Power Electronics

Published By:

Physics Wallah

ISBN: 978-93-94342-39-2

Mobile App: Physics Wallah (Available on Play Store)

Website: www.pw.live

Email: support@pw.live

POWER ELECTRONICS

INDEX

1 Power Semiconductor Devices

Power semiconductor devices are electronic devices made of semiconductor material but rating of these devices are high.

1.1. Classification of Devices

- Uncontrolled devices (BJT, DIAC etc)
- Semicontrolled devices (SCR)
- Fully controlled devices. (BJT, MOSFET, IGBT, GTO, etc.)

- Unidirectional devices (Diode, BJT, IGBT, SCR, GTO etc)
- Bidirectional devices (MOSFET, RCT, DIAC, TRIAC etc)

- Unipolar directional devices (Schottky diode, MOSFET etc)
- Bipolar devices (BJT, IGBT, Diode, SCR, GTO, DIAC, TRIAC etc)

- Unipolar voltage blocking (Diode, BJT, MOSFET, RCT etc)
- Bipolar voltage blocking (IGBT, SCR, TRIAC, GTO etc)

- Continuous singal devices (BJT, MOSFET, IGBT etc)
- Latching devices (SCR, GTO, TRIAC etc)

1.1.1. Semiconductor Devices as a Switch

Power semiconductor devices may work as a static switches. It has two stable state

(1) ON state (conduction)

(2) OFF state (Blocking)

Switch can operate in 4 mode of operation.

(1) Forward conduction mode :

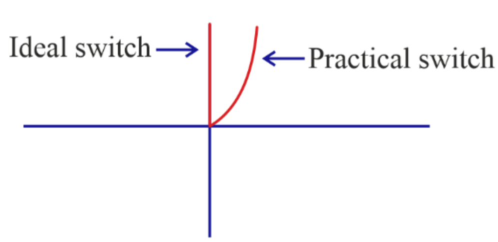


Fig. 1.1

(2) Forward blocking mode :

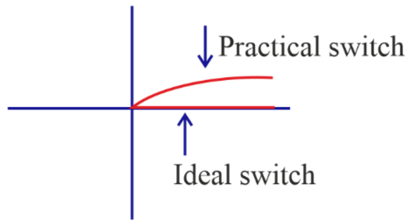


Fig. 1.2

(3) Reverse conducting mode :

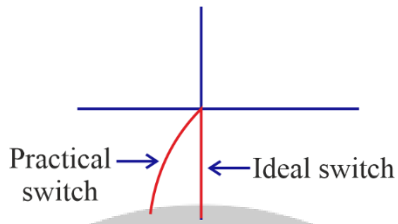


Fig. 1.3

(4) Reverse blocking mode :

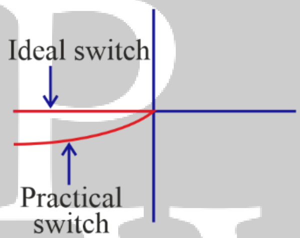


Fig. 1.4

1.1.2. Computation of power in Power Electronics

- In PE voltage and current are penodic in nature
- Instantaneous power $P(t) = v(t)\ i(t)$
- Energy losses in a time period

$$E = \int_O^T v(t)\ i(t)\, dt$$

- Average power loss

$$P_{av} = \frac{1}{T}\int_O^T v(t)\ i(t)\, dt$$

Case-I If voltage is constant $V(t) = V$

$$P_{av} = V\ I_{av}$$

Case-II If current is constant $i(t) = I$

$$P_{av} = I\ V_{av}$$

Case-III If current is flowing through R

$$P_{av} = I_{rms}^2 R$$

Losses in Power Semiconductor devices:

1. **Conduction losses –** it is power loss when device are in conduction mode

   Avg. conduction loss = $\frac{1}{T}\int_{O}^{T} V_{on}\, i_{on}\, dt$

   V_{on} = "on state" voltage drop

   i_{on} = "on state" current.

2. **Blocking losses :** it is power loss when device are in blocking mode. It occur due to leakage current

   Avg. blocking losses = $\frac{1}{T}\int_{O}^{T} V\, i_L\, dt$

   i_L = leakage current

   Note : In modern semiconducter devices these losses are neglected.

3. **Switching losses :** it is power loss during switching transition either during turning ON or during turning OFF.

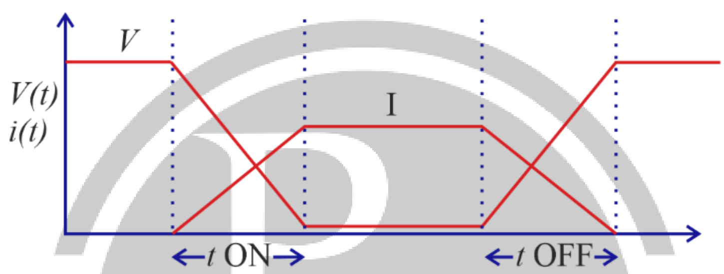


Fig. 1.5

- Energy loss during "turn on" period

$$E_{ON} = \frac{V\,I}{6}\, t_{ON}$$

- Instantaneous maximum power loss occur at $t = \frac{t_{ON}}{2}$ time and magnitude of maximum power loss

$$P_{\max} = \frac{V\,I}{4}$$

- Energy loss during "turning off" period

$$E_{OFF} = \frac{V\,I}{6}\, t_{OFF}$$

- Instantaneous maximum power loss occur at $t = \frac{t_{OFF}}{2}$ time and magnitude of maximum power loss

$$P_{\max} = \frac{V\,I}{4}$$

- Average switching power losses

$$P_{swt} = \frac{1}{T}\frac{V\,I}{6}(t_{ON} + t_{OFF})$$

Power Diode:

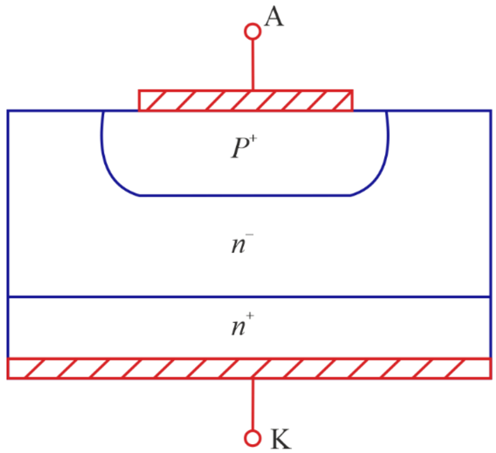


Fig. 1.6

- In power diode *P* and *N* semiconductor layer are connected in vertical configuration it reduce "ON state" resistance of diode.
- Lightly doped n^- layer (Drift layer) increase reverse blocking capacity of diode.
- It is bipolar, uncontrolled device
- It is unidirectional device, current can flows only from anode to cathode
- It is unipolar voltage blocking capacity. It can block reverse voltage only.
- Conductivity modulation occurs in power diode, which reduce drift layer resistance during conduction time.

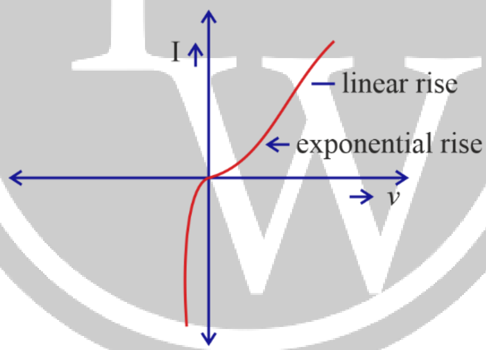


Fig. 1.7

- Turn off characteristic of diode is also called reverse recovery characteristic

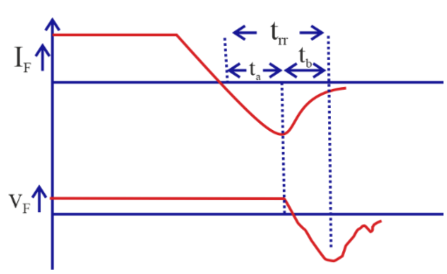


Fig. 1.8

- Reverse recovery time $t_{rr} = \sqrt{\dfrac{2Q_R}{di/dt}}$
- Peak value of reverse current $I_{RM} = \sqrt{2Q_R \dfrac{di}{dt}}$

- Softness factor s = t_b / t_a
- In slow recovery diode s = 1
- In fast recovery diode s < < 1
- In fast recovery diode, doping of gold and platinum is done. It reduce turn off time and increase "on state" voltage drop.
- The Schottky diode is metal semiconductor junction diode. It is majority carrier device and its turn off time is nano seconds.

Diode Circuit:

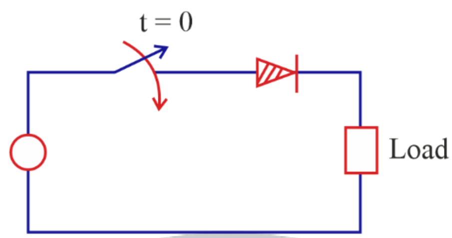


Fig. 1.9

- For purely resistive load, diode conduct for π period.
- For purely inductive load, diode conduct for 2π period.
- For purely capacitive load, diode conduct for $\frac{\pi}{2}$ period.

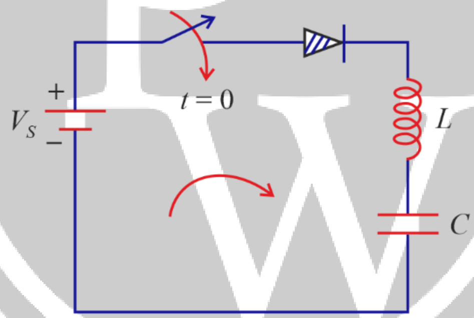


Fig. 1.10

- Current in circuit $i(t) = \frac{V_S}{\omega_o L} \sin \omega_o t$
- Voltage across inductor $V_L(t) = V_S \cos \omega_o t$
- Voltage across capacitor $V_C(t) = V_S [1 - \cos \omega_o t]$

Where, $\omega_0 = \frac{1}{\sqrt{LC}}$

Power BJT:

- It is a three terminal, fully controlled device, in which collector and emitter is main terminals and base is control terminal.
- It is unidirectional device, current can flows only from collector to emitter.
- It has unipolar voltage blocking capacity it can block only forward voltage.
- It has negative temperature coefficient, so its parallel operation is not possible and it also has of the possibility of secondary break down.

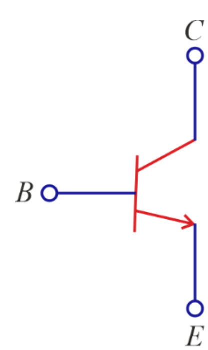


Fig. 1.11

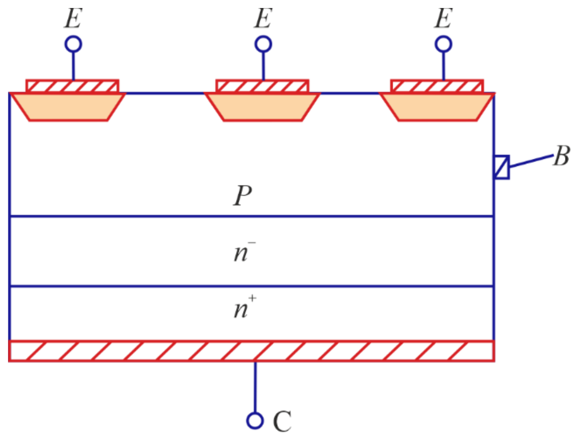


Fig. 1.12

- BJT operate in three region

Region	J_{CB}	J_{BE}	Application
Cut-off	RB	RB	OFF switch
Active (linear)	RB	FB	Amplifier
Saturation	FB	FB	ON switch

- BJT is the current controlled device. Control signal is base current I_B. It I_B =0 it act as a "OFF switch". It base current $I_B > I_{BS}$ it act as a "ON switch"

  Where I_{BS} is the minimum value of base current, which may bring device into saturation region.
- If operating point of BJT lies within SOA (Safe Operating Area) then may be damaged.

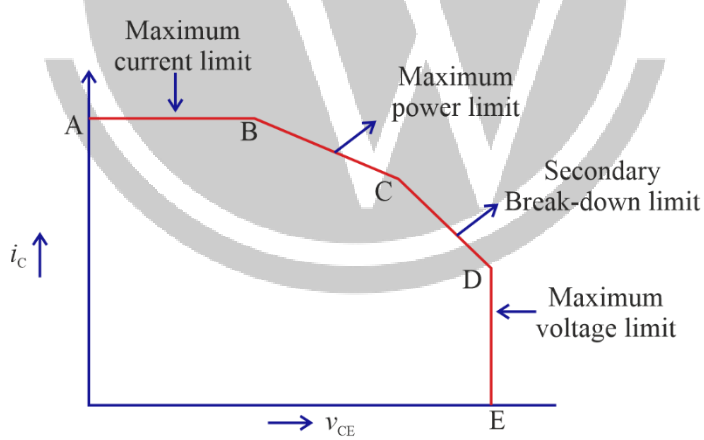


Fig. 1.13

Power MOSFET:

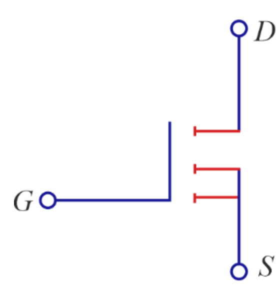


Fig. 1.14

- It is a three terminal device, in which drain and source are main terminal and gate is control terminal.
- It is a Bidirectional device.
- It is unipolar device, current flows only due to electrons.
- It is fully controlled device, control signal is v_{gs}.
- It has positive temperature coefficient.
- It has large conduction losses and less switching losses
- Due to SiO_2 its input impedance is high
- It is fully controlled device when $v_{gs} < v_{gst}$ it behaves like "OFF switch" and when $v_{gs} > v_{gst}$ it behave like "ON switch"

  v_{gst} = threshold gate to source voltage, it is minimum voltage required to formed n channel.

  v_{gso} = minimum gate to source voltage to bring MOSFET into ohmic region.

1.2. IGBT (Insulated Gate Bipolar Transistor)

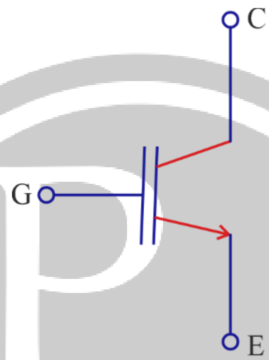


Fig. 1.15

- IGBT is three terminal device in which collector and emitter are main terminal and gate is control terminal.
- It is voltage control device, where control signal is v_{ge}.
- It is unidirectional device, current can flows only from collector to emitter.
- It has bipolar voltage blocking capacity.
- It has positive temperature coefficient
- It has high input impedance due to SiO_2
- It is a hybrid device of BJT and MOSFET.
- Due to conductivity modulation, the resistance of drift layer is reduced during conduction period.
- It is a fully controlled device. If $v_{ge} < v_{get}$ it behave like "OFF switch" and if $v_{ge} > v_{geo}$ it behave like "ON switch"

  Where v_{get} = gate to emitter threshold voltage it is minimum voltage required for formation of n channel.

  v_{geo} = minimum gate to emitter voltage to bring IGBT into ohmic region.

