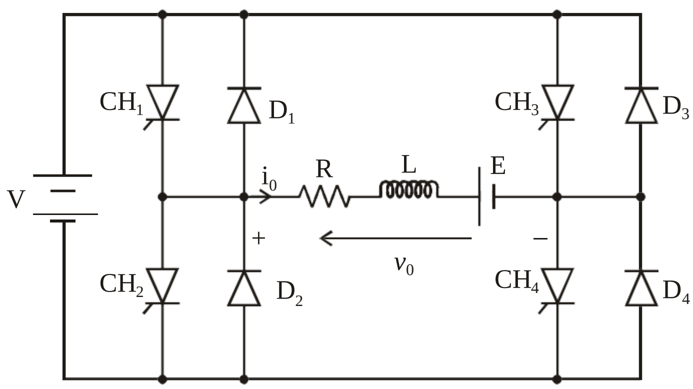


- Class D is a two quadrant chopper.
- When both *CH1* and *CH2* are triggered simultaneously, the output voltage *vO* = *V* and output current flows through the load.
- When *CH1* and *CH2* are turned OFF, the load current continues to flow in the same direction through load, *D1* and *D2* , due to the energy stored in the inductor L.
- Output voltage *vO* = - *V* .
- Average load voltage is positive if chopper ON time is more than the OFF time
- Average output voltage becomes negative if *tON* < *tOFF* .
- Hence the direction of load current is always positive but load voltage can be positive or negative.

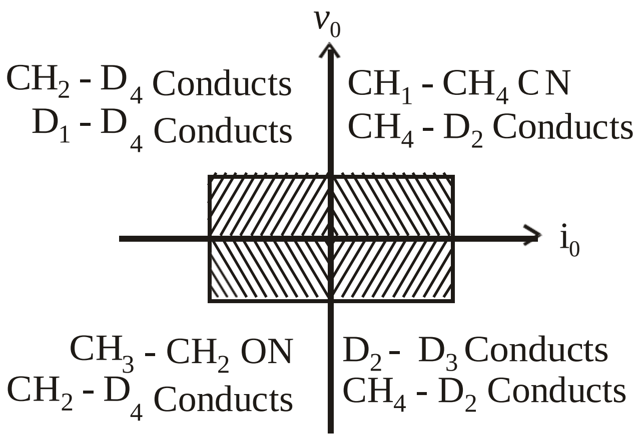




5. Class E Chopper



Four Quadrant Operation



- Class E is a four quadrant chopper
- When *CH1* and *CH4* are triggered, output current i_O flows in positive direction through *CH1* and *CH4*, and with output voltage $v_O = V$.
- This gives the first quadrant operation.
- When both *CH1* and *CH4* are OFF, the energy stored in the inductor L drives i_O through D2 and *D3* in the same direction, but output voltage $v_O = -V$.
- Therefore the chopper operates in the fourth quadrant.
- When *CH2* and *CH3* are triggered, the load current i_O *flows* in opposite direction & output voltage $v_O = -V$.
- Since both i_O and v_O are negative, the chopper operates in third quadrant.
- When both *CH2* and *CH3* are OFF, the load current i_O continues to flow in the same direction *D1* and *D4* and the output voltage $v_O = V$.
- Therefore the chopper operates in second quadrant as v_O is positive but i_O is negative.

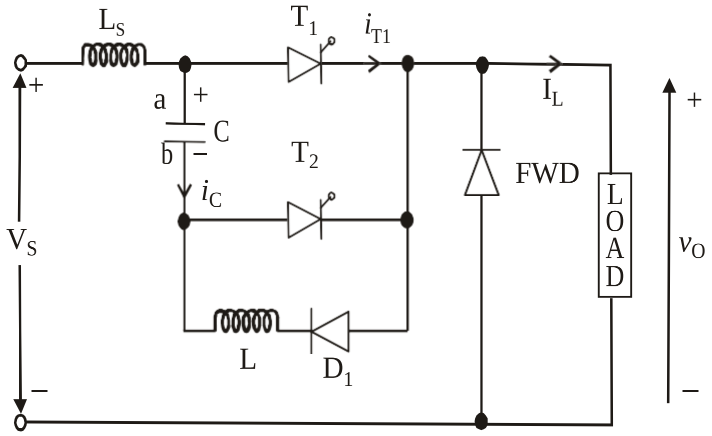
Effect Of Source & Load Inductance

- The source inductance should be as small as possible to limit the transient voltage.
- Also source inductance may cause commutation problem for the chopper.
- Usually an input filter is used to overcome the problem of source inductance.
- The load ripple current is inversely proportional to load inductance and chopping frequency.
- Peak load current depends on load inductance.
- To limit the load ripple current, a smoothing inductor is connected in series with the load.

