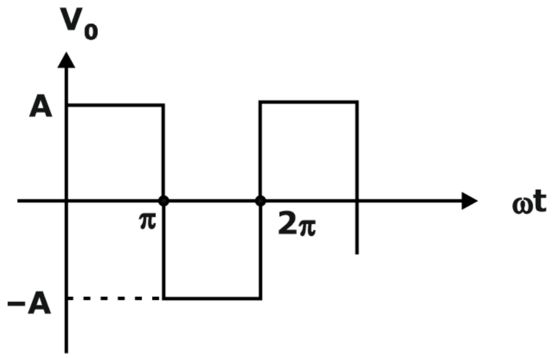
POWER ELECTRONICS FORMULA NOTES

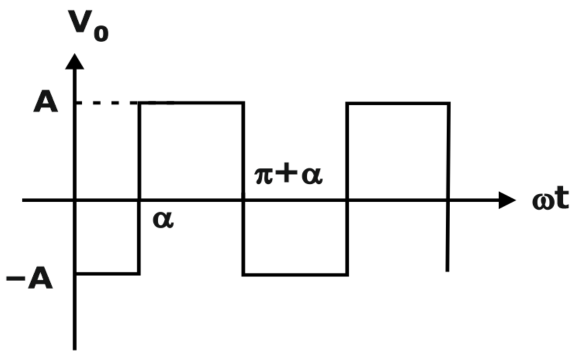
Important Fourier series representations :

1)



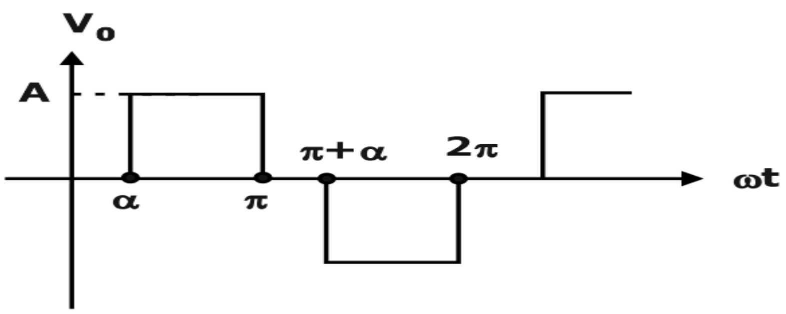
$$V_0 = \sum_{n=1,3,5} \frac{4A}{n\pi} \text{Sin}\, n\omega t$$

2)



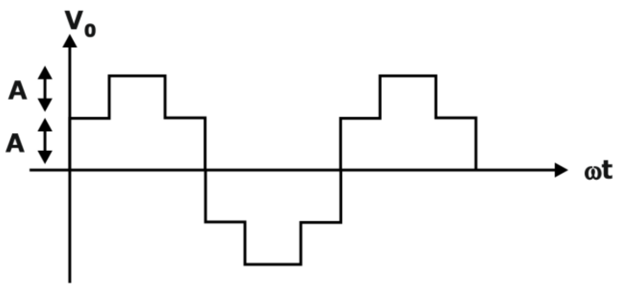
$$V_0 = \sum_{n=1,3,5} \frac{4A}{n\pi} \text{Sin}(n\omega t - n\alpha)$$

3)



$$V_0 = \sum_{n=1,3,5} \frac{4A}{n\pi} \text{Cos}\left(\frac{n\alpha}{2}\right) \text{Sin}(n\omega t - \frac{n\alpha}{2})$$

4)



$$V_0 = \sum_{n=1,5,7} \frac{6A}{n\pi} \text{Sin}\, n\omega t$$

Each pulse width of 60^0 Duration

5) For output of half wave uncontrolled rectifier Fourier series expression is

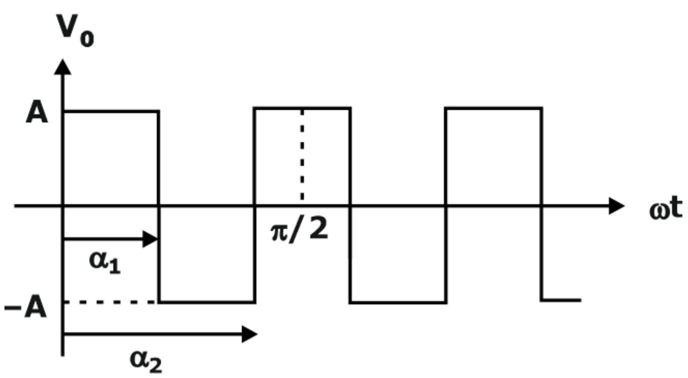
$$V_0 = \frac{A}{\pi} + \frac{A}{2} \text{Sin}\,\omega t + \sum_{n=2,4,6} \frac{2A}{\pi(1-n^2)} \cos n\omega t$$

Where A= Amplitude of signal

6) For output of Full wave uncontrolled rectifier Fourier series expression is

$$V_0 = \frac{2A}{\pi} + (fundamental = 0) + 2 \sum_{n=2,4,6} \frac{2A}{\pi(1-n^2)} \cos n\omega t$$

7)