1 IGBT = 2 BJT + 1 MOSFET

1 IGBT = 1 SCR + 1 MOSFET

❒❒❒

2 THYRISTOR

- Any power semiconductor device which have minimum 3 junctions and two stable state is called thyristor.
- SCR is widely and oldest use member of this family.
- SCR is semi controlled, unidirectional, bipolar voltage blocking capacity, 3 terminal device.

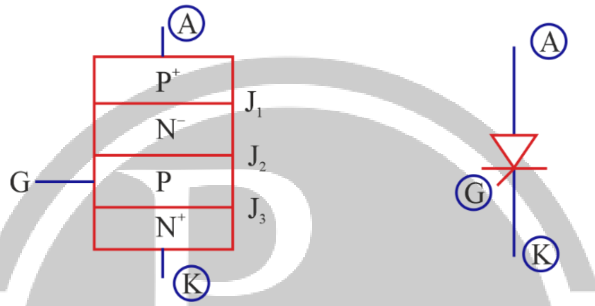


Fig. 2.1.

2.1. Static I-V Characteristic

Reverse Blocking

- J_1 & J_3 Junction are reverse bias but J_2 is forward bas
- Mainly reverse voltage is blocked by junction J_1
- Only reverse leakage current flows.

Forward Blocking Mode

- J_1 & J_3 Junction are Forward bias but J_2 junction are in reverse bias.
- Only forward leakage current flows.

Forward Conduction Mode:

- All three junctions are in forward bias.
- In symmetrical SCR $V_{BR} \geq V_{BO}$
- I_L = 2 to 3 I_H

Turn-ON Method:

- Forward voltage triggering.
- Gate triggering.
  (I) Constant gate triggering
  (II) Pulse gate triggering
  (III) High frequency. Gate triggering

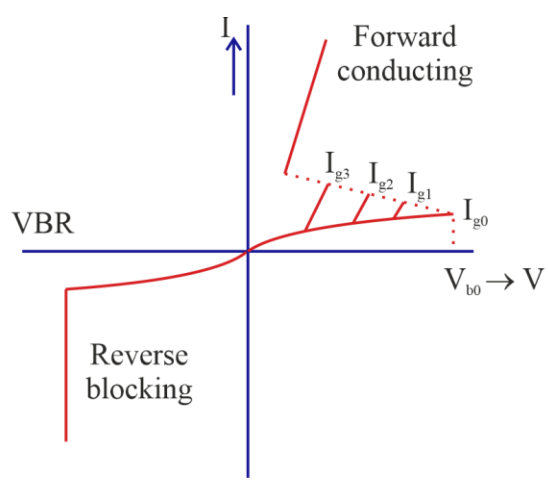


Fig. 2.2.

Pulse width = time taken by anode current to reach upto latching current value.

- In RL load $i(a) = \frac{V}{R}\left[1 - e^{-Rt/L}\right] = I_L$

  Find out *t*, it is pulse width.
- If pulse width is not sufficient to reach anode current up to latching current value, then we connect a resistance in parallel of R-L load.
- $\frac{dv}{dt}$ triggering
- Thermal triggering
- Light triggering.
- It gate pulse is applied in reverse bias.

  SCR. Then

  (I) Magnitude of leakage current increase

  (II) Power losses will be increase so SCR may be damaged.

2.1.1. Switching Characteristic

Turn ON time = time required to bring SCR from forward blocking mode to forward conducting mode.

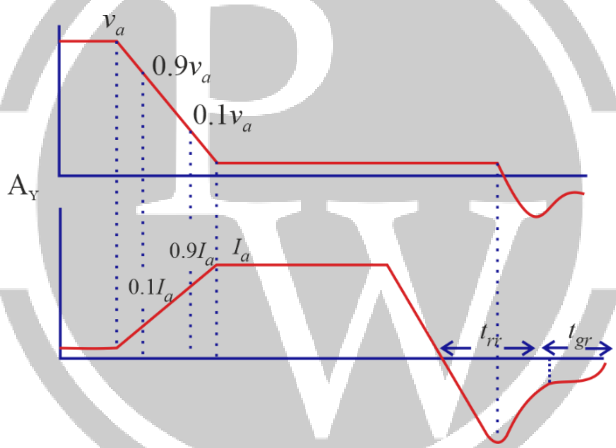


Fig. 2.3.

$$t_{ON} = t_d + t_r + t_s$$

t_d $v_a \to 0.9v_a$

leakage current $\to$ 0.1 I_a

current flow in very low area.

High gate current and more forward voltage decrease delay time.

t_r 0.1 I_a – 0.9 I_a

0.9 v_a – 0.1 v_a

- Rise time mainly depend on circuit element
- Power losses is maximum during rise time.

t_s 0.9 I_a – I_a

0.1 v_a – ON state voltage drop.

- It depend on area of cathode & gate structure

Turn OFF time – time to bring SCR from forward conduction mode to forward blocking mode

$$t_{OFF} = t_{rr} + t_{gr}$$

t_{rr} – Storage charge near junction J_1 & J_3 is removed & SCR regain its reverse blocking capacity. After t_{rr}, SCR behave like diode

t_{gr} – Trapped storage charge near middle junction J_2 is also removed. After t_{gr} it regain forward blocking capacity.

$$t_q = t_{rr} + t_{gr}$$

Converter grade SCR $t_q = 50 - 100$ m sec

Inverter grade SCR $t_q = 3 - 50$ m sec

- For sucessful commutation $t_c > t_q$

$$t_c = (\text{F.O.S.})\, t_q$$

- If $t_q > t_c$ $\Rightarrow$ Commutation failure

Circuit turn off time – It is time for which SCR is reverse bias after anode current is become less than holding current

2.2. Thyristor Gate Characteristic

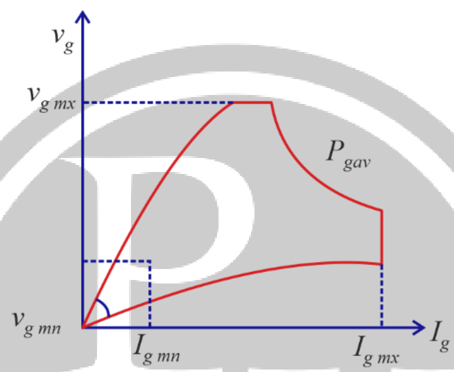


Fig. 2.4.

$$I_{g\min} \le I_g \le I_{g\max}$$

$$V_{g\min} \le V_g \le V_{g\max}$$

- For pulse width less than 100ms

$$V_g I_g \le P_{g\max}$$

$P_{g\max}$ = peak power dissipation limit

- For pulse width greater than 100 μs

$$V_g I_g \le P_{g\,av}$$

P_{gav} = average power dissipation limit

$$P_{gmx} T_1 = P_{gav} T$$

T = time period of pulse

T_1 = pulse width (T_n time)

Mark to space ratio $\dfrac{T_1}{T - T_1}$

$$E_S = v_g + I_g R_S$$

If v_g is not given assume it zero.

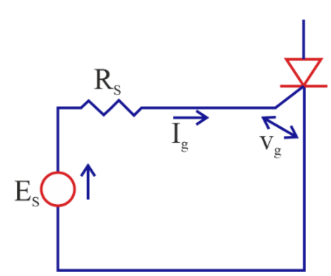


Fig. 2.5.

$$E_S = \left(I_g + \frac{v_g}{R_1}\right)R_S + v_g\ .$$

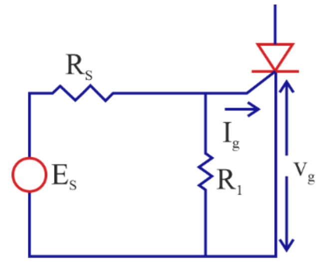


Fig. 2.6.

RMS on State Current Rating

- It is given by manufacturer
- It does not depent on current wave form.

Average on State Current Rating

- Not given by manufacturer.
- $\underset{(rating)}{I_{Tav}} = \frac{I_{TRMS}}{FF}$ (Rating)
- It depend on FF of wave form.
- If conduction angle increase I_{Tav} increase
- If load inductance increase, I_{Tav} increase.

Surge Current Rating:

$$I_{s1} = \sqrt{n}\ I_{sn}$$

I_{s1} = one cycle surge current rating

I_{sn} = n cycle surge current rating

$$(I_s)_{1/n} = \sqrt{n}\, I_{s1}$$

$(I_s)_{1/n}$ = Surge current rating for 1/*n* period

2.3. Thyristor protection:

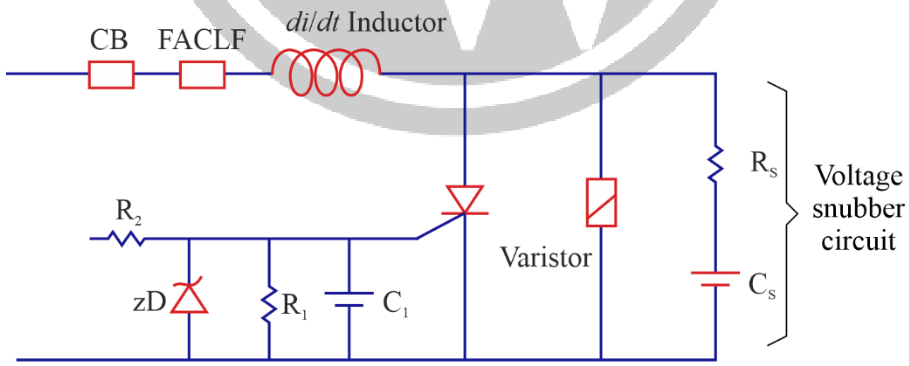


Fig. 2.7.

di/dt protection:

- Current snubber circuit (L) is used in series of SCR.
- Inductor value can be calculated by $\left(\frac{di}{dt}\right)_{\text{actual}} \le \left(\frac{di}{dt}\right)_{\text{rated}}$

dv/dt protection:

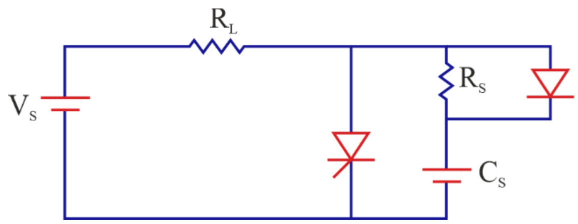


Fig. 2.8.

$$v_T = v_C = v_S\left(1 - e^{-t/R_L C}\right)$$

$$\frac{dv_T}{dt} = \frac{v_S}{R_L C}$$

$$C = \frac{v_S}{R_L\ dv_T / dt}$$

Discharging current $= \dfrac{v_S}{R_S}$

Total current through SCR $= \dfrac{v_S}{R_S} + \dfrac{v_S}{R_L}$

- Is source is a A.C source $v_S = v_m \sin wt$ then use maximum voltage v_m in formula $\dfrac{dv_T}{dt} = \dfrac{v_m}{R_L C}$

$$C = \frac{v_m}{R_L dv_T / dt}$$

$\dfrac{dv}{dt}$ as well as $\dfrac{di}{dt}$:

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

(1) if source is AC use v_m in place of v_s

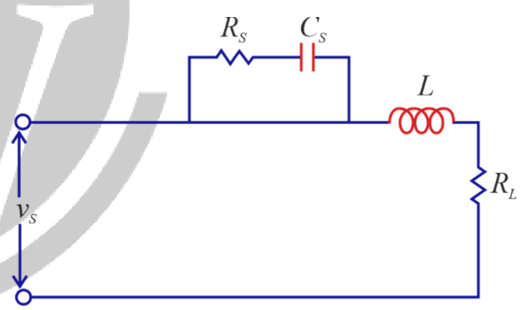


Fig. 2.9.

$$\left(\frac{dv}{dt}\right)_{max} = R_S\left(\frac{di}{dt}\right)_{max}$$

$$\left(\frac{dv}{dt}\right)_{max} = R_S \frac{v_S}{L}$$

$$R_S = \frac{L}{R_S}\left(\frac{dv}{dt}\right)_{max}$$

$$R_S = 2\xi\sqrt{\frac{L}{C_S}} \Rightarrow C_S = \left(\frac{2\xi}{R_S}\right)^2 L$$

2.3.1. Over Voltage Protection

Varistor (voltage clamping device is used) whose resistance decrease with increment of voltage.

Over Current Protection

- CB and FACLF (fast acting current limiting fuse is used).
- Electronic crowbar protection is used.

Gate Protection

- $R_2 \rightarrow$ over current protection
- $R_1||C_1 \rightarrow$ For Noise immunity
- ZD $\rightarrow$ over voltage protection

Shielded cable & twisted gate lead $\rightarrow$ spurious firing.

2.3.2. Thermal Protection

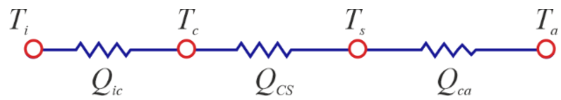


Fig. 2.10.

$$P_{av} = \frac{T_i - T_c}{Q_{ic}} = \frac{T_c - T_s}{Q_{cs}} = \frac{T_s - T_a}{Q_{sa}} = \frac{T_i - T_a}{Q_{ic} + Q_{cs} + Q_{sa}}$$

Rating $\propto \sqrt{P_{av}}$

P_{av} = average power dissipation

T_i = junction temperature

T_c = Thyristor case temperature

T_s = Sink temperature

T_a = ambient temperature

Q_{ic} = Thermal resistance between junction & case

Q_{cs} = Thermal resistance between case & sink

Q_{sa} = Thermal resistance between sink & atmosphere.

Increment of *di/dt* rating:

- By using centre gate thyristor
- Interdigitating of gate-cathode region.

Increment of *dv/dt* Rating:

- By cathode – short structure

Series and Parallel Connection

- SCR are connected in series for HV application
- SCR are connected in parallel for high current application.
- String efficiency measure “degree of utilization” of SCR’s in a string.

$$n = \frac{\text{Actual voltage / Current of whole string}}{\text{no. of SCR} \times \text{Indivisual voltage / Current rating of SCR}}$$

- DRF (Derating factor) give reliability of string.