7. 5 Impulse Commutated Chopper

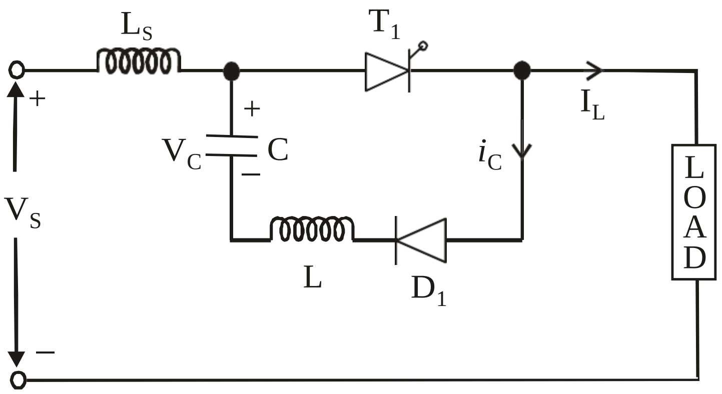
- Impulse commutated choppers are widely used in high power circuits where load fluctuation is not large.
- This chopper is also known as
  - Parallel capacitor turn-off chopper
  - Voltage commutated chopper

– Classical chopper.



- To start the circuit, capacitor *'C'* is initially charged with polarity (with plate 'a' positive) by triggering the thyristor *T2.*
- Capacitor *'C'* gets charged through *VS, C, T2* and load.
- As the charging current decays to zero thyristor *T2* will be turned-off.
- With capacitor charged with plate 'a' positive the circuit is ready for operation.
- Assume that the load current remains constant during the commutation process.
- For convenience the chopper operation is divided into five modes.
    - Mode-1
    - Mode-2
    - Mode-3
    - Mode-4
    - Mode-5

Mode-1 Operation



- Thyristor *T1* is fired at *t = 0.*
- The supply voltage comes across the load.
- Load current *IL* flows through *T1* and load.
- At the same time capacitor discharges through *T1, D1, L1,* & *'C'* and the capacitor reverses its voltage.
- This reverse voltage on capacitor is held constant by diode *D1*.

Capacitor Discharge Current

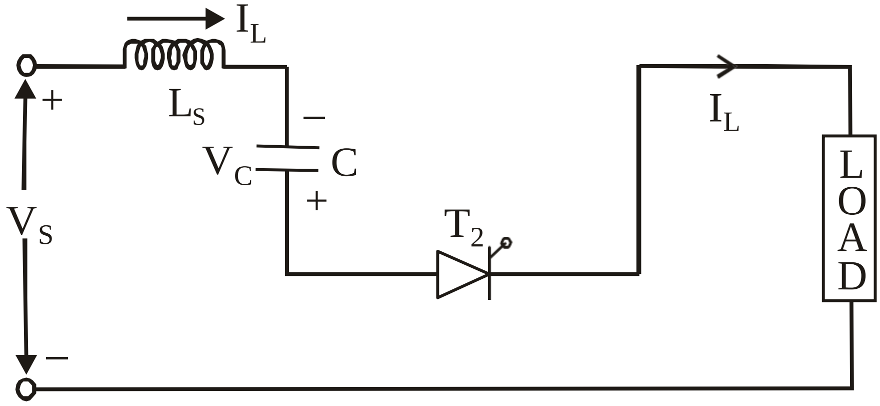
$$i_C(t) = V\sqrt{\frac{C}{L}}\sin \omega t$$

Where $\omega = \frac{1}{\sqrt{LC}}$

& Capacitor Voltage

$$V_C(t) = V\cos\omega t$$

Mode-2 Operation



- Thyristor *T2* is now fired to commutate thyristor *T1*.
- When *T2* is ON capacitor voltage reverse biases *T1* and turns if off.
- The capacitor discharges through the load from $-V$ to *0*.
- Discharge time is known as circuit turn-off time
- Capacitor recharges back to the supply voltage (with plate ‘a’ positive).
- This time is called the recharging time and is given by