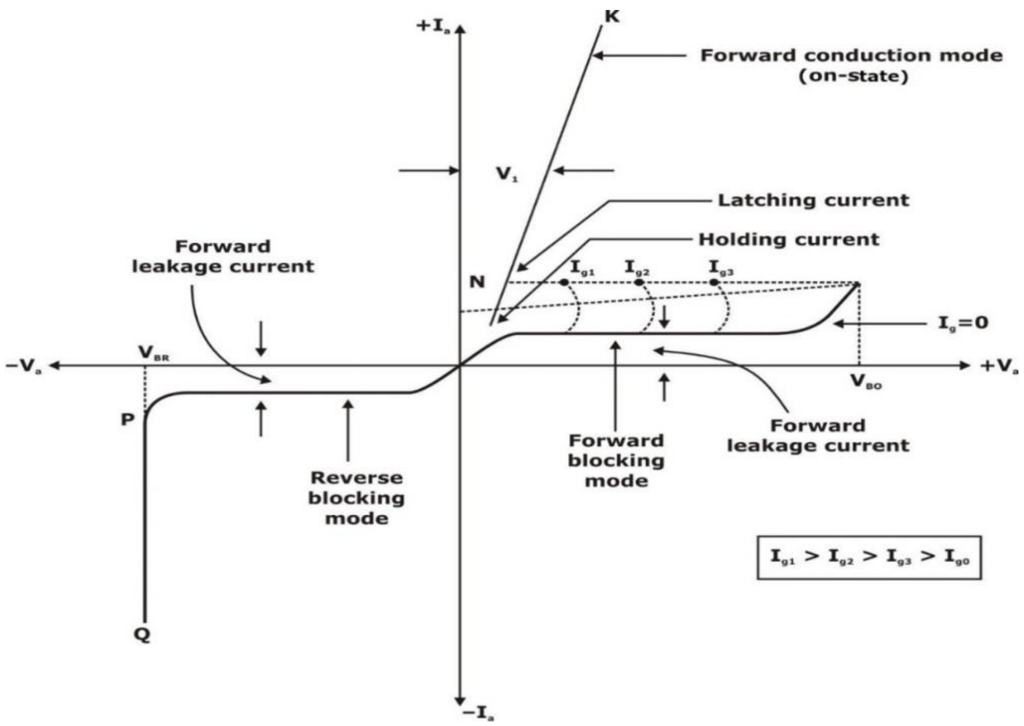
$$V_0 = \frac{4A}{n\pi}\left(1 - 2\cos n\alpha_1 + 2\cos n\alpha_2\right)$$

Diode	BJT/MOSFET/IGBT	SCR and GTO	Triac

• Uncontrolled device • Unipolar and unidirectional	• Fully controlled • Unipolar and unidirectional (Without body diodes)	• SCR-Semi controlled • GTO- Fully controlled • Both are Bipolar and unidirectional	• Semi controlled device • Bipolar and Bidirectional

- Conduction losses in BJT is less than MOSFET.
- Switching time in MOSFET is less than BJT.
- Majority carrier devices: MOSFET and Schottky diode are having Positive Temperature Coefficient property.
- Minority carrier devices: SCR, BJT, GTO, IGBT, Power diode and having Negative Temperature Coefficient property.

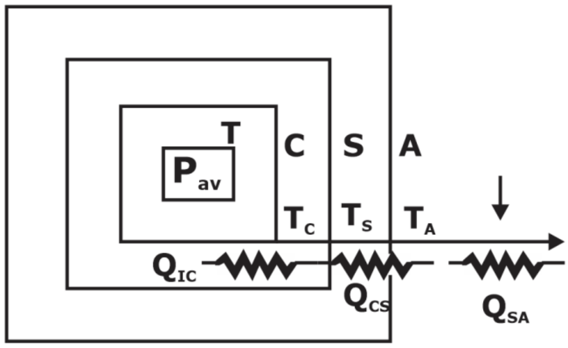
Static V-I characteristics of SCR



- Latching Current: Minimum current required for conduction even after the gate pulse is removed.
- Holding Current: Minimum Current below which SCR is turned off

- Usually Latching current is 1.5 to 3 times of Holding current

Heat Sink Model:



$$P_{avg} = \frac{T_J - T_C}{Q_{JC}} = \frac{T_C - T_S}{Q_{CS}} = \frac{T_S - T_A}{Q_{SA}}$$

Rating of thyristor $\propto \sqrt{P_{avg}}$

Charge stored in depletion region:

Let Q_R be the charge stored in depletion region of power diode.

$$Q_R = \frac{1}{2}.I_{RM}.t_{rr}$$

$$I_{RM} = \frac{2Q_R}{t_{rr}} = t_a.\frac{di}{dt}$$

$$\text{If } t_a \approx t_{rr},\ t_{rr} = \sqrt{\frac{2Q_R}{di/dt}}$$

$$I_{RM} = t_{rr}.\frac{di}{dt} = \sqrt{2Q_R\left(\frac{di}{dt}\right)}$$

$$t_{rr} \propto \sqrt{Q_R}$$

$$Q_R \propto I_f$$

$$t_{rr} \propto \sqrt{I_f}$$

$$I_{RM} \propto \sqrt{I_f}$$

Relation Between α and β:

$$\boxed{\alpha = \frac{I_C}{I_E}} \quad \boxed{\beta = \frac{I_C}{I_B}}$$

$$\frac{I_E}{I_C} = 1 + \frac{I_B}{I_C}$$

$$\frac{1}{\alpha} = 1 + \frac{1}{\beta}$$

$$\boxed{\alpha = \frac{\beta}{\beta+1}} \quad \boxed{\beta = \frac{\alpha}{1+\alpha}}$$

Design of Snubber circuit:

For Inductor (L):

$$\left(\frac{di}{dt}\right)_{max} = \frac{V_s}{L}$$

$$L = \frac{V_s}{(di/dt)_{max}}$$

For resistor (R_s):

$$\left(\frac{dv_a}{dt}\right)_{max} = R_s\left(\frac{di}{dt}\right)_{max}$$

$$\text{or } R_s = \frac{L}{V_s}\left(\frac{dv_a}{dt}\right)_{max}$$

For Capacitor (C_s):

$$C_s = \left(\frac{2\xi}{R_s}\right)^2 L \qquad \text{where } 0.5 < \xi < 1$$

Design of Snubber circuit:

$$\text{String efficiency} = \frac{\text{Actual voltage/current rating of string.}}{n \times \text{individual voltage/current rating of SCR}}$$

Where n is the number of SCR in string.

Derating factor, DRF=1- string efficiency.

Parallel Operation of Thyristors:

When current required by the load is more than the rated current of a single thyristor, SCR's are connected in parallel in a string

Series Operation of Thyristors:

Consider n thyristor connected in series, Let SCR_1 has minimum leakage current I_{bmn}. SCR with lower leakage current blocks more voltage.

Remaining (n-1) SCRs have the same leakage current I_{bmx}

$I_{bmx} > I_{bmn}$

$$\boxed{R_s = \frac{nV_{bm} - V_s}{(n-1)\Delta I_b}}$$

Here V_{bm} is the maximum permissible blocking voltage as SCR1.

R_s is the static equalizing resistance

Similarly Static equalizing capacitance $C = \dfrac{(n-1)\Delta Q_T}{nV_{bm} - V_s}$

ΔQ_T = difference in recovery charge

Ratings of Thyristors:

1)I_{Trms} Rating: The actual Thyristor rms in a converter must always be less than thyristor RMS ratings.

$[(I_T]_{rms}$ value in a converter] < $(I_f)_{rms}$ rating.

2)(I_{Tavg}) Rating: (average on-state current ratings)

(I_{Tavg}) rating = $\dfrac{(I_T)_{rms} \text{ Rating}}{\text{Form Factor of thyristor current waveform}}$

Average rating of a thyristor depends on:

- Conduction angle of thyristor increases which decrease the form factor and then increase the average thyristor rating.
- Type of load: Smoothness of thyristor current waveform increase the FF decreases and therefore $(I_{Tavg})_{Rating}$ increases.
- Type of converter: because FF of thyristor waveform depends on average value of converter.

11.3. I^2t Rating of thyristor: specified to select a proper fuse for overcurrent protection.

I^2t current Rating of thyristor > I^2t current Rating of Fuse.

11.4. Surge current rating of thyristor:

General values

$(I_T)_{rms}$ = 35A

$(I_S)_{rms}$ = 2000A for one cycle and 3000A for 2MW

N-cycle surge current rating: (I_m): It is the surge current that the SCR can withstand for n-cycles.

$(I_{Sn})^2\left(\dfrac{nT}{2}\right) = I^2t$ rating of thy   from the equation, we can find the value of 'I_{sn}'

One-cycle surge current rating (Is): It is the surge current that the SCR can withstand for a cycle. $I_{s1}^2 = (I_{sn})^2$ $I_{S_1} = \sqrt{n}\, I_{sn}$

Sub-cycle surge current rating: It is the surge current that the SCR can withstand for 1/nth period of a cycle. $(I_{s/n})^2 = (I_{sn})^2$ $\dfrac{I_s}{n} = \sqrt{n}\, I_{s1}$

RECTIFIERS

- For n-pulse converter:

  Source current has $nk \pm 1$ Harmonics k=1,2,3……..

  Output voltage has nk Harmonics.

Single Phase Half Wave controlled rectifier:

R-load:

Average output voltage $V_{o,avg} = \dfrac{V_m}{2\pi}(1+\cos\alpha)$

RMS output voltage $V_{o,rms} = \sqrt{\frac{V_m^2}{4\pi}\left((\pi-\alpha)+\frac{\sin 2\alpha}{2}\right)}$

RL-Load:

Average output voltage $V_{o,avg} = \frac{V_m}{2\pi}(\cos\alpha - \cos\beta)$

RMS output voltage $V_{o,avg} = \frac{V_m}{2\sqrt{\pi}}\left(\sqrt{(\beta-\alpha)+\frac{1}{2}(\sin 2\alpha - \sin 2\beta}\right)$

Circuit Turnoff time: $t_c = \frac{2\pi-\beta}{\omega}$

For a constant output current refer below table:

	1-ϕ Full conv.	3ϕ Full conv.	1ϕ Semi conv.	3ϕ semi conv
Output voltage	$\frac{2V_m}{\pi}\cos\alpha$	$\frac{3V_{m,line}}{\pi}\cos\alpha$	$\frac{V_m}{\pi}(1+\cos\alpha)$	$\frac{3V_{m,line}}{2\pi}(1+\cos\alpha)$
Fundamental source current RMS(I_{s1})	$\frac{2\sqrt{2}}{\pi}I_0$	$\frac{\sqrt{6}}{\pi}I_0$	$\frac{2\sqrt{2}}{\pi}I_0\cos\left(\frac{\alpha}{2}\right)$	$\frac{\sqrt{6}}{\pi}I_0\cos\left(\frac{\alpha}{2}\right)$
Source current RMS(I_s)	I_0	$\sqrt{\frac{2}{3}}I_0$	$I_0\sqrt{\frac{\pi-\alpha}{\pi}}$	$\alpha \le 60^0 \rightarrow I_0\sqrt{\frac{2}{3}}$ $\alpha > 60^0 \rightarrow I_0\sqrt{\frac{\pi-\alpha}{\pi}}$
Displacement power factor(DPF)	$\cos\alpha$	$\cos\alpha$	$\cos\left(\frac{\alpha}{2}\right)$	$\cos\left(\frac{\alpha}{2}\right)$