DRF = 1–n

Series Operation:

- Problem – unequal voltage distribution during static condition (during T_{off}).
- Reason – Due to difference in FB characteristic

- Soulution – Static equalizing circuit (ResistanceR in parallel of each SCR)

$$R = \frac{nv_{bm} - v_s}{(n-1)\Delta I_b}$$

v_{bm} = Maximum blocking voltage

v_s = String voltage

$$\Delta I_b = I_{b\max} - I_{b\max}$$

I_{bmx} = Maximum blocking current

I_{bmn} = Minimum blocking current generally

I_{bmn} = 0

- Problem – unequal voltage distribution during dynamic time (during turning on and turning off time)
- Reason – Difference in dynamic characteristic
- Solution – Dynamic equalizing circuit (R_c & c in parallel of each SCR.

$$C = \frac{(n-1)\Delta Q}{nv_{bm} - v_s}$$

ΔQ = Difference in storage charges.

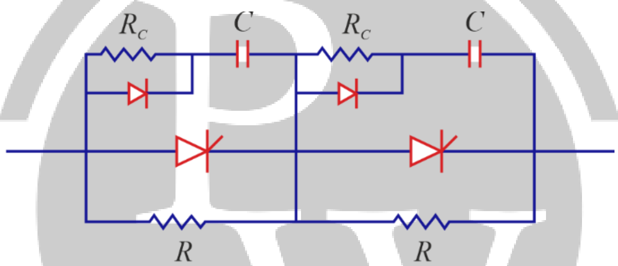


Fig. 2.11.

- If n is fraction number while given data of string efficiency always use higer integer number.

Suppose n = 6.25 $\rightarrow$ take it n = 7

2.3.3. DIAC (Diode for Alternating Current)

- It is two terminal uncontrolled device
- It is AC switch, can operate in all 4 modes of operation.
- Its like two diode connected in anti parallel
- Its is used in firing circuit of Triac.

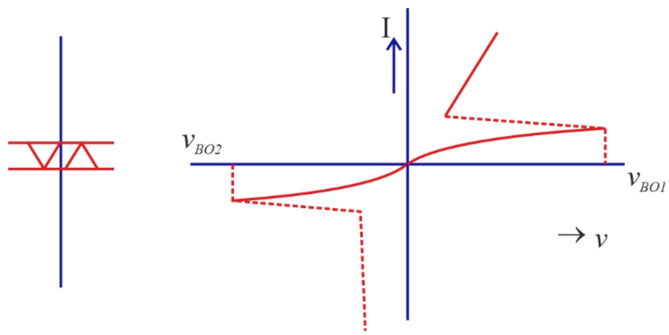


Fig. 2.12.

2.3. TRIAC (Triode for Alternating Current)

- It is 3 terminal semi controlled device
- It is like two SCR connected in antiparallel
- If MT_2 is positive w.r.t. MT_1 and positive gate pulse given it start conducting in forward direction
- If MT_2 is negative w.r.t MT_1 and negative gate pulse is given, it start conducting is reverse direction.
- The voltage and current rating is low as compared to SCr.

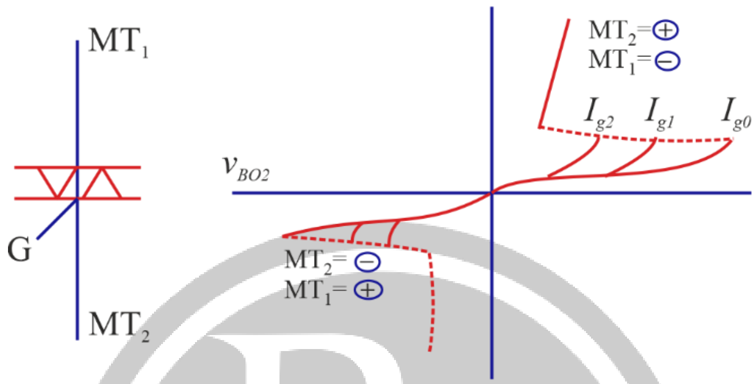


Fig. 2.13.

2.3.1. ASCR

- Its reverse blocking capacity is less as compared to normal SCR.
- Its turn off time is less than that of normal SCR.
- In ASCR lightly doped inner n layer is replaced by highly doped layer.

RCT (Reverse Conducting Thyristor)

- A diode is connected antiparallel to SCR on same chip. So its reverse blocking capacity is zero.
- Undesirable stray inductance is elliminate between SCR/ASCR and diode, so unwanted reverse voltage transient is eliminated.

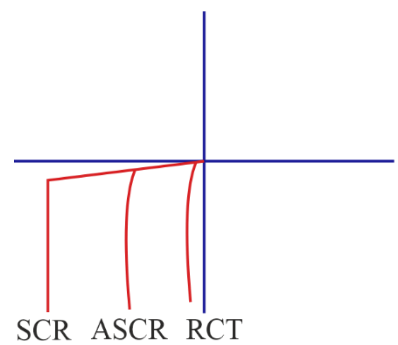


Fig. 2.14.

2.3.2. GTO (Gate Turn off Thyristor)

- It is 3 terminal fully controlled device. It can be turn off by negative pulse.
- Its latching and holding current is high
- On state voltage drop and associated loss is high
- It required high gate current so associated gate power loss is high
- Its *di/dt* rating is high.
- GTO circuit has lower size and weight so it is more efficient.

$$t_{off} = t_s + t_f + t_t$$

- During storage time (t_s) excess charge are removed from inner P layer the anode current and voltage remain constant.
- During fall time (t_f) , current fall and voltage increase.
- At starting of t_t (tail time). There is abrupt change of current so transient voltage is created.

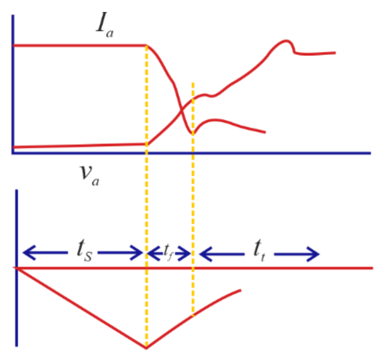


Fig. 2.15.

Firing Circuit:

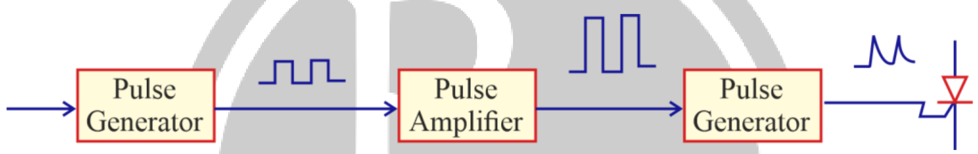


Fig. 2.16.

Resistance Firing:

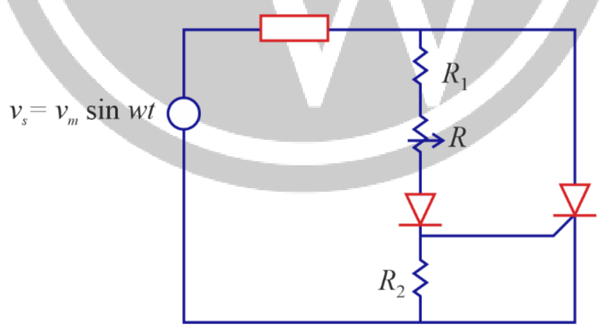


Fig. 2.17.

- R_1 is used to limit current

$$\frac{v_m}{R_1} \le I_{g\max} \quad \text{or} \quad R_1 \ge \frac{v_m}{I_{g\max}}$$

- R_2 is used to limit gate voltage $\frac{R_2}{R_1 + R_1} v_m \le v_{g\max}$
- By varying R we can get firing angle between 0 to 90º

R–C Firing Circuit

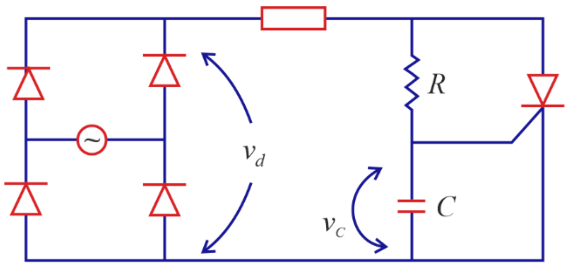


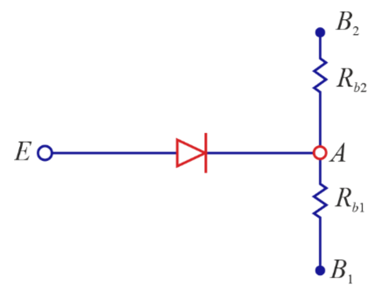
Fig. 2.18.

$$v_c = v_d(1 - e^{-t/RC})$$

- When $v_c = v_{gt}$ the SCR turn on.
- The firing limit may be from 0 to 180°

UJT (Unijunction Transistor)

- It is 3 terminal dence, where B_1 & B_2 is base terminal and E is emitter terminal.



$$v_{AB_1} = v_{BB} \cdot \frac{R_{B_1}}{R_{B_1} + R_{B_2}}$$

$$v_{AB_1} = n\, v_{BB}$$

n = 0.51 to 0.82

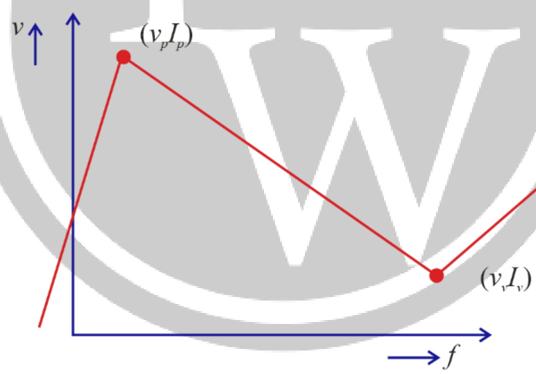


Fig. 2.19.

if voltage > v_p ⇒ UJT turn on
voltage < v_v ⇒ UJT turn off

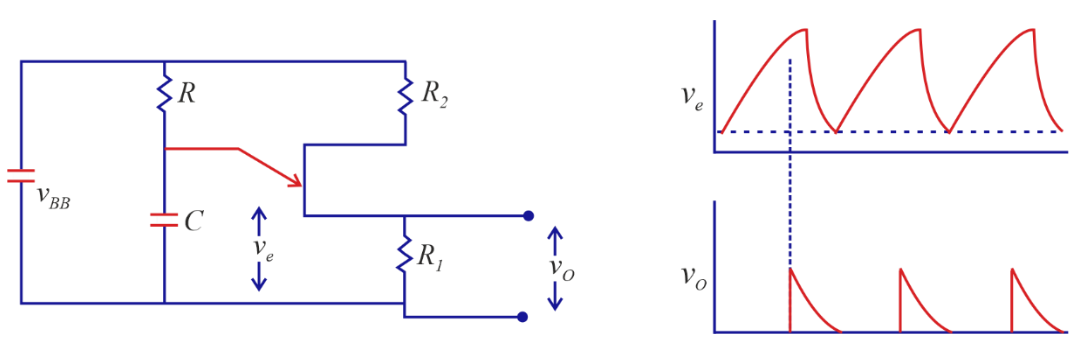


Fig. 2.20.

- The UJT is used as a relaxation oscillator which is used to fired SCR
- The time period of relaxation oscillator

$$T = \text{RC ln}\left(\frac{1}{1-n}\right)$$

- Firing angle $\alpha_1 = \omega T = \omega RC \ln\left(\frac{1}{1-n}\right)$
- The maximum value of R $R_{\max} = \frac{v_{BB} - v_P}{I_P}$
- Minimum value of R $R_{\min} = \frac{v_{BB} - v_P}{I_P}$

$$v_{BB} = \text{leakage current } (R_1 + R_2 + R_{BB})$$

Ideal characteristic of Devices:

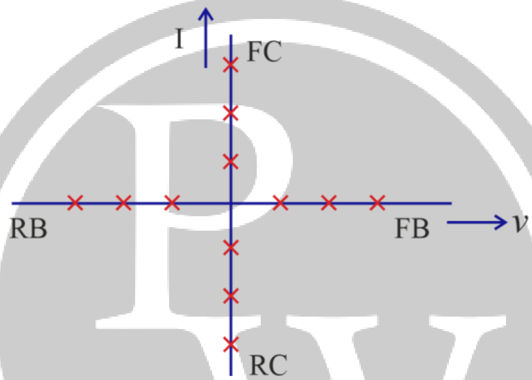


Fig. 2.21.

- In composite switch first on and off the diode during forward & reverse bias.
- Then see all other device would be conducting or blocking mode with or without control signal.

❑❑❑

3 RECTIFIER

3.1. Classification

1. (i) Uncontrolled rectifier (only diode)
   (ii) Semi controlled rectifier (diode + SCR)
   (iii) Fully controlled rectifier (only SCR)
2. (i) Single pulse
   (ii) Two pulse
   (iii) Three pulse
   (iv) Six pulse

Pulse width = $\frac{2\pi}{m}$ [$m \neq 1$, for m = 1 pulse width = π]

Output voltage ripple frequency = mfs

$m\uparrow \Rightarrow Ripple\downarrow$

3.1.1. Fourier Series

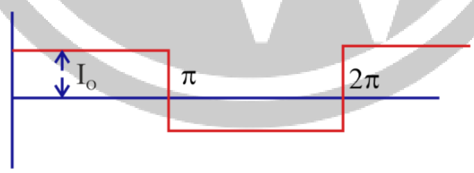


Fig. 3.1.

$$i(t) = \sum_{n=1,3,5...}^{\infty} \frac{4I_0}{n\pi} \sin nwt$$

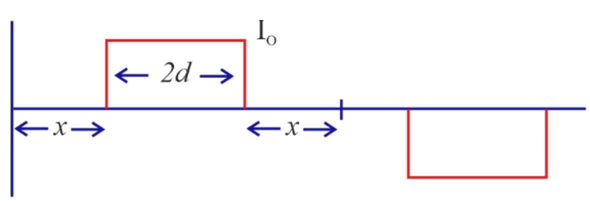


Fig. 3.2.

$$i(t) = \sum_{n=1,3,5...}^{\infty} \frac{4I_0}{n\pi} \sin\frac{n\pi}{2} \sin nd \sin nwt$$

3.1.2. Performance Parameter

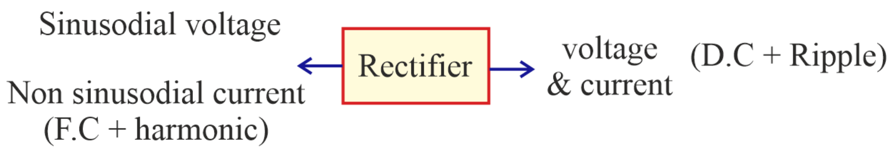


Fig. 3.3.

Input parameter:

- Distortion factor $g = \dfrac{I_{s1}}{I_{sr}}$
- Displacement angle is angle between sinusoidal voltage & F.C. of current (ϕ)
- Displacement factor $DF = \cos\phi$
- Input power factor $= \dfrac{\text{Active power}}{vA}$

$$= \frac{v_{sr} I_{s1} \cos\phi}{v_{sr} I_{sr}} = \frac{I_{s1}}{I_{sr}} \cos\phi$$

IPF = g × DF.