Circuit turn-off time is given by

$$t_C = \frac{V_C \times C}{I_L}$$

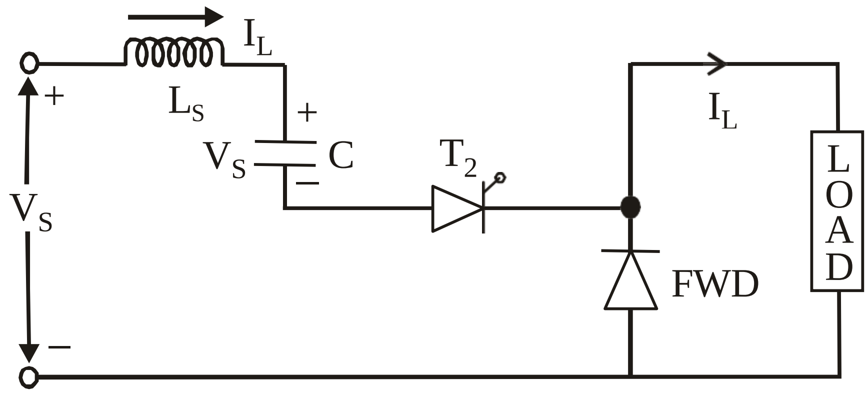
Where I_L is load current.

t_C depends on load current, it must be designed for the worst case condition which occur at the maximum value of load current and minimum value of capacitor voltage.

- The total time required for the capacitor to discharge and recharge is called the commutation time and it is given by

- At the end of Mode-2 capacitor has recharged to V_S *and* the freewheeling diode starts conducting.

Mode-3 Operation



- *FWD* starts conducting and the load current decays.
- The energy stored in source inductance *LS* is transferred to capacitor.
- Hence capacitor charges to a voltage higher than supply voltage, T2 naturally turns off.