- Distortion factor(DF) = $\frac{I_{s1}}{I_s}$
- Input power Factor= DF*DPF
- Total Harmonic distortion = $\sqrt{\left(\frac{1}{DF}\right)^2 - 1}$

For R-Load refer below table:

	3ϕ Half wave rectifier	3ϕ full wave rectifier

Continuous	$\alpha < 30^0$ $\frac{3V_{m,line}}{2\pi}\text{Cos}\,\alpha$ **Hint:** Integrate from 30+ α to 150+ α and Time period T=120^0 and function take in phase, You will get above formula Like this $\frac{1}{\left(\frac{2\pi}{3}\right)}\int_{30+\alpha}^{150+\alpha} V_{m,phase}\,\text{Sin}\,\omega t\, dwt$	$\alpha < 60^0$ $\frac{3V_{m,line}}{\pi}\cos\alpha$ **Hint:** Integrate from 60+ α to 120+ α and Time period T=60^0 and function take in line, You will get above formula
Discontinuous	$\alpha \ge 30^0$ $V_0 = \frac{3V_{m,phase}}{2\pi}\left(1+\cos\left(\alpha+\frac{\pi}{6}\right)\right)$ **Hint:** Integrate from 30+ α to 180^0 and Time period T=120^0 and function take in phase, You will get above formula	$\alpha \ge 60^0$ $V_0 = \frac{3V_{m,line}}{\pi}\left(1+\cos\left(\alpha+\frac{\pi}{3}\right)\right)$ **Hint:** Integrate from 60+ α to 180^0 and Time period T=60^0 and function take in line, You will get above formula

Effect of Source Inductance:

- **1** ϕ Half wave:

$$V_0 = \frac{V_m}{2\pi}(1+\cos\alpha) - fL_s I_0$$

$$I_0 = \frac{V_m}{\omega L_S}(\cos\alpha - \cos(\alpha+\mu))$$

- **1** ϕ Full wave:

$$V_0 = \frac{2V_m}{\pi}\cos\alpha - 4fL_s I_0$$

$$I_0 = \frac{V_m}{2\omega L_S}(\cos\alpha - \cos(\alpha+\mu))$$

Regulation $= \dfrac{\cos\alpha - \cos(\alpha+\mu)}{2\cos\alpha}$

Displacement power factor: $\cos\left(\alpha+\frac{\mu}{2}\right)$

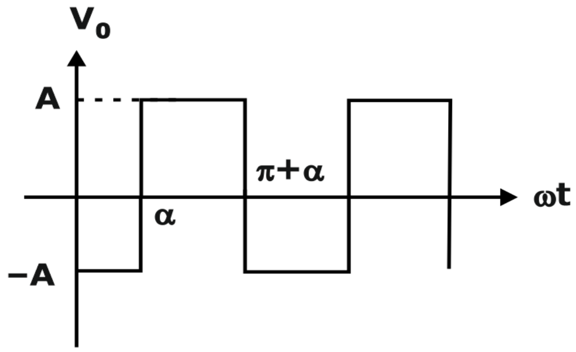
- 3ϕ Full Wave:

$$V_0=\frac{3V_{m,line}}{\pi}\cos\alpha-6fL_sI_0$$

$$I_0=\frac{V_{m,line}}{2\omega L_S}\left(\cos\alpha-\cos(\alpha+\mu)\right)$$

Single Phase Full converter:

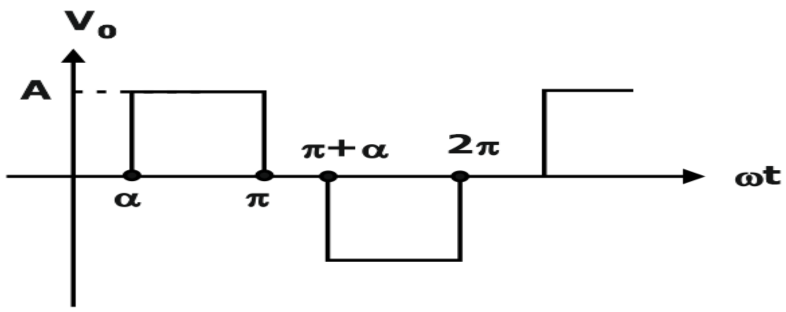
Source current waveform:



Fundamental source current is $i_{s1}=\frac{2\sqrt{2}}{\pi}I_0$

Single phase half controlled or Semi converter:

Source current waveform:



- In this there are two configurations:

Symmetrical configuration: On one leg one thyristor and one diode

Unsymmetrical configuration: on one leg two thyristors or two diodes

$\gamma = represents\ conduction$ in below table

D- Diode, T-Thyristor, α -Firing angle

Symmetrical configuration	Unsymmetrical configuration	Full converter with Freewheeling diode

$\gamma_T = \pi$ $\gamma_D = \pi$	$\gamma_T = \pi - \alpha$ $\gamma_D = \pi + \alpha$	$\gamma_T = \pi - \alpha$ $\gamma_D = 2\alpha$