- Current harmonic factor/total harmonic Distortion $= \sqrt{\dfrac{1}{g^2} - 1}$

Output Parameter:

- D.C output power $V_o I_o$
- A.C output power $V_{or} I_{or}$
- Rectification efficiency $n = \dfrac{P_{ac}}{P_{dc}} = \dfrac{V_{or} I_{or}}{V_o I_o}$
- Form factor $(FF) = \dfrac{v_{or}}{v_o}$ (for voltage)
- Voltage ripple factor $VRF = \sqrt{FF^2 - 1}$
- Current ripple factor $CRF = \sqrt{\left(\dfrac{I_{or}}{I_o}\right)^2 - 1}$
- Transformer utilization factor $TUF = \dfrac{P_{dc}}{VA\,\text{Rating of transformer}}$
- Same frequency component create active & reactive power.

3.2. Single Phase Half Wave Rectifier

(1) R Load:

- Average o/p voltage $v_o = \frac{v_m}{2\pi}(1+\cos\alpha)$
- Average o/p current $I_o = \frac{v_m}{2\pi R}(1+\cos\alpha)$
- RMS o/p voltage $v_{or} = \frac{v_m}{2\sqrt{\pi}}\left[(\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]^{1/2}$
- RMS o/p current $I_{or} = \frac{v_{or}}{R}$
- Output power $P = \frac{v_{or}^2}{R}$. (always use RMS voltage to find out power in R load)
- Power factor $= \frac{v_{or}}{v_o} = \frac{1}{\sqrt{2\pi}}\left[(\pi-2)+\frac{\sin 2\alpha}{2}\right]^{1/2}$
- $\omega_{tc} = \pi$
- For diode rectifier $v_o = \frac{v_m}{\pi}, v_{or} = \frac{v_m}{2}$

(2) R-L Load :

- Average o/p voltage $V_o = \frac{V_m}{2\pi}$, $[\cos\alpha - \cos\beta]$

  β = extinction angle
- Average o/p current $I_o = \frac{V_o}{R}$
- RMS o/p voltage $V_{or} = \frac{V_m}{2\sqrt{\pi}}\left[(\beta-\alpha)+\frac{1}{2}(\sin 2\alpha - \sin 2\beta)\right]^{1/2}$
- Instantaneous current $i(t) = \frac{v_m}{z}\sin(wt-\phi) - \frac{v_m}{z}\sin(\alpha-\phi)\exp\left[\frac{-R}{wL}(wt-\alpha)\right]$
- o/p power $p_o = V_o I_o$
- $\omega_{tc} = (\pi - \beta)$

(3) RL Load with Freewheeling Diode:

- Average o/p voltage $V_o = \frac{V_m}{2\pi}(1+\cos\alpha)$
- Average o/p current $I_o = \frac{V_o}{R}$

- RMS o/p voltage $V_{or} = \frac{V_m}{2\sqrt{\pi}}\left[(\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]^{1/2}$
- $\omega_{tc} = \pi$

Advantage :

(I) The input P.f is improved

(II) The average o/p voltage is increased.

(III) The chances of continuous current increases.

(IV) The average o/p power is increased.

(4) RE Load:

- Peak inverse voltage (PIV = (v + E_m)
- Average o/p voltage $v_o = \frac{1}{2\pi}[v_m(\cos\alpha - \cos\theta_2) + E(2\pi + \alpha - \theta_2)]$

  ↓ Radian
- Average charging current $I_o = \frac{1}{2\pi R}[v_m(\cos\alpha - \cos\theta_2) - E(\theta_2 - \alpha)]$

  ↓ Radian
- $P.f = \frac{I_{or}^2 R + EI_o}{v_{sr} I_{sr}} = \frac{V_o I_o}{v_{sr} I_{sr}}$
- RMS current $I_{or}^2 = \frac{1}{2\pi}\int_{\alpha}^{\theta_2}\left(\frac{v_m \sin wt - E}{R}\right)^2 d(wt)$
- Average charging current for diode rectifier $I_o = \frac{1}{2\pi R}[2v_m\cos\theta_1 - E(\pi - 2\theta_1)]$

  ↓ *Radian*
- Average o/p voltage for diode rectifier $v_o = \frac{1}{2\pi}[2v_m \cos\theta_1 + E(\pi + 2\theta_1)]$

(5) RLE Load

- $\theta_1 = \sin^{-1}\frac{E}{v_m}$ $\qquad \theta_2 = (\pi - \alpha_1)$

  $\theta_1 < \alpha < \theta_2$

  PIV = $(E + V_n)$

  ωt_c = $(2\pi + \theta_1 - \beta)$
- Average output current

$$I_o = \frac{1}{2\pi R}[v_m(\cos\alpha - \cos\beta) - E(\beta - \alpha)]$$

- Average output voltage,

$$V_o = \frac{1}{2\pi}\left[V_m(\cos\alpha - \cos\beta) - E(2\pi + \alpha - \beta)\right]$$

$$P.f. = \frac{I_{or}^2 R + EI_o}{V_{sr} I_{sr}} = \frac{V_o I_o}{V_{sr} I_{sr}}$$

- Heater & lightening load is resistive load if heater rating is given in V and P then find out it's resistance

$$R = \frac{V^2}{P}$$

- In half wave rectifier (without FD)

  Supply Current = Thyristor Current = Load Current

- It is one pulse converter.

3.3. 1ϕ Full Wave Rectifier

Midpoint converter (M-2)

Bridge converter (B-2)

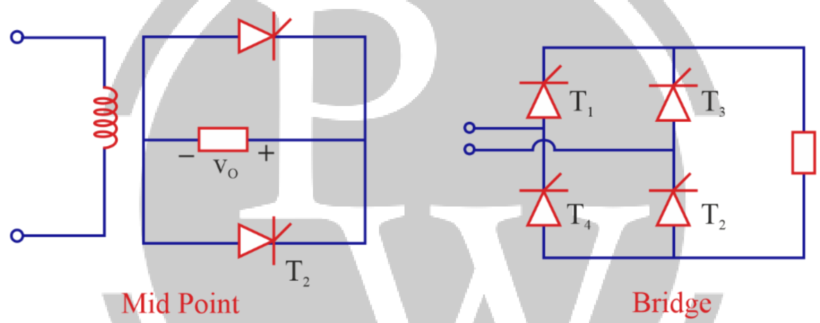


Fig. 3.4.

(1) For R Load :

- Average o/p voltage $V_o = \frac{V_m}{\pi}(1 + \cos\alpha)$
- Average o/p current $I_o = \frac{V_o}{R}$
- RMS o/p voltage $V_{or} = \frac{V_m}{\sqrt{2\pi}}\left[(\pi - \alpha) + \frac{\sin 2\alpha}{2}\right]^{1/2}$
- $\omega_{tc} = \pi$

(2) For RL/RLE load (Cont. Conduction)

- Average o/p voltage $v_o = \frac{2v_m}{\pi}\cos\alpha$
- Average o/p current (as an rectifier) $I_o = \frac{V_o}{R}$ (RL load)

  $I_o = \frac{V_o - E}{R}$ (RLE load)

- RMS output voltage $V_{or} = v_s$
- $\omega_{tc} = (\pi - \alpha)$
- PIV = $2V_m$ (for midpoint converter)

  = V_m (for bridge converter)

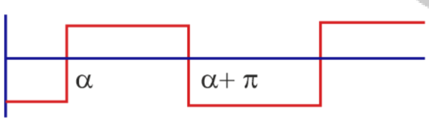
(3) For RL load Discontinuous Conduction

- Average o/p voltage $V_o = \frac{V_m}{\pi}[\cos\alpha - \cos\beta]$
- Average o/p current $I_o = \frac{V_o}{R}$
- RMS o/p voltage $V_{or} = \frac{V_m}{\sqrt{2\pi}}\left[(\cos\alpha - \cos\beta) + \frac{1}{2}(\sin 2\alpha - \sin 2\beta)\right]^{1/2}$

(4) For RL load with freewheeling diode:

- Average o/p voltage $V_o = \frac{V_m}{\pi}(1 + \cos\alpha)$
- RMS o/p voltage $V_{or} = \frac{V_m}{\sqrt{2\pi}}\left[(\pi - \alpha) + \frac{\sin 2\alpha}{2}\right]^{1/2}$

Performance parameter of full converter for RL/RLE Load Continuous Conduction

- Average value of Thyristor current $I_T = \frac{I_o}{2}$
- RMS value of Thyristor current $I_{Tr} = \frac{I_o}{\sqrt{2}}$
- RMS value of supply current $I_{sr} = I_o$
- Is 

- Instataneous value of supply current $i_s(t) = \sum_{n=1,2,3}^{\infty} \frac{4I_o}{n\pi} \sin n(wt - \alpha)$
- RMS value of fundamental component of supply current $I_{s1} = \frac{2\sqrt{2}}{\pi} I_o$
- Displacement factor DF = $\cos\alpha$
- Distortion factor $g = \frac{2\sqrt{2}}{\pi}$
- THD/CHF = 0.4834 = 48.34%

Single phase full converter as an Inverter:

(1) There must be D.C. source on load side

(2) $\alpha > 90^\circ$

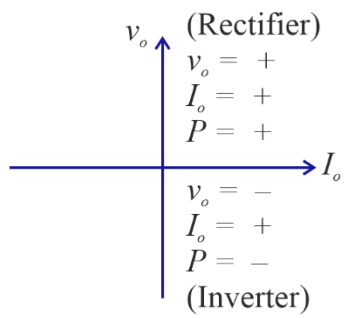
(3) Polarity of E should be reverse

Application :

(I) Discharging of Battery

(II) Regenerative braking of D.C. Motor

Average current during Inverter mode



$$I_o = \frac{v_o + E}{R}$$

$$I_o = \frac{\frac{2v_m}{\pi}\cos\alpha + E}{R}$$

Average Power Rating of Converter:

- For mid point converter $2v_m \times \text{F.O.S} = \text{voltage rating}$

  Power rating = $\frac{2v_m}{\pi} \times I_{Tav}$

- For bridge converter $v_m \times \text{F.O.S} = \text{voltage rating}$

  Power rating = $\frac{2v_m}{\pi} \times I_{Tav}$

- Active power $P = V_{sr} I_{s1} \cos\alpha = V_o I_o$
- Reactive power $Q = P\tan\alpha$
- Voltage ripple factor = $\sqrt{\frac{\pi^2}{8\cos^2\alpha} - 1}$

(5) Full Converter with RE Load

- Average o/p voltage $v_o = \frac{1}{\pi}[V_m(\cos\alpha - \cos\beta) + E(\pi + \alpha - \theta_2)]$
- Average charging current $I_o = \frac{1}{\pi R}[(v_m(\cos\alpha - \cos\theta_2) - E(\theta_2 - \alpha)]$
- Charging current for diode rectifier $I_o = \frac{1}{\pi R}[(2v_m\cos\theta_1 - E(\pi - 2\theta_1)]$

RLE Load (Discontinuous Conduction)

$$v_o = \frac{1}{\pi}[(v_m(\cos\alpha - \cos\beta) + E(\pi + \alpha - \beta)]$$

3.4. Single Phase Semi Converter

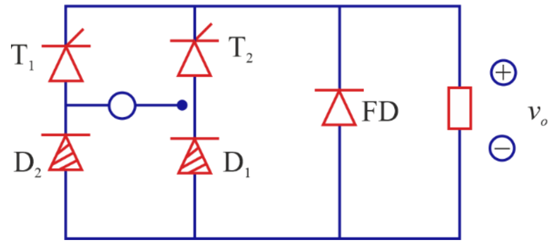


Fig. 3.5.

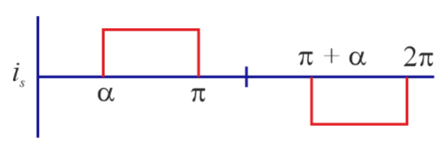
- Average o/p voltage $v_o = \frac{v_m}{\pi}(1+\cos\alpha)$
- RMS o/p voltage $v_o = \frac{v_m}{\sqrt{2\pi}}\left[(\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]^{1/2}$

3.4.1. Performance Parameter with Continuous Conduction

- Average current of Thyristor $I_T = I_o\frac{(\pi-\alpha)}{2\pi}$
- RMS current of Thyristor $I_{Tr} = I_o\sqrt{\frac{\pi-\alpha}{2\pi}}$
- RMS value of supply current $I_{sr} = I_o\sqrt{\frac{\pi-\alpha}{\pi}}$
- Average current of freewheeling diode $I_{FD} = I_o\left(\frac{\alpha}{\pi}\right)$
- RMS value of freewheeling diode $I_{FDr} = I_o\sqrt{\frac{\alpha}{\pi}}$

$$i_s = \sum_{n=1,3,5}^{\infty}\frac{4I_o}{n\pi}\cos\left(\frac{n\alpha}{2}\right)\sin n\left(wt-\frac{\alpha}{2}\right)$$

- RMS value of fundamental component of supply current $I_{s1} = \frac{2\sqrt{2}}{\pi}\cos\frac{\alpha}{2}$
- Distortion factor $g = \frac{I_{s1}}{I_{sr}} = \frac{2\sqrt{2}\cos\frac{\alpha}{2}}{\sqrt{\pi(\pi-\alpha)}}$



- Displacement factor DF = $\cos\frac{\alpha}{2}$
- Input Pf = $g \times DF$ $= \frac{\sqrt{2}(1+\cos\alpha)}{\sqrt{\pi(\pi-\alpha)}}$
- Total harmonic distortion/CHF = $\sqrt{\frac{1}{g^2}-1} = \sqrt{\frac{\pi(\pi-\alpha)}{8\cos^2\alpha}-1}$

- Active power $p = v_{sr} I_{s1} \cos\frac{\alpha}{2} = v_o I_o$
- Reactive power $\theta = p \tan\frac{\alpha}{2}$
- VRF = $\sqrt{FF^2 - 1}$

(1) Single phase semiconverter RLE load Discontinuous Conduction

If extinction angle $\beta < \pi$

$$v_o = \frac{1}{\pi}\left[v_m(\cos\alpha - \cos\beta) + E(\pi + \alpha - \beta)\right]$$

for $\beta > \pi$,

$$v_o = \frac{1}{\pi}\left[v_m(1 + \cos\alpha) + E(\pi + \alpha - \beta)\right]$$

(2) RE Load :

V_o = Same as full converter

I_o = same as full converter

Symmetrical half controlled rectifier (cont. conduction without freewheeling diode) :

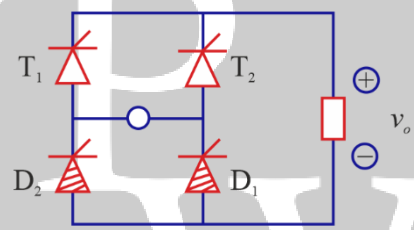


Fig. 3.6.

