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KREATRYX

K Notes

POWER ELECTRONICS AND DRIVES

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Contents

Manual for K-Notes 2
Power Semi-Conductor Devices 3
Phase Controlled converter 10
Chopper 15
Inverters 21
AC - AC Converters 26

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Manual for K-Notes

Why K-Notes?

Towards the end of preparation, a student has lost the time to revise all the chapters from his / her class notes / standard text books. This is the reason why K-Notes is specifically intended for Quick Revision and should not be considered as comprehensive study material.

What are K-Notes?

A 40 page or less notebook for each subject which contains all concepts covered in GATE Curriculum in a concise manner to aid a student in final stages of his/her preparation. It is highly useful for both the students as well as working professionals who are preparing for GATE as it comes handy while traveling long distances.

When do I start using K-Notes?

It is highly recommended to use K-Notes in the last 2 months before GATE Exam (November end onwards).

How do I use K-Notes?

Once you finish the entire K-Notes for a particular subject, you should practice the respective Subject Test / Mixed Question Bag containing questions from all the Chapters to make best use of it.

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Power Semi-Conductor Devices

Properties of ideal switch

1. Conduction state , $V_{ON} = 0, -\infty \le I_{ON} \le \infty$
2. Blocking state , $V_{OFF} = 0, -\infty \le V_{OFF} \le \infty$
3. Ideal switch can change its state instantaneously $T_{ON} = 0$, $T_{OFF} = 0$
4. No power loss while switching.
5. Stable under all operating conditions.

Classification of switches

1. **Uncontrolled switch (Passive switch)**

   Switching state cannot be controlled by any control signal E.g. Diode

2. **Semi-controlled switch**

   Only one switching state can be controlled by an external control signal. E.g. SCR

3. **Fully controlled switch**

   If both switching states can be controlled by switchable control signal. E.g. BJT, MOSFET.

Other Classification

1. **Unipolar switch**

   The switch can block only one polarity of voltage when it is in OFF state.

2. **Bipolar switch**

   This switch can block both polarity of voltage when it is in blocking state.

3. **Unidirectional