3-Phase:

Phase Voltage reference:

$$V_{an} = V\angle 0$$
$$V_{bn} = V\angle -120$$
$$V_{cn} = V\angle +120$$

Line Voltage reference

$$V_{AB} = V\angle 0$$
$$V_{BC} = V\angle -120$$
$$V_{CA} = V\angle +120$$

3Phase half wave controlled Rectifiers:

- Take phase voltage reference in the integration function for the below mentioned limits for calculations
- For R-Load $\alpha < 30^0$

  $\alpha < 30^0$: Continuous conduction: 30+ α to 150+ α

  $\alpha \geq 30^0$: Discontinuous conduction: 30+ α to 180^0
- For current stiff load:

  Without Freewheeling diode: 30+ α to 150+ α

  With Freewheeling diode: $\alpha < 30^0$:30+ α to 150+ α

  $\alpha \geq 30^0$: 30+ α to 180^0

✓ Mentioned limits are useful while calculating output voltage average or RMS values for those particular conditions. Use phase as reference while doing calculations of average and RMS

3Phase Full wave controlled Rectifiers:

- Take Line voltage reference in the integration function for the below mentioned limits for calculations
- Limits are 60+ α to 120+ α for calculating output voltage average or RMS values
- Circuit Turnoff time:

$$\alpha \leq 60^0, t_c = \frac{240^0 - \alpha}{\omega}$$

$$\alpha > 60^0, t_c = \frac{180^0 - \alpha}{\omega}$$

3Phase Semi converter:

- $\alpha < 60^0$ it is 6 Pulse converter

  $\alpha \geq 60^0$ it is 3 Pulse converter
- Freewheeling Action Duration:

$\alpha < 60^0$, Duration = zero (No freewheeling action)

$\alpha \geq 60^0$, Duration= $3\left(\alpha - \frac{\pi}{3}\right)$

➢ Limits for calculating output voltage average or RMS values(Line voltages are reference)

$\alpha < 60^0:\ 60^0 + \alpha\ to\ 120^0 \rightarrow V_{AB}\ reference$

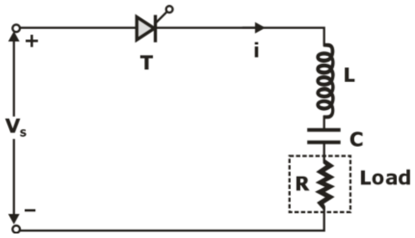
$:\ 120^0\ to\ 180^0 + \alpha \rightarrow V_{AC}\ reference$

$\alpha \geq 60^0:\ 60^0 + \alpha\ to\ 240^0 \rightarrow V_{AC}\ reference$

.

Commentation Techniques

1) Class A Commutation (Load Commutation/self-commutation)



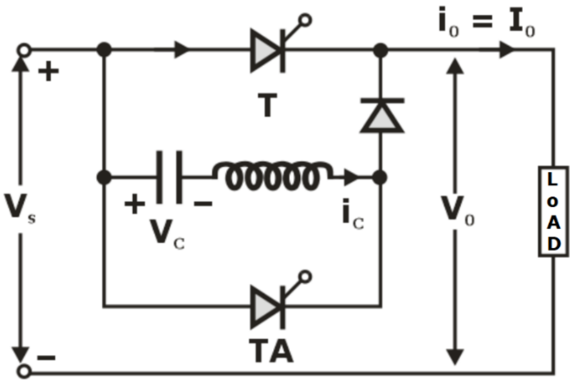
- For successful Load commutation, circuit must be under damped
- For under damped $I = I_p e^{-\alpha t} \text{Sin}\,\omega_r t$

$$I_p = \frac{V_s}{\omega_r L}, \alpha = Dampingfactor = \frac{R}{2L},\ \omega_r^2 = \omega_0^2 - \alpha^2$$

ω_r is ringing frequency, $\omega_0 = Naturalfrequency = \frac{1}{\sqrt{LC}}$

- Conduction time of thyristor, $t_c = \frac{\pi}{\omega_r}$

2) Class B Commutation/Current Commutation/Resonant pulse commutation:



- Voltage across capacitor $V_c = V_s \cos \omega_0 t$
- Circuit turn-off time for the main thyristor (T_1); $tc = C\frac{V_{ab}}{I_0}$

$$V_{ab} = V_s \cos \omega_0 (t_3 - t_2)$$

Where t_3 = time when the main thyristor is turned off

t_2= time when auxiliary thyristor is turned off

$$\omega_0 (t_3 - t_2) = \sin^{-1}\left(\frac{I_0}{I_p}\right)$$

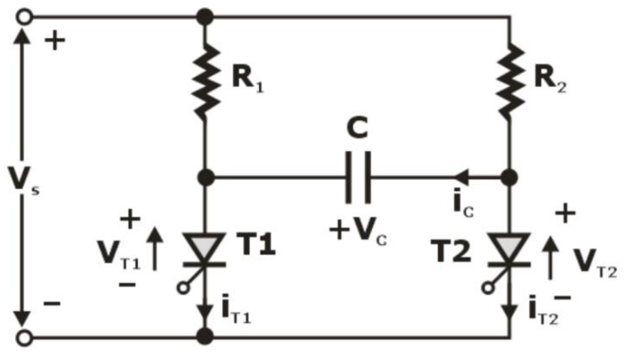
- Main thyristor peak current $=I_0$
- Auxiliary Thyristor peak current= $V_s\sqrt{\frac{C}{L}}$
- Conduction time of auxiliary thyristor= $\pi\sqrt{LC}$
- Conduction time of main thyristor = $\pi\sqrt{LC} + \sqrt{LC}\sin^{-1}\left(\frac{I_0}{I_p}\right)$