- Average o/p voltage $v_o = \frac{V_m}{\pi}(1 + \cos\alpha)$
- Average Thyristor current $I_T = \frac{I_o}{2}$
- RMS Thyristor current $I_{Tr} = \frac{I_o}{\sqrt{2}}$
- Average diode current $I_D = \frac{I_o}{2}$
- RMS diode current $I_{Dr} = \frac{I_o}{\sqrt{2}}$
- RMS value of supply current $I_{sr} = I_o\sqrt{\frac{\pi - \alpha}{\pi}}$

Asymmetrical half controlled rectifier (without freewheeling conduction) cont. conduction:

- Average o/p voltage $v_o = \frac{V_m}{\pi}(1 + \cos\alpha)$
- Average Thyristor current $I_T = I_o\frac{(\pi - \alpha)}{2\pi}$

- RMS Thyristor current $I_{Tr} = I_o\sqrt{\frac{(\pi-\alpha)}{2\pi}}$
- Average diode current $I_D = I_o\frac{(\pi+\alpha)}{2\pi}$
- RMS diode current $I_{Dr} = I_o\sqrt{\frac{(\pi+\alpha)}{2\pi}}$
- RMS value of supply current $I_{sr} = I_o\sqrt{\frac{\pi-\alpha}{\pi}}$

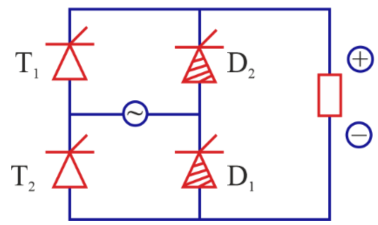


Fig. 3.7.

3.5. 3ϕ rectifier

3.5.1. 3ϕ Half Wave Rectifier

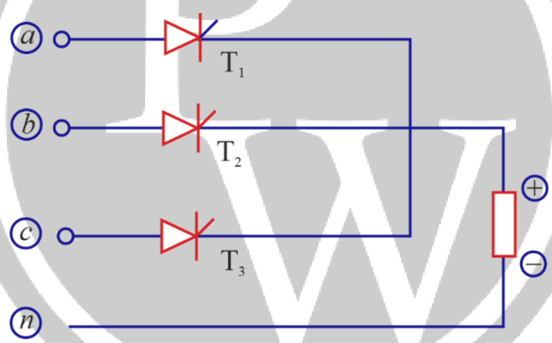


Fig. 3.8.

(1) For R load α < 30/RL & RLE load for any α (cont. conduction)

- $v_0 = \frac{3v_{ml}}{2\pi}\cos\alpha$
- RMS o/p voltage $V_{or} = V_{ml}\left[\frac{1}{6}+\frac{\sqrt{3}}{8\pi}\cos 2\alpha\right]^{1/2}$
- Peak inverse voltage = V_{ml}

(2) For R load α > 30/RL & RLE load with FD (α > 30)

- $v_o = \frac{3V_{mp}}{2\pi}[1+\cos(\alpha+30)]$
- RMS o.p voltage $v_{or} = \frac{v_{ml}}{2\sqrt{\pi}}\left[\left(\frac{5\pi}{6}-\alpha\right)+\frac{1}{2}\sin\left(2\alpha+\frac{\pi}{3}\right)\right]^{1/2}$
- $-PIV = v_{ml}$

(3) For α < 30/RL & RLE load for any α cont. Conduction:

- FD does not conduct and each SCR conduct $\frac{2\pi}{3}$ time for a time period of 2π.
- I_T (average value of Thyristor current) = $\frac{I_o}{3}$
- RMS value of Thyristor current = $I_{Tr} = \frac{I_o}{\sqrt{3}}$
- RMS value of supply current = $I_{sr} = \frac{I_o}{\sqrt{3}}$

(4) For α > 30 RL/RLE load with FD :

- FD conduct for $\left(\alpha - \frac{\pi}{6}\right)$ for time period of $\frac{2\pi}{3}$
- SCR conduct $\left(\frac{5\pi}{6} - \alpha\right)$ for time period of 2π.
- Average current of Thyristor = $\frac{I_o\left(\frac{5\pi}{6} - \alpha\right)}{2\pi}$
- RMS value of Thyristor/supply current = $I_o \times \sqrt{\frac{\frac{5\pi}{6} - \alpha}{2\pi}}$
- Average value of FD current = $\frac{I_o\left(\alpha - \frac{\pi}{6}\right)}{\frac{2\pi}{3}}$.
- RMS value of FD current $I_{FDr} = I_o\sqrt{\frac{\left(\alpha - \frac{\pi}{6}\right)}{\frac{2\pi}{3}}}$
- If v_T is voltage drop in a SCR then average o/p voltage $v_o = \frac{3v_m}{2\pi}\cos\alpha - v_T$ (cont. conduction)
- Average power dissipated in a SCR = $I_{TA}V_T$
- Normally 3ph half wave rectifier does not have FD so untill it is mentioned in question do not consider FD.
- In 3phase rectifier ($TUF = \frac{P_{dc}}{\sqrt{3}v_L I_L} = \frac{P_{dc}}{3v_{sr}I_{sr}}$) .
- 3ph half wave rectifier source current contain D.C component so it saturate the transformer core.

3.6. 3 Phase Full Converter (Six Pulse Converter)

(1) α < 60 for R load / RL & RLE load for any α cont. Conduction:

- Average o/p voltage $v_o = \frac{3v_{ml}}{\pi}\cos\alpha$

RMS voltage $v_{or} = \sqrt{\frac{3}{2\pi}} v_{ml} \left[\frac{\pi}{3} + \frac{1}{2}\left[\sin\left(2\alpha + \frac{\pi}{3}\right) - \sin\left(2\alpha + \frac{4\pi}{3}\right)\right]\right]^{1/2}$

or

$$v_{or} = v_{ml}\sqrt{\frac{3}{2\pi}}\left[\frac{\pi}{3} + \frac{\sqrt{3}}{2}\cos 2\alpha\right]^{1/2}$$

- Average value of Thyristor current $I_T = \frac{I_o}{3}$
- RMS value of Thyristor current $I_{Tr} = \frac{I_o}{\sqrt{3}}$
- RMS value of supply current $I_{sr} = \sqrt{\frac{2}{3}} I_o$

Performance Parameter :

$$i_s = \sum_{6k+1}^{\infty} \frac{4I_o}{n\pi}\sin\left(\frac{n\pi}{3}\right)\sin n(wt - \alpha)$$

- Triplen harmonic does not exist in supply current so minimum order harmonic is 5 harmonic.
- RMS value of fundamental component of supply current $I_{s1} = \frac{\sqrt{6}}{\pi} I_o$
- Displacement factor DF = cosα
- Distortion factor $g = \frac{3}{\pi}$
- Input power factor $Pf = \frac{3}{\pi}\cos\alpha$
- $THD = \sqrt{\frac{1}{g^2} - 1} = 0.31 = 31\%$
- Active power $P = \sqrt{3} v_{sr} I_{s1} \cos\alpha = v_o I_o$
- Reactive power $Q = P\tan\alpha$
- $\omega_{tc} = 240 - \alpha$ $(\alpha < 60)$
- $\omega_{tc} = 180 - \alpha$ $(\alpha > 60)$
- PIV = v_{ml}
- Average o/p current $I_o = \frac{v_o - E}{R}$ (α < 90)
- Average o/p current as an inverter $I_o = \frac{v_o + E}{R}$ (only for α > 90)

(2) For α > 60 for R Load:

$$v_o = \frac{3v_{ml}}{\pi}[1+\cos(\alpha+60)]$$

$$v_{or} = \sqrt{\frac{3}{2\pi}} v_{ml}\left[\left(\frac{2\pi}{3}-\alpha\right)+\frac{1}{2}\sin\left(2\alpha+\frac{2\pi}{3}\right)\right]^{1/2}$$

- In 3 phase half wave rectifier first pulse start from $\omega_t = 30$ and each pulse width = 120

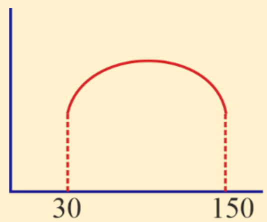


Fig. 3.9.

So at any α, voltage $Mag. = V_{MP}\sin(wt+30)$

- In 3-ϕ full wave rectifier first pulse start from $wt = 60$ and each pulse width is 60

  So for any firing angle, voltage $Mag. = v_{ml}\sin(\alpha+60)$

- In 3ph converter, $P.f$ can be find out $\sqrt{3}v_{sr}I_{sr}Pf = v_o I_o$
- For constant current $I_o = I_{or}$

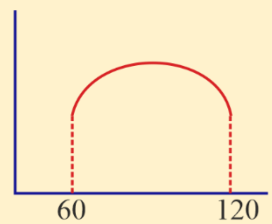


Fig. 3.10.

For P pulse converter (in general) average o/p voltage $v_o = v_{ml}\left(\frac{P}{\pi}\right)\sin\left(\frac{\pi}{p}\right)\cos\alpha$

3.7. 3ϕ Semi Converter

- If $\alpha < 60$ it work as a 6 pulse converter
- If $\alpha \geq 60$ it work as a 3 pulse converter width of pulse $= 60 - \alpha$

  $= 60 + \alpha$

- Average o/p voltage $v_o = \frac{3v_{ml}}{2\pi}(1+\cos\alpha)$
- PIV = v_{ml}

For α ≤ 60°:

FD does not conduct

- Average value of Thyristor current $I_T = \frac{I_o}{3}$
- RMS value of Thyristor $I_{Tr} = \frac{I_o}{\sqrt{3}}$
- RMS value of supply current $I_{sr} = \sqrt{\frac{2}{3}}I_o$

For α ≥ 60 :

FD will conduct

- Conduction of each Thyristor (π – α) for every 2π radian

  Average current, $I_T = \frac{I_o(\pi-\alpha)}{2\pi}$

- RMS value of Thyristor current $I_{Tr} = I_o\sqrt{\frac{(\pi-\alpha)}{2\pi}}$
- RMS value of supply current $I_{sr} = I_o\sqrt{\frac{(\pi-\alpha)}{\pi}}$
- Average value of FD current $I_{FD} = I_o \frac{\left(\alpha-\frac{\pi}{3}\right)}{\frac{2\pi}{3}}$
- RMS value of FD current $I_{FDr} = I_o\sqrt{\frac{\left(\alpha-\frac{\pi}{3}\right)}{\frac{2\pi}{3}}}$

3.8. Effect of Source Inductance

- One pulse converter/(1ϕ) half wave

$$I_o = \frac{v_{ml}}{wL_s}\left[\cos\alpha - \cos(\alpha+\mu)\right]$$

$$v_o = \frac{v_{ml}}{2\pi}(1+\cos\alpha) - f\ L_s I_o$$

- During overlapping period, SCR and FD both conduct simultaneously.

3.8.1. Two Pulse Converter

$$I_o = \frac{V_{ml}}{2wL_s}\left[\cos\alpha - \cos(\alpha+\mu)\right]$$

$$v_o = \frac{2v_{ml}}{\pi}\cos\alpha - 4f\ L_s I_o$$

$$v_o = \frac{2v_{ml}}{\pi}\cos(\alpha+\mu) + 4f\ L_s I_o$$

- During overlapping period incoming as well as out going SCR conduct simultaneously.
- Each SCR conduct (π + μ)period.
- Displacement factor = $\cos\left(\alpha+\frac{\mu}{2}\right)$
- Inductive voltage regulation = $\frac{\cos\alpha - \cos(\alpha+\mu)}{2}$

3.8.2. 6 Pulse Converter

$$I_o = \frac{v_{ml}}{2wL_s}[\cos\alpha - \cos(\alpha+\mu)]$$

$$v_o = \frac{3v_{ml}}{\pi}\cos\alpha - 6f\ L_s I_o$$

$$v_o = \frac{3v_{ml}}{\pi}\cos(\alpha+\mu) + 6f\ L_s I_o$$

During over lapping period 3 SCR conduct simultaneously either 2 from positive group & one from negative group or 2 from negative group & one from positive group.

3.8.3. 3 Pulse Converter:

$$v_o = \frac{3v_{ml}}{2\pi}\cos\alpha - 3f\ L_s I_o$$

In general:

Average o/p voltage of 1ϕ full converter

$$v_o = \frac{2v_{ml}}{\pi}\cos\alpha - 4f\ L_s I_o - I_o r_s - 2v_T$$

r_s = Source resistance

L_s = Source Inductance

v_T = Voltage drop of SCR

Average current $I_o = \frac{v_o - E}{R}$

Average current as Inverter $I_o = \frac{v_o + E}{R}$

Average o/p voltage for 3ϕ full converter $v_o = \frac{3v_{ml}}{\pi}\cos\alpha - 6f\ L_s I_o - 2I_o r_s - 2v_T$

Average current $I_o = \frac{V_o - E}{R}$

Average current as Inverter $I_o = \frac{V_o + E}{R}$

3.9. Dual Converter

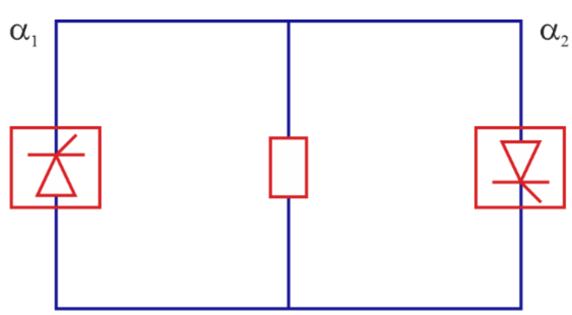


Fig. 3.11.

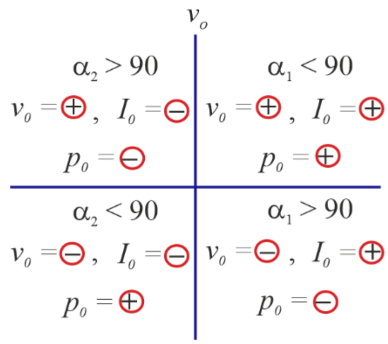


Fig. 3.12.

→ Non circulating current type
→ Circulating current type

- In circulating current type $\alpha_1 + \alpha_2 = 180$ one act as a rectifier & second act as a inverter.
- Mid point reactor is used to limit circulating current
- Peak value of circulating current

$$i_{cp} = \frac{\sqrt{3}v_{ml}}{wL}[1 - \sin\alpha_1]$$

4 CHOPPER

4.1. Step down/Class A Chopper

4.1.1. R Load

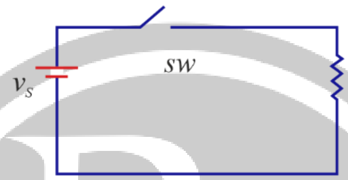


Fig. 4.1.