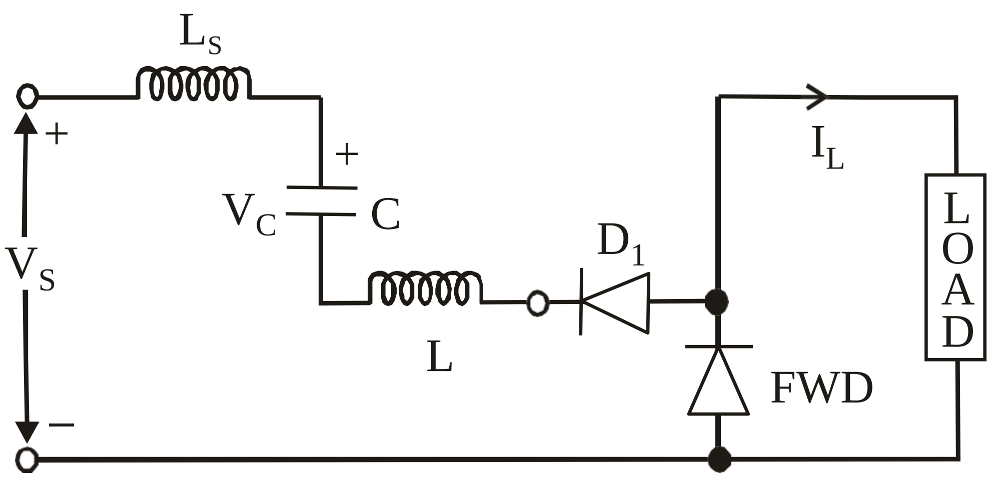
The instantaneous capacitor voltage is

$$V_C(t) = V_S + I_L\sqrt{\frac{L_S}{C}}\sin\omega_S t$$

Where

$$\omega_S = \frac{1}{\sqrt{L_S C}}$$

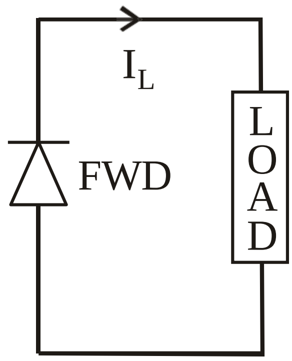
Mode-4 Operation



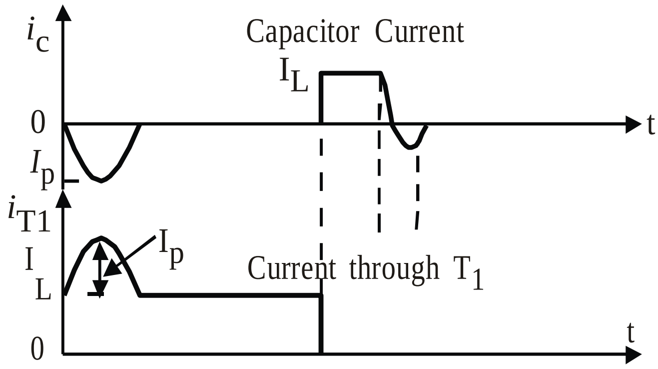
- Capacitor has been overcharged i.e. its voltage is above supply voltage.
- Capacitor starts discharging in reverse direction.
- Hence capacitor current becomes negative.
- The capacitor discharges through *LS, VS, FWD, D1 and L.*

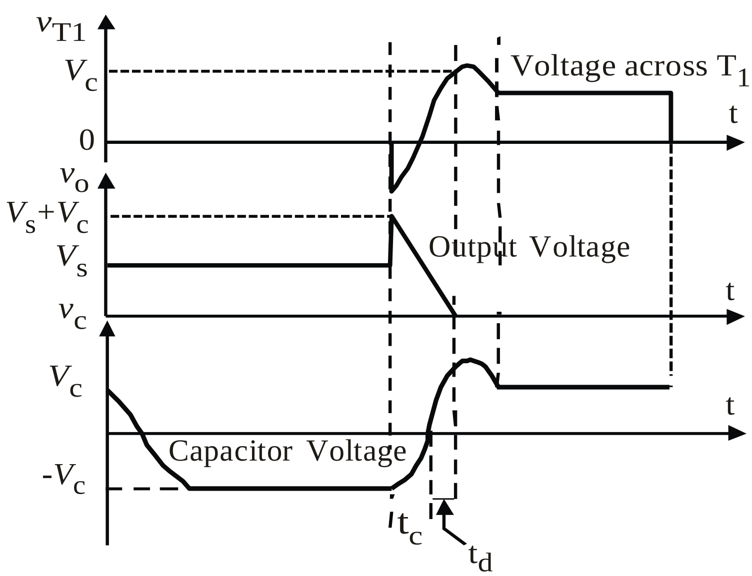
- When this current reduces to zero *D1* will stop conducting and the capacitor voltage will be same as the supply voltage.

Mode-5 Operation



- Both thyristors are off and the load current flows through the FWD.
- This mode will end once thyristor *T1* is fired.





Disadvantages

- A starting circuit is required and the starting circuit should be such that it triggers thyristor *T2* first.
- Load voltage jumps to almost twice the supply voltage when the commutation is initiated.
- The discharging and charging time of commutation capacitor are dependent on the load current and this limits high frequency operation, especially at low load current.
- Chopper cannot be tested without connecting load.

Thyristor *T1* has to carry load current as well as resonant current resulting in increasing its peak current rating.

Recommended questions:

1. Explain the principle of operation of a chopper. Briefly explain time-ratio control and PWM as applied to chopper
2. Explain the working of step down shopper. Determine its performance factors, VA, Vo rms, efficiency and Ri the effective input resistane
3. Explain the working of step done chopper for RLE load. Obtain the expressions for minimum load current I1max load current I2, peak – peak load ripple current di avg value of load current Ia, the rms load current Io and Ri.
4. Give the classification of stem down converters. Explain with the help of circuit diagram one-quadrant and four quadrant converters.
5. The step down chopper has a resistive load of R=10ohm and the input voltage is Vs=220V. When the converter switch remain ON its voltage drop is Vch=2V and the chopping frequency is 1 KHz. If the duty cycle is 50% determine a) the avg output voltage VA, b) the rms output voltage Vo c) the converter efficiency d) the effective input resistance Ri of the converter.
6. Explain the working of step-up chopper. Determine its performance factors.