Minimum Conduction time of main thyristor= $\pi\sqrt{LC}$

Maximum Conduction time of main thyristor = $\frac{3}{2}\pi\sqrt{LC}$

- Time for which capacitor current exists = $\frac{C}{I_0}(V_{ab} + V_s)$

Class C Commutation (Impulse/Complementary commutation):



When T_1 is turned on at t=0

- The charging current $I_s = \frac{V_s}{R_z}.e^{-t/R_2 C}$
- Voltage across capacitor

$V_c(t) = V_s(1 - e^{-t/R_2 C})$

When T_1 is to be turned-off, T_2 is turned-on at T_1

- The charging current $I_c(t) = -\frac{2V_S}{R_1}.e^{-t/R_1 C}$
- The Voltage across capacitor

$V_c(t) = V_s[2e^{-t/R_1C} - 1]$

- Maximum current though thyristor T_1

$$I_{T_1(max)} = V_s\left[\frac{1}{R_1} + \frac{2}{R_2}\right]$$

- Maximum current though thyristor T_2,

$$I_{T_2(max)} = V_s\left[\frac{2}{R_1} + \frac{1}{R_2}\right]$$

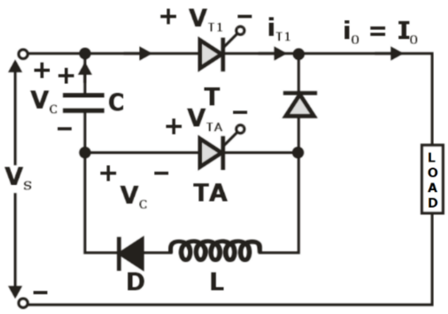
Circuit turn-off time t_{c_1} for thyristor T_1

$t_{c_1} = R_1C\ln(2)$

Circuit turn-off time t_{c_2} for thyristor T_2

$t_{c_2} = R_2C\ln(2)$

Class D Commutation (Voltage commutation):



- Maximum thyristor current Peak= $I_0 + V_s\sqrt{\frac{C}{L}}$
- Auxiliary Thyristor peak current= I_0
- Capacitor peak current = $V_s\sqrt{\frac{C}{L}}$
- Circuit turn-off time for main thyristor T_1 is $t_c = C\frac{V_s}{I_0}$

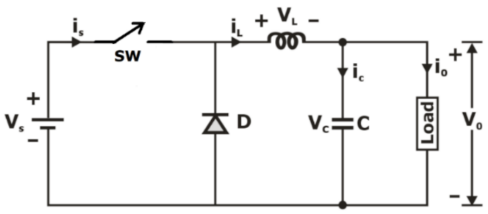
For R-load it t_c= RC ln2

- Circuit turn-off time for main thyristor (TA)

$$t_{c_1} = \frac{\pi}{2\omega_0}$$

DC-DC Converters

Buck Converter:



In Buck regulator, the average output voltage V_0 is less than the input voltage V_S.

$$\Delta I = \frac{(V_S - V_0)T_{ON}}{L}$$

$$\Delta I = \frac{V_0 T_{OFF}}{L}$$

$$V_0 = V_S \frac{T_{ON}}{T} = V_S \alpha$$

Where $\Delta I = I_2 - I_1$ is the peak to peak current ripple of the inductor L.

The peak to peak ripple current is $\Delta I = \frac{V_S \alpha (1-\alpha)}{fL}$

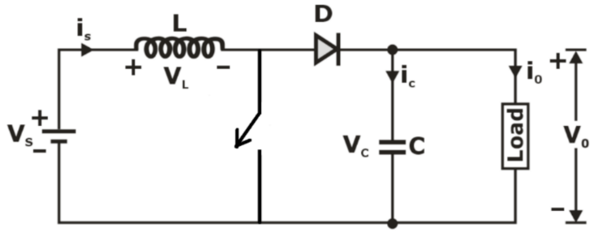
The peak to ripple voltage of the capacitor is $\Delta V_C = \frac{V_S \alpha (1-\alpha)}{8LCf^2}$

Condition for continuous inductor current and capacitor voltage:

If I_L is average inductor current, the inductor ripple current $\Delta I = 2I_L$, which gives the critical value of the inductor L_C as $L_C = L = \frac{(1-\alpha)R}{2f}$

If V_C is the average capacitor voltage, the capacitor ripple voltage $\Delta V_C = 2V_0$, which gives the critical value of capacitor C_C as $C_C = C = \frac{1-\alpha}{16Lf^2}$

Boost Converter:



$$\Delta I = \frac{V_S T_{ON}}{L} = \frac{(V_0 - V_S) T_{OFF}}{L}$$

where $\Delta I = I_2 - I_1$ is peak to peak ripple current of the inductor L.