- Pulse width = T_{ON}
- Duty cycle $\alpha = \frac{T_{ON}}{T}$
- $T_{ON} = \alpha T$ & $T_{OFF} = (1-\alpha)T$
- Average o/p voltage, $V_o = \alpha V_s$

  or

  $v_o = \alpha(v_s - v_T)$

  Where v_T = voltage drop across switch

- Average o/p current $I_o = \frac{v_o}{R}$
- RMS o/p voltage $v_{or} = \sqrt{\alpha}(v_s - v_T)$
- RMs o/p current $I_o = \frac{\sqrt{\alpha}(v_s - v_T)}{R}$
- $I_S = I_O$
- Effective I/P resistance $R_s = \frac{v_S}{I_S}$
- Chopper efficiency $n = \frac{V_{or} I_{or}}{V_S I_O}$ $(I_O = I_S)$

4.1.2. RL/RLE Load Continuous Conduction

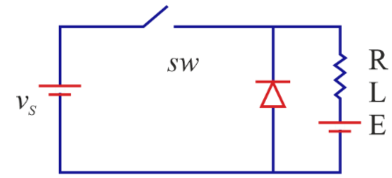


Fig. 4.2.

- $V_o = \alpha V_s$
- $I_o = \dfrac{V_o}{R}$ for RL load
- $I_o = \dfrac{V_o - E}{R}$ for RLE load
- $I_S = \alpha I_o$
- $I_{FD} = (1-\alpha) I_o$
- $v_o(t) = \alpha v_s + \sum_{n=1}^{\infty} \dfrac{2v_s}{n\pi} \sin n\pi\alpha \sin(nwt + \theta_n)$

$$\theta_n = \tan^{-1}\left(\frac{\cos n\pi\alpha}{\sin n\pi\alpha}\right)$$

- To reduce n harmonic $\left(\alpha = \dfrac{1}{n}\right)$
- $VRF = \sqrt{FF^2 - 1} = \sqrt{\dfrac{1}{\alpha} - 1}$
- Minimum current $I_{mx} = \dfrac{v_s}{R}\left[\dfrac{e^{Tm/Ta} - 1}{e^{T/Ta} - 1}\right] - \dfrac{E}{R}$
- Maximum current $I_{mx} = \dfrac{v_s}{R}\left[\dfrac{1 - e^{-Tn/Ta}}{1 - e^{-T/Ta}}\right] - \dfrac{E}{R}$
- Peak to peak current ripple for any α

$$\Delta I = \frac{v_s}{R} \frac{\left[1 - e^{-\alpha T/Ta}\right]\left[1 - e^{-(1-\alpha)T/Ta}\right]}{[1 - e^{-T/Ta}]}$$

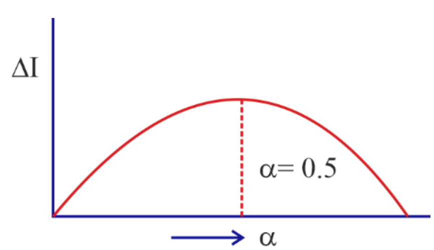


Fig. 4.3.

So ΔI will be maximum for $\alpha = 0.5$

$(\Delta I)_{\max} = \dfrac{V_S}{4fL}$ (applicable only for $\alpha = 0.5$)

- For any other α it is always better to use this formula to find out ΔI

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

4.1.3. Step Down Chopper with RLE Load

Discontinuous Conduction:

- Whether current is continuous or discontinuous it may be checked by two methods.

(i) $\alpha^1 = \frac{T_a}{T}\ln\left[1 + me^{(T/T_a - 1)}\right]$ $m = \frac{E}{v_s}$, $T_a = \frac{L}{R}$

Is actual $\alpha < \alpha^1 \Rightarrow$ discontinuous.

(ii) Find out $I_{\min} = \frac{v_S}{R}\left[\frac{e^{T_{on}/T_a} - 1}{e^{T/Ta} - 1}\right] - \frac{E}{R}$

If $I_{\min}$= negative current is discontinuous.

- In case of discontinuous conduction $v_o = \alpha v_s + E\left(1 - \frac{t_x}{T}\right)$

t_x = extinction time

- RMS output voltage $v_{or} = \left[\alpha v_s^{\,2} + E^2\left(1 - \frac{t_x}{T}\right)\right]^{1/2}$

4.2. Step up Chopper

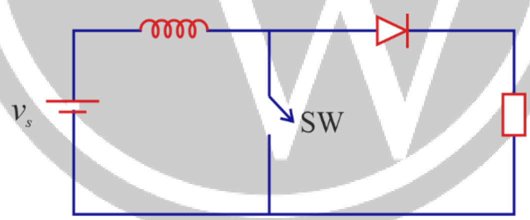


Fig. 4.4.

- Pulse width = T_{OFF}
- Average o/p voltage $V_o = \frac{V_s}{1 - \alpha}$

4.3. Step up/down Chopper

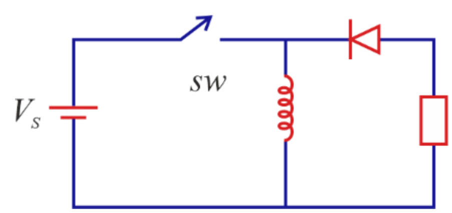


Fig. 4.5.

- Pulse width = T_{OFF}
- Average o/p voltage $V_o = \frac{\alpha}{1-\alpha} V_s$.

Buck Regulator:

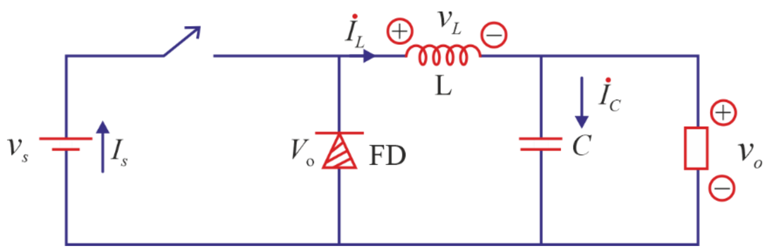


Fig. 4.6.

- Peak to peak current ripple $(v_s - v_o) = L \frac{\Delta I_L}{T_{ON}}$

$$\Delta I_L = \frac{\alpha(1-\alpha)v_s}{fL} = \Delta I_C$$

- Average supply current $V_s I_s = V_o I_o$

$$I_s = \alpha I_o = \frac{\alpha^2 v_s}{R}$$

- Peak to peak voltage ripple

$$\Delta v_C = \frac{\Delta I_L}{8fC} = \frac{\alpha(1-\alpha)V_s}{8f^2LC}$$

- $(I_L)_{mx} = (I_{sw})_{mx} = (I_s)_{mx} = I_L + \frac{\Delta I_L}{2}$ and $I_L = I_O$
- $(I_L)_{mn} = (I_{sw})_{mn} = (I_S)_{mn} = I_L - \frac{\Delta I_L}{2}$
- Critical Inductance $I_L = I_o = \frac{\Delta I_L}{2}$

$$L_C = \frac{(1-\alpha)R}{2f}$$

- Critical capacitance $v_o = \frac{\Delta v_C}{2}$,

$$C_C = \frac{(1-\alpha)}{16f^2L_C} = \frac{1}{8fR}$$

- $(i_C)_{mx} = (l_L)_{mx} - I_o$
  $(i_C)_{mn} = (l_L)_{mn} - I_o$

Discontinuous Conduction:

- $V_o = \frac{\alpha}{\beta} V_s$ $\quad (v_O)_{\text{discontinuous}} > (v_O)_{\text{Continuous}}$

$$I_{mx} = \frac{(V_S - V_O)\alpha T}{L} = \frac{\alpha(1-\alpha)v_S}{fL}$$

$$\frac{V_S(V_S - V_O)\alpha T}{2L} = \frac{V_O^2}{R}$$

(Use this formula when R and L is given)

Boost Regulator:

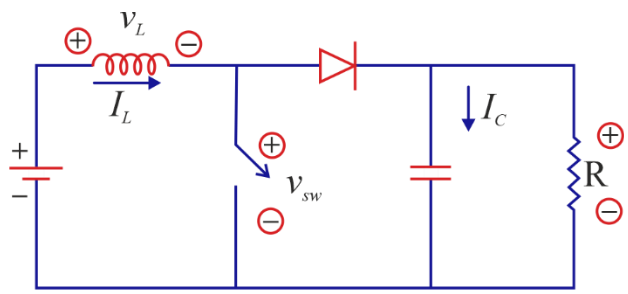


Fig. 4.7.

- Peak to peak current ripple $V_s = L\frac{\Delta I_L}{T_{ON}}$

$$\Delta I_L = \frac{\alpha v_s}{f\,L}$$

- Average supply current $V_S I_S = V_O I_O$

$$I_S = \frac{I_O}{(1-\alpha)} = \frac{V_S}{(1-\alpha)^2 R}$$

- Peak to peak voltage ripple

$$\Delta v_C = \Delta v_o = \frac{I_o \alpha}{f\,C}$$

- Average current through switch $I_{sw} = \frac{\alpha}{1-\alpha}\cdot I_o$
- Average current of Inductor = $I_L = I_S = \frac{I_o}{(1-\alpha)}$
- $(I_L)_{mx} = (I_s)_{mx} = (I_{sw})_{mx} = I_L + \frac{\Delta I_L}{2}$
- $(I_L)_{mn} = (I_s)_{mn} = (I_{sw})_{mn} = I_L - \frac{\Delta I_L}{2}$
- Critical Inductance $I_L = \frac{\Delta I_L}{2}$

$$L_C = \frac{\alpha(1-\alpha)^2 R}{2f}$$

- Critical capacitance $v_o = \frac{\Delta v_C}{2}$,

$$C_C = \frac{\alpha}{2\,f\,R}$$

- $(I_S)_{RMS} = (I_L)_{RMS}$

- $(I_{sw})_{RMS} = \sqrt{\alpha}(I_L)_{RMS}$
- $(I_D)_{RMS} = \sqrt{1-\alpha}(I_L)_{RMS}$

Discontinuous Conduction:

$$I_{mx} = \frac{\alpha v_s}{f L}$$

$$v_o = \frac{v_s}{1-\alpha/\beta}$$

$(v_o)_{Discont.} > (v_o)_{cont.}$

Buck-Boost Regulator:

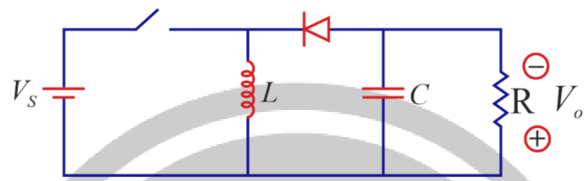


Fig. 4.8.

- Peak to peak current ripple

$$V_s = L\frac{\Delta I_L}{T_{ON}}$$

$$\Delta I_L = \frac{\alpha v_s}{f L}$$

- Average supply current $V_s I_s = V_o I_o$

$$I_s = \frac{\alpha}{1-\alpha} I_o \equiv \left(\frac{\alpha}{1-\alpha}\right)^2 \frac{v_s}{R}$$

- Average Inductor current = $I_L = \frac{I_o}{(1-\alpha)}$
- $(I_L)_{mx} = (I_s)_{mx} = (I_{sw})_{mx} = I_L + \frac{\Delta I_L}{2}$
- $(I_L)_{mn} = (I_s)_{mn} = (I_{sw})_{mn} = I_L - \frac{\Delta I_L}{2}$
- Peak to peak capacitor voltage ripple $\Delta v_c = \frac{I_o \alpha}{f C}$
- Critical Inductance $I_L = \Delta I_L / 2$

$$L_C = \frac{(1-\alpha)^2 R}{2f}$$

- Critical capacitance $v_o = \frac{\Delta v_c}{2}$

$$C_C = \frac{\alpha}{2 f R}.$$

- $(I_s)_{RMS} = (I_{sw})_{RMS} = \sqrt{\alpha}(I_L)_{RMS}$
- $(I_D)_{RMS} = \sqrt{1-\alpha}(I_L)_{RMS}$

Discontinuous Conduction:

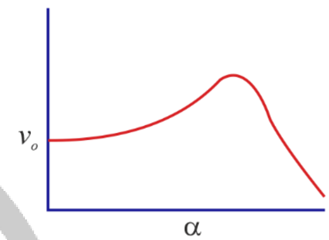
$$I_{mx} = \frac{\alpha v_s}{f\,L}$$

$$v_o = v_s \frac{\alpha/\beta}{1-\alpha/\beta}$$

$$(v_o)_{Discont.} > (v_o)_{cont.}$$

4.3.1. Effect of Source Inductance in boost Regulator

$$v_o = \frac{v_s}{(1-\alpha) + \frac{r}{R(1-\alpha)}}$$

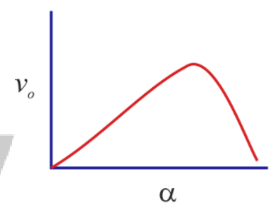


v_o is maximum at $\alpha = 1 - \sqrt{\frac{r}{R}}$

$$(v_s)_{mx} = \frac{v_s}{2}\sqrt{\frac{R}{r}}$$

4.3.2. Effect of Source Inductance on Buck Boost Regulator

$$v_o = \frac{\alpha v_s}{(1-\alpha) + \frac{r}{R(1-\alpha)}}$$



v_o is maximum at $\alpha = 1 + \frac{r}{R} - \sqrt{\frac{r}{R}\left(1+\frac{r}{R}\right)}$

$$(v_o)_{max} = \frac{v_s}{2}\left[\sqrt{1+\frac{r}{R}} - 1\right]$$

4.4 Voltage Commutated Chopper

- Peak circulating current = $\frac{v_s}{w_o L} = v_s\sqrt{\frac{C}{L}}$
- Peak current through main Thyristor = $I_o + v_s\sqrt{\frac{C}{L}}$
- Peak current through auxillary Thyristor = I_o
- PIV of main and auxillary Thyristor = V_s
- PIV of freewheel diode = $2V_s$.
- Circuit turn off time of auxillary Thyristor = $\frac{\pi}{2}\sqrt{LC}$

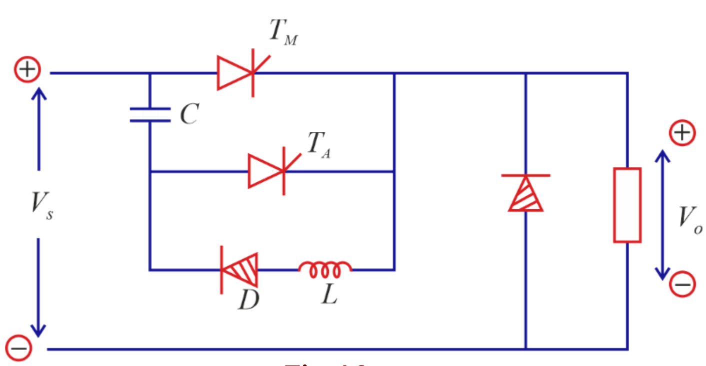


Fig. 4.9.

- Circuit turn off time of main Thyristor $t_c = \frac{CV_s}{I_o}$
- Minimum turn ON time $(T_{ON})_{mx} = \pi\sqrt{LC}$
- Minimum duty cycle = $\frac{\pi\sqrt{LC}}{T}$
- Effective on period $T_{ON}{}^1 = T_{ON} + \frac{2cv_s}{I_o}$
- Average o/p voltage $T_{ON}{}^1 = T_{ON} + \frac{2cv_s}{I_o}$

$$v_o = \frac{\left[T_{ON} + \frac{2cv_s}{I_o}\right]}{T} v_s$$

- Minimum load voltage $(v_o)_{mn} = \frac{\left[\pi\sqrt{Lc} + \frac{2cv_s}{I_o}\right]}{T} v_s$
- Maximum on period $(T_{ON})_{mx} = \left(T - \frac{2cv_s}{I_o}\right)$
- Maximum load voltage $(v_o)_{mx} = \frac{\left(T - \frac{2cv_s}{I_o}\right) + \frac{2cv_s}{I_o}}{T} v_s = v_s$
- Total commutation period = $2tc = \frac{2cv_s}{I_o}$

4.5. Current Commutated Chopper

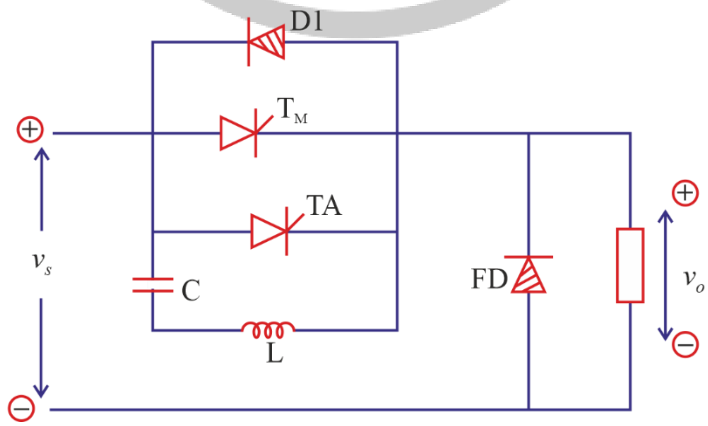


Fig. 4.10.

- $l_{cp} > I_o$

$v_s = xI_o$ $x = 1.4$ to 3

- Circuit turn off time of main SCR $t_{cA} = \frac{(\pi - 2\theta_1)}{w_o}$ $\theta_1 = \sin^{-1}\left(\frac{I_o}{I_{cp}}\right)$
- Circuit turn off time of auxillary SCR $t_{cA} = \frac{(\pi - \theta_1)}{w_o}$
- Total commutation period = $\left(\frac{5\pi}{2} - \theta_1\right)\sqrt{Lc} + cv_s \frac{(1-\cos\theta_1)}{I_o}$
- Peak capacitor voltage = $v_s + I_o\sqrt{\frac{L}{c}}$

4.6. Load Commutated Chopper

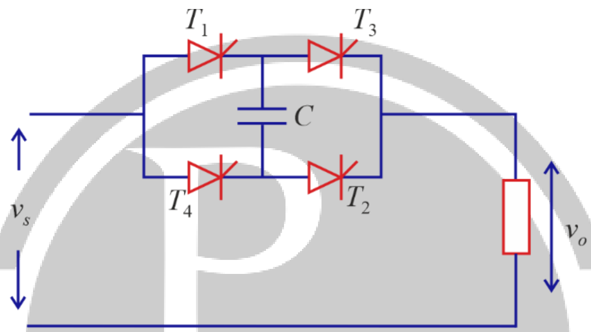


Fig. 4.11.

- Output voltage $v_o = \frac{\frac{2v_s}{2}T_{ON}}{T} = V_s T_{ON} f$
- $T_{ON} = \frac{2CV_S}{I_o}$
- So $V_o = \frac{2V_s^2 C f}{I_o}$
- Maximum chopping frequency $f = \frac{1}{T_{ON}}$
- Circuit turn off time = $\frac{T_{ON}}{2} = \frac{cv_s}{I_o}$
- Total commutation Interval = $2t_c = \frac{2cv_S}{I_o}$

❑❑❑

5 INVERTER

5.1. INTRODUCTION

5.1.1. Single Phase Half Bridge Inverter

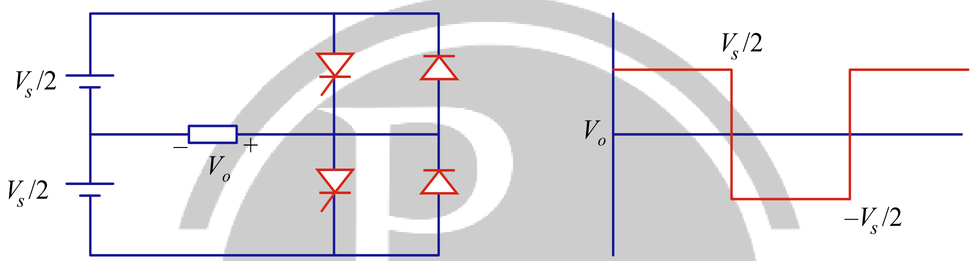


Fig. 5.1.

- RMS output voltage = $\frac{V_s}{2}$
- Fourier Series = $\sum_{n=1,3,5}^{\infty} \frac{2V_s}{n\pi} \sin n\omega t$
- RMS of Fundamental Voltage

$$V_{o1} = \frac{\sqrt{2}V_s}{\pi}$$

- Distortion factor, $g = \frac{V_{o1}}{V_{or}} = \frac{2\sqrt{2}}{\pi}$
- THD = $\sqrt{\frac{1}{g^2} - 1}$ = 0.4834.
- n^{th} harmonic component $i_{on} = \frac{2V_s}{n\pi z_n} \sin(n\omega t - \theta_n)$

$$z_n = \sqrt{R^2 + \left(n\omega L - \frac{1}{n\omega C}\right)^2}$$

$$\theta_n = \tan^{-1}\left(\frac{n\omega L - \frac{1}{n\omega C}}{R}\right)$$

5.1.2. Single Phase Full Bridge Inverter

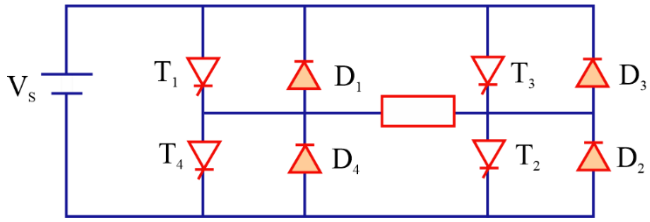


Fig. 5.2.

- RMS O/P voltage $V_{or} = V_s$
- Fourier series

$$V_0(t) = \sum_{n=1,3,5...}^{\infty} \frac{4Vs}{n\pi} \sin n\,wt$$

- RMS value of fundamental component = $\frac{2\sqrt{2}\,Vs}{\pi}$
- $g = \frac{2\sqrt{2}}{\pi}$ and THD = 48.34%
- When Vo = ⊕, Io = ⊕ (T_1 T_2 conduct)

  Vo = ⊖, Io = ⊖ (T_3 T_4 conduct)

  Vo = ⊕, Io = ⊖ (D_1 D_2 condcut)

  Vo = ⊖, Io = ⊕, (D_3 D_4 conduct)

- In a time period of 2π

  Each Diode conduct $= \phi = \tan^{-1}\left(\frac{X_L - X_C}{R}\right)$

  each SCR conduct = $\phi = (\pi - \phi)$

  for purely inductive load current is triangular in nature and each didoe and SCR conduct for $\frac{\pi}{2}$

- For RL load current vary from $-I_0$ to I_0

$$I_0 = \frac{V_S}{R} - \frac{1-e^{-RT/2L}}{1+e^{-RT/2L}} \text{ (in stcady state)}$$

- In RLC under damped circuit

  load commutation is possible is $t_c > t_q$

$$\omega_c = \tan^{-1}\frac{X_C - X_L}{R}$$

$$t_c = \frac{1}{\omega}\left[\tan^{-1}\frac{X_C - X_L}{R}\right]$$

- n harmonic component of current

$$i_{on} = \frac{4v_s}{n+1|Z_n|}\sin(n\omega t - \theta_n)$$

$$Z_n = \sqrt{R^2 + \left(n\omega L - \frac{1}{n\omega c}\right)^2}$$

$$\theta_n = \tan^{-1}\frac{\left(n\omega L - \frac{1}{n\omega c}\right)}{R}$$

- In 1ϕ full inverter/half converter.
  RMS value of thyristor current,

$$(I_T)^2_{RMS} = \frac{1}{2\pi}\int_0^{\phi}(I_m \sin\omega t)^2 d(\omega t)$$

$$I_m = \sqrt{2}\, I_{o1}$$

I_{o1} = RMS value of F.C. of load current

$$\phi = \tan^{-1}\frac{X_c - X_L}{R}$$

RMS values of Diode current

$$(I_D)^2_{\text{RMS}} = \frac{1}{2\pi}\int_0^{\pi-\phi}(I_m \sin\omega t)^2\, d(\omega t)$$

5.1.3. Phase Inverter (180° Mode)

- Each SCR conduct for 180°
- Positive & negative group SCR trigger at a interval of 120°
- Same phase SCR trigger at a interval of 180°

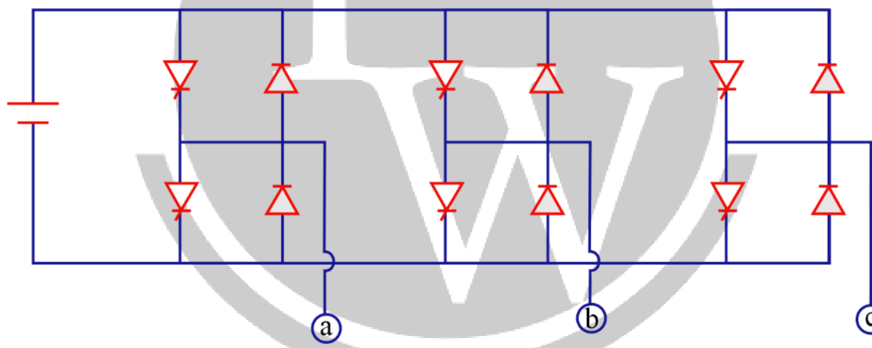


Fig. 5.3.

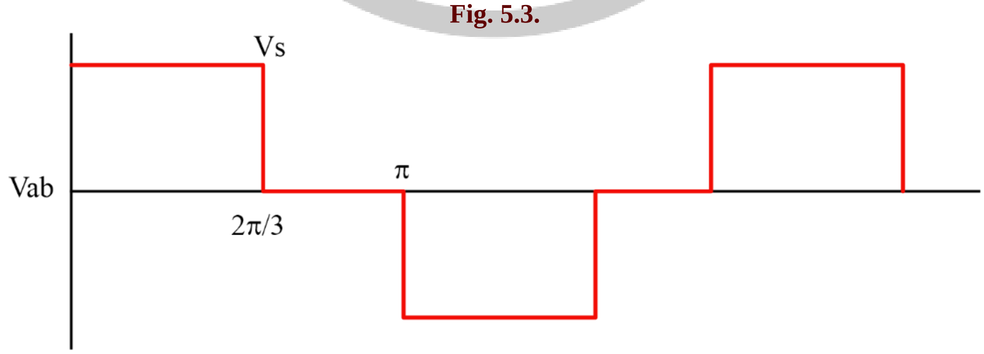


Fig. 5.4.

Only Remember line voltage is a quasi square wave of pulse width $\frac{2\pi}{3}$ in a time period of 2π & magnitude V_S

$$V_{Lr} = V_s \times \frac{\sqrt{2\pi/3}}{\pi} = \sqrt{\frac{2}{3}}V_s$$

$$V_{Phr} = \frac{V_{Lr}}{\sqrt{3}} = \frac{\sqrt{2}}{3}V_s$$

$$I_{phr} = \frac{V_{phr}}{R} = \frac{\sqrt{2}Vs}{3R}$$

$$I_{Lr} = I_{phr} = \frac{\sqrt{2}Vs}{3R}$$

$$P = 3\,I_{ph}^2 R = \frac{3V_{ph}^2}{R} = 3.\frac{2}{g}\frac{Vs^2}{R} = \frac{2}{3}\frac{Vs^2}{R}$$

$$I_{Tr} = \frac{I_{Lr}}{\sqrt{2}} = \frac{Vs}{3R}$$

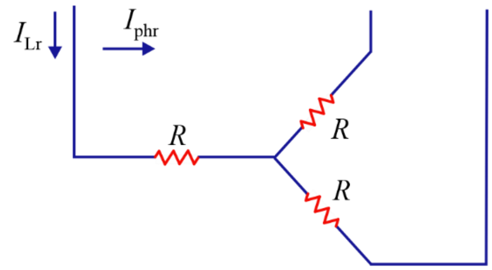


Fig. 5.5.

- P = Vs Is

$$I_s\,(avg) = P/Vs$$

- Average thyristor current $I_T = \frac{I_s}{3}$
- Fourier series of line voltage

$$V_{L(t)} = \sum_{6k\pm1}^{n} \frac{4Vs}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin n\left(wt + \frac{\pi}{6}\right)$$

Fundament component of line voltage

$$V_{LI} = \frac{\frac{4Vs}{\pi}.1.\frac{\sqrt{3}}{2}}{\sqrt{2}} = \frac{\sqrt{6}}{\pi}Vs$$

Fundament component of phase voltage $V_{ph_1} = \frac{V_{L_1}}{\sqrt{3}} = \frac{\sqrt{2}V_s}{\pi}$

Fundament component of current $I_{ph_1} = \frac{V_{ph}L}{R} = \frac{\sqrt{2}V_s}{\pi R}$

Fundament component of power = $I_{ph_1}^2 R$

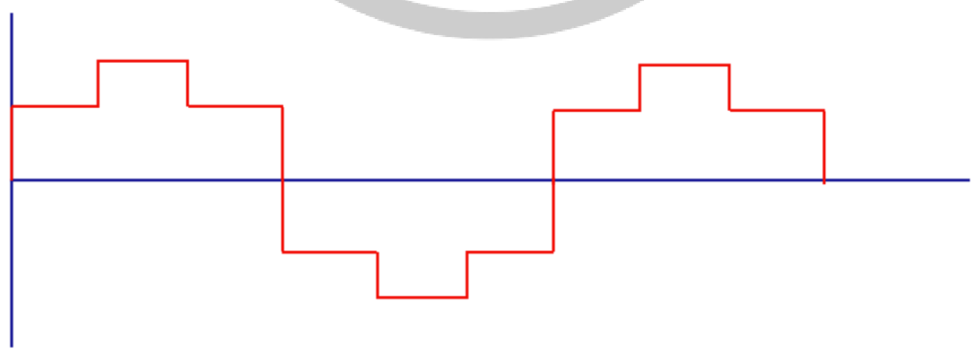


Fig. 5.6.

$$v_a(t) = \sum_{6k+1}^{n} \frac{2V_s}{n\pi}\sin n\omega t \quad \text{(No need to Remember)}$$

Per phase current $I_{ph}(t) = \frac{2V_s}{n\pi|Z_n|}\sin(n\omega t - \theta_n)$

$$\theta_n = \tan^{-1}\frac{X_{Ln} - X_{Cn}}{R}$$

- For RLC load
  Diode conduct for $= \phi$
  SCR conduct for $= (\pi - \phi)$
- Both line voltage and phase voltage does not have any triplen harmonics.

$$g = \frac{3}{\pi} \text{ and T. H. D} = 31\%$$

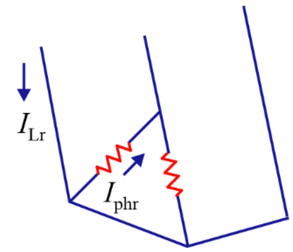


Fig. 5.7.