The average output voltage,

$$V_0 = V_S \frac{T}{T_{OFF}} = \left(\frac{1}{1-\alpha}\right) V_S$$

The peak to peak current ripple is, $\Delta I = \frac{V_S \alpha}{fL}$

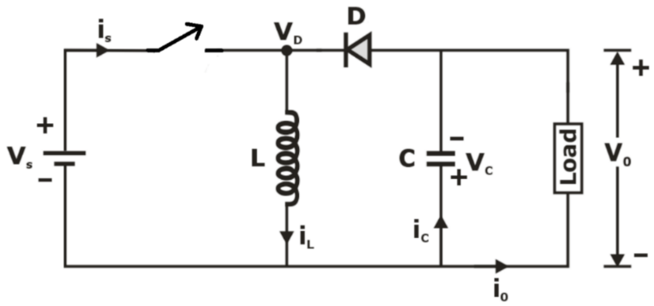
The peak to peak ripple voltage of capacitor, $\Delta V_C = \frac{I_0 \alpha}{fC}$

Condition of continuous inductor current and capacitor voltage:

If V_C is the average capacitor voltage, the capacitor ripple voltage $\Delta V_C = 2V_0$, which gives the critical value of the capacitor C_C as $C_C = \frac{\alpha}{2fR}$

If I_L is average inductor current, the inductor ripple current $\Delta I = 2I_L$, which gives the critical value of the inductor L_C as $L_C = L = \frac{\alpha (1-\alpha)^2 R}{2f}$

Buck Boost Converter:



$$\Delta I = \frac{V_S T_{ON}}{L} = \frac{-V_0 T_{OFF}}{L}$$

where $\Delta I = I_2 - I_1$ is the peak to peak ripple current of inductor L.

The average output voltage is, $V_0 = -\frac{V_S \alpha}{1-\alpha}$

The peak to peak current ripple is, $\Delta I = \frac{V_S \alpha}{fL}$

peak to peak ripple voltage of the capacitor is, $\Delta V_C = \frac{I_0 \alpha}{fC}$

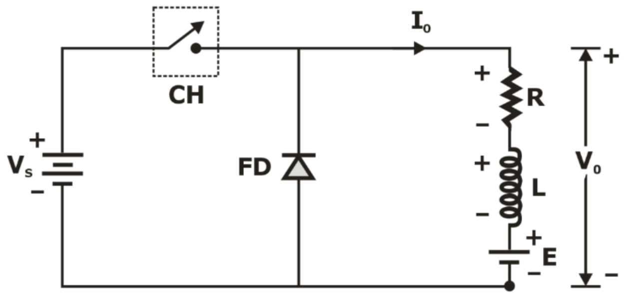
Condition of continuous inductor current and capacitor voltage:

If V_C is the average capacitor voltage, the capacitor ripple voltage, $\Delta V_C = 2V_0$, which gives the critical value of the capacitor C_C as $C_C = \frac{\alpha}{2fR}$.

If I_L is average inductor current, the inductor ripple current $\Delta I = 2I_L$, which gives the critical value of the inductor L_C as $L_C = L = \frac{(1-\alpha)^2 R}{2f}$

Expression for V_0	BUCK	BOOST	BUCK BOOST
In CCM	$V_0 = \alpha V_s$	$V_0 = \frac{V_s}{1-\alpha}$	$V_0 = -\frac{\alpha V_s}{1-\alpha}$
In DCM	$V_0 = \frac{\alpha}{\beta} V_s$	$V_0 = \frac{\beta V_s}{\beta - \alpha}$	$V_0 = -\frac{\alpha V_s}{\beta - \alpha}$

Steady State analysis of Type A Chopper:



Average output voltage

$$V_0 = \alpha V_s$$

$V_{or} = \sqrt{\alpha}\, V_S$ (Rms value of output voltage)

$$I_{max} = \frac{V_S}{R}\left[\frac{1 - e^{-T_{on}/T_a}}{1 - e^{-T/T_a}}\right] - \frac{E}{R}$$

$$I_{min} = \frac{V_S}{R}\left[\frac{e^{T_{on}/T_a} - 1}{e^{T/Ta} - 1}\right] - \frac{E}{R}$$

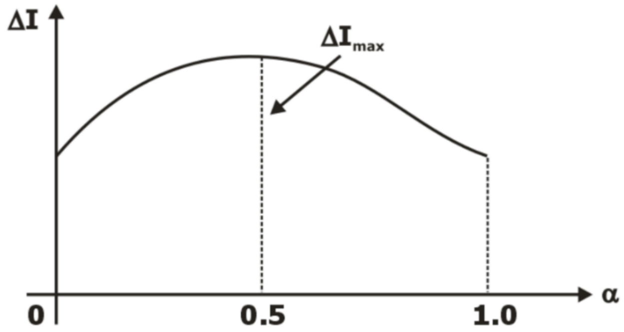
Where, T_a = load time constant

$$T_a = \frac{L}{R}$$

Current ripple,

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

$$\Delta I = \frac{V_S}{R}\left[\frac{\left(1-e^{-T_{on}/T_a}\right)\left(1-e^{-T_{off}/T_a}\right)}{\left(1-e^{-T/T_a}\right)}\right]$$



$T_{on} = \alpha T$

$T_{off} = (1 -) \alpha T$

Per unit ripple (or) Ripple is a function of duty cycle 'α'. Ripple is minimum at α = 0, increases maximum at α = 0.5 and decrease at α = 1.0. For α = 0.5, ripple would be maximum.

$$(\Delta I)_{max} = \frac{V_S}{R}\left(\frac{\left(1-e^{-0.5x}\right)\left(1-e^{-0.5x}\right)}{1-e^{-x}}\right) \qquad \left(\text{Let, } \frac{T}{T_a} = x\right)$$

$$(\Delta I)_{max} = \frac{V_S}{R}\tanh\left(\frac{R}{4fL}\right)$$

Inverters

Series Inverters: In a series inverter, the commutating elements L and C are connected in series with the load resistance R. The load resistance R can also be in parallel with C. The value of L and C are such that those form an underdamped circuit i.e.

$$R^2 < \frac{4L}{C}$$

$f = \left[\frac{1}{2\left(\frac{T}{2} + T_{off}\right)}\right]$ is the frequency of output voltage.