Delta Load:

$$V_{phr} = V_{Lr} = \frac{\sqrt{2}V_s}{3}$$

$$I_{phr} = \frac{\sqrt{2}Vs}{3R} \quad I_{Lr} = \frac{\sqrt{2}}{\sqrt{3}}\frac{Vs}{R}$$

5.1.4. 3 phase Inverter (120° Mode)

- Each SCR conduct only for 120°.
- Positive and negative group SCR are trigged at 120° time interval
- Same phase SCR are trigger at time interval of 180°

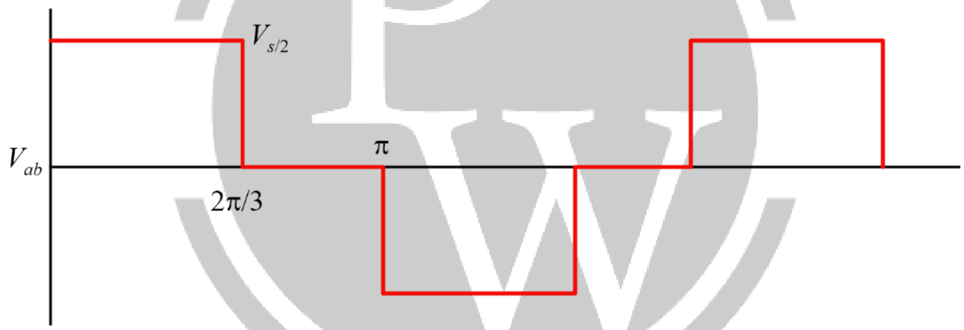


Fig. 5.8.

Only remember that phase voltage is quasi square wave of magnitude Vs/2. The pulse width is $\frac{2\pi}{3}$ is a time period of 2π.

$$V_{phr} = \frac{V_s}{2} \times \sqrt{\frac{2\pi/3}{\pi}} = \frac{V_s}{\sqrt{6}}$$

$$V_{Lr} = \sqrt{3} \times \frac{Vs}{\sqrt{6}} = \frac{Vs}{\sqrt{2}}$$

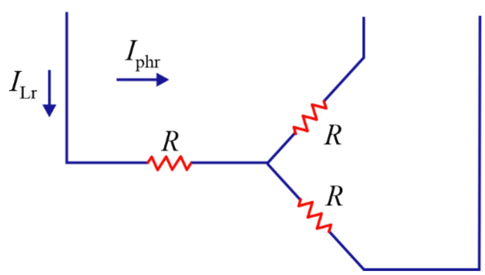


Fig. 5.9.

$$I_{phr} = \frac{V_{phr}}{R} = \frac{Vs}{R\sqrt{6}}$$

$$I_{Lr} = I_{phr} = \frac{Vs}{R\sqrt{6}}$$

$$P = 3I_{phr}^2 R = 3\frac{Vs^2}{R^2 6} \times R = \frac{Vs^2}{2R}$$

- RMS value of thyristor current $I_{Tr} = \frac{I_{Lr}}{\sqrt{2}} = \frac{Vs}{R\sqrt{12}}$

$$P = V_s I_s$$

So avg value of supply current = $\frac{P}{Vs}$

- Average thyristor current $I_T = \frac{I_S}{3}$

Fourier series of phase voltage

$$\underset{(a)}{V_{ph}}(T) = \sum_{6+\pm 1}^{n} \frac{2Vs}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\pi}{3} \sin\left(n\left(wt + \frac{\pi}{6}\right)\right)$$

Fourier Component of phase voltage

$$V_{ph_1} = \frac{\frac{2Vs}{\pi}.\sin\frac{\pi}{3}}{\sqrt{2}} = \frac{\frac{2Vs}{\pi}.\frac{\sqrt{3}}{2}}{\sqrt{2}} = \sqrt{\frac{3}{2}}\frac{Vs}{\pi}$$

$$I_{ph_1} = \frac{V_{ph_1}}{R} = \frac{\sqrt{3}}{\sqrt{2}}\frac{Vs}{\pi}.\frac{1}{R}$$

Fundamental component of power $P_1 = I_{ph_1}^2 R$

Fundamental component of line voltage $V_{L1} = \sqrt{3}V_{ph_1} = \frac{3}{\sqrt{2}}\frac{Vs}{\pi}$

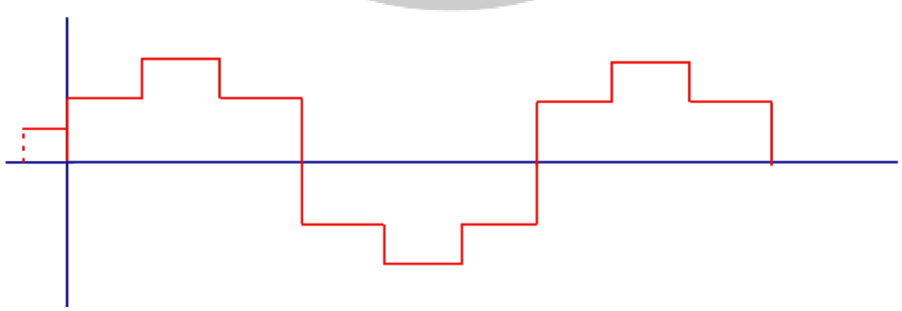


Fig. 5.10.

$$V_{ab}(t) = V_L(t) = \sum_{6k \pm 1}^{n} \frac{3V_s}{n\pi} \sin n\left(\omega t + \frac{\pi}{3}\right)$$

- Both line and phase voltage are free from triplen harmonics
- $g = \frac{3}{\pi}$ THD = 31%

Delta Load:

$$V_{phr} = V_{Lr} = \frac{Vs}{\sqrt{2}}$$

$$I_{phr} = \frac{Vs}{\sqrt{2}R}$$

$$I_{Lr} = \frac{\sqrt{3}}{\sqrt{2}}\frac{Vs}{R}$$

$$P = 3I_{phr}^2 R = \frac{3V_s^2}{2R}$$

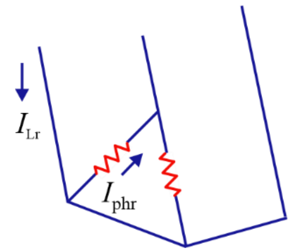


Fig. 5.11.

5.2. Voltage and Frequency Control in Inverter

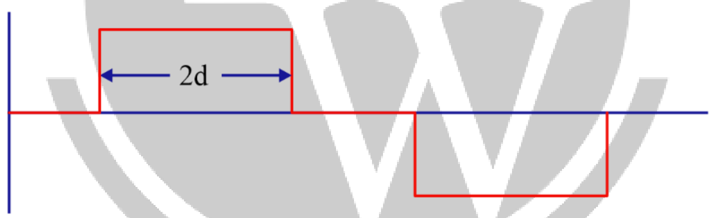
- Frequency can be change by changing the time of conduction for thyristor

- In External control of voltage we use extra power controller. It increase cost and filter circuit requirement.

5.2.1. Internal Control of Voltage

Single Pulse Width Modulation:

- Single pulse per half cycle



5.12.

$$V_{0(t)} = \sum_{n=1,3,5}^{\infty} \frac{4Vs}{n\pi}\sin\frac{n\pi}{2}\sin nd \sin nwt$$

$$V_{or} = Vs\sqrt{\frac{2d}{\pi}}$$

$$V_{o1} = \frac{2\sqrt{2}Vs}{\pi}\sin d$$

- Frequency modulating Index $m_f = \frac{f_c}{f_r}$
- No of pulses per half cycle = $\frac{M_f}{2}$
- In multiple pulse modulation. The amplitude of lower harmonic is reduced by amplitude of higher harmonic is increased.

Sinusoidal Pulse width Modulation:

- Triggcring pulses is generated by comparing sinusoidal reference wave with high frequency triangular wave.
- If peak of carrier wave coincide with zero of ref wave.

$$\text{No of pulse per half cycle} = \frac{f_c}{2f_r} = \frac{m_f}{2}$$

- If zero of carrier wave coincide with zero of reference wave.

$$\text{No of pulses per half cycle} = \frac{f_c}{2f_r} - 1 = \frac{m_f}{2} - 1$$

$$g = \frac{v_{o1}}{v_{or}}$$

$$\text{THD} = \sqrt{\frac{1}{g^2} - 1}$$

- To eliminate n harmonic pulse width $2d = \frac{2\pi}{n}$

Multiple pulse width modulation:

- Multiple pulses per half cycle.
- Triggering pulses is generated by comparing square ref (modulating) pulse with high frequency. triangular pulse.
- Pulse width depend on amplitude modulating Index $\text{MI} = \frac{V_r}{V_c}$

$$\text{Single Pulse width} = (1 - MI)\frac{\pi}{N}$$

- Frequency of o/p voltage is same as frequency of reference wave.
- No of pulses per half cycle is determined by carrier wave frequency.
- Dominating harmonic = $2N \pm 1$

  N = No of pulses per half cycle.
- For multiple and sinusoidal pulse width modulation.

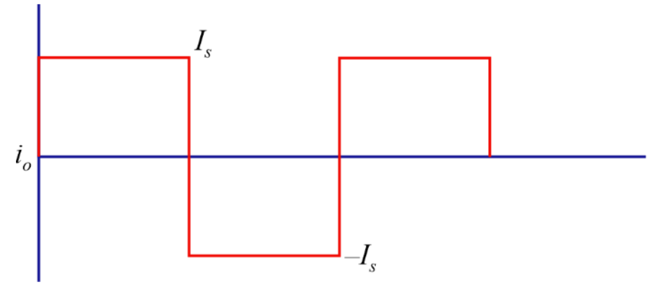
  Fundamental component of output voltage = $V_{DC} \times \text{MI} \sin w_0 t$

$$\text{Max}^n \text{ (Peak) value of F.C} = V_{bc} \times \text{MI}$$

$$\text{RMS value of fundamental component} = \frac{V_{DC} \times \text{MI}}{\sqrt{2}}$$

5.3. Current Source Inverter

- Output current wave form does not depend on load but voltage wave from depend on load.
- Mainly suitable for capacitive type of load.



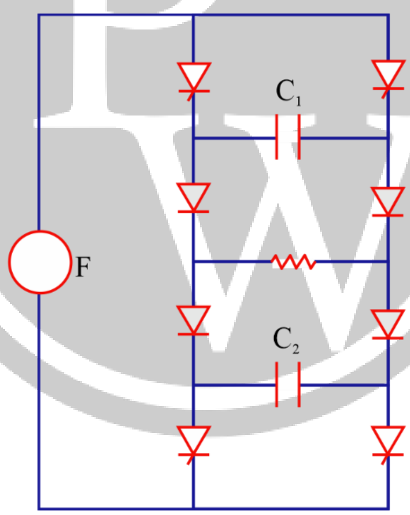
5.13.

$$i_o(t) = \sum_{n=1,3,5...}^{\infty} \frac{4I_s}{n\pi} \sin n\omega t$$

$$g = \frac{2\sqrt{2}}{\pi}$$

- THD = 0.4834 = 48.34%
- IN CSI we need a switch which can operats forward conducting, forward blocking and reverse blocking.
- In VSI we need a switch which can operate forward conducting, forward blocking and reverse blocking.

5.4. ASCI (Auto Sequential Commutated Inverter)



5.14.

- Use class C commutation technique

$$\text{Maximum frequency} = \frac{1}{8RC} \text{ or } \frac{1}{10RC}$$

where $C = C_1 + C_2$

- circuit turn off time $t_C = RC \ln 2$

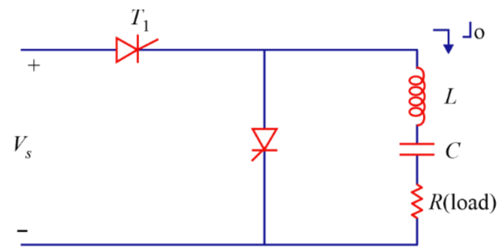
$$C = C_1 + C_2$$

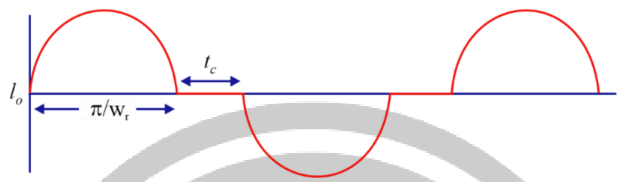
- If it is fed from supply voltage then Inductance connected in series of source to line current change.

$$V_s = L_s \frac{di}{dt}$$

$$L_S = \frac{V_s}{di/dt}$$

5.5. Series Inverter





5.15.

$$T = 2\left(\frac{\pi}{\omega_r} + t_c\right)$$

$$\xi_o = \frac{R}{2L} \qquad \omega_o = \frac{1}{\sqrt{LC}}$$

$$\omega_r = \sqrt{\omega_o^2 - \xi^2}$$

$$t_c = \left(\frac{\pi}{\omega} - \frac{\pi}{\omega_r}\right)$$

$$i(t) = \frac{V_s + V_{co}}{\omega_r L} e^{-\xi t} \sin \omega_r t$$

V_{CO} = Initial voltage of capacitor.

Maximum current occur at $t_1 = \dfrac{\pi}{2\omega_r}$

$$I_{omax} = \frac{Vs + V_{CO}}{W_{rL}} e^{-\xi t_1}$$

$$I_{RMS} = \frac{I_{omax}}{\sqrt{2}}$$

❑❑❑