Where, $\frac{T}{2}$ is the time period of oscillations.

T_{off} is the time gap between turn-off one thyristor and turn-on of the second thyristor.

$$\frac{T}{2} = \frac{\pi}{\sqrt{\left(\frac{1}{LC} - \frac{R^2}{4L^2}\right)}}$$

The period of oscillation

Bridge Inverter: Bridge circuits are commonly used in DC-AC conversion. Moreover, an output transformer is not essential in a bridge circuit.

1φ Half Bridge Inverter - The output voltage volt $V_0 = \sum_{n-1,3,5...}^{\infty} \frac{2V_s}{n\pi} \sin n\omega t$

1φ Full Bridge Inverter- The output voltage

$$V_0 = \sum_{n-1,3,5,...}^{\infty} \frac{4V_s}{n\pi} \sin n\omega t$$

Where, n = order of harmonic

ω=2πf, is frequency of the output voltage in red/sec

Key points:

- The load impedance (Z_n) is

$$Z_n = \left[R^{2+}\left(n\omega L - \frac{1}{n\omega C}\right)^2\right]^{1/2}$$

- Phase angle, $\phi_n = \tan^{-1}\frac{\left[n\omega L - \frac{1}{n\omega C}\right]}{R}$

3phase Full Bridge VSI:

	180^0 Conduction	120^0 Conduction
Line Voltage RMS	$V_s\sqrt{\frac{2}{3}}$	$V_s\frac{1}{\sqrt{2}}$
Phase voltage RMS	$V_s\frac{\sqrt{2}}{3}$	$V_s\frac{1}{\sqrt{6}}$
Fundamental line voltage RMS	$V_s\frac{\sqrt{6}}{\pi}$	$V_s\frac{3}{\pi\sqrt{2}}$
Fundamental phase voltage RMS	$V_s\frac{\sqrt{2}}{\pi}$	$V_s\frac{1}{\pi}\sqrt{\frac{3}{2}}$

180^0 Conduction:

1) Pole Voltages = $V_{A0} = \sum_{n-1,3,5...}^{\infty} \frac{2V_s}{n\pi} \sin n\omega t$

2) Line Voltages = $\sum_{n=1,3,5}\left(\frac{4V_s}{n\pi}\cos\left(n\frac{\pi}{6}\right)\right)\sin(n(\omega t+30^0))$

When n=3, 9, 15 Line voltage= 0, So Line voltages are free from Triplet harmonics

3) Phase Voltage= $\sum_{n=6k\pm1}\frac{2V_{dc}}{n\pi}\sin n\omega t$

$n = 6k \pm 1$ is due to stepped waveform

120⁰ Conduction:

1) Pole and Phase Voltage are of same waveform

2) Triplet harmonics are absent in Phase and pole voltages

3) Line voltage contains $n = 6k \pm 1$ Harmonics

Pulse Width Modulation:

- Let N= number of pulses per half cycle

  Each pulse width = $\frac{2d}{N}$

  Then Output voltage Expression is

$$V_0 = \sum_{n=1,3,5}\left(N\frac{4V_s}{n\pi}\sin n\gamma \sin\frac{nd}{N}\right)\sin n\omega t$$

  Where $\gamma = \frac{\pi-2d}{N+1}+\frac{d}{N}$

- Number of pulses per half cycle $N = \frac{f_c}{2f}$

  f = reference input frequency

  f_c = Carrier input frequency

- Modulation Index m_a= $\frac{V_{Ref}}{V_{carrier}}$

- Relation between Pulse width and modulation index

$$\frac{2d}{N} = \frac{\pi}{N}(1-m_a)$$

Amplitude Modulation Depth:

$$m_0 = \frac{\hat{V}_m}{\hat{V}_c}$$

Where V_m, V_c are the modulating and carrier signal voltage, respectively.

For sinusoidal PWM, the amplitude modulation depth must be less than 1.0

Output Voltages by Sinusoidal PWM:

- In single phase half bridge VSI

  Fundamental peak pole voltage $= \hat{V}_{Ao1} = m_a \frac{V_s}{2}$

- In single phase Full bridge VSI

  Fundamental peak pole voltage $= \hat{V}_{Ao1} = m_a V_s$

- In Three phase Full bridge VSI

  Peak Fundamental Phase voltage $\hat{V}_{an1} = m_a \frac{V_{DC}}{2}$

  The fundamental line-line rms voltage is given by

$$V_{LLO_1} = \frac{\sqrt{3}}{2\sqrt{2}} m_a V_{DC}$$

- If peak value of carrier input and zero crossing of reference sinusoidal coincidence then, Number of Pulses per half cycle will be $N = \frac{f_c}{2f}$
- If Zero Crossing of carrier input and reference sinusoidal coincidence then, Number of Pulses per half cycle will be $N = \frac{f_c}{2f} - 1$
- If N is the number of pulses per half cycle then the predominant harmonics in the output is $2N \pm 1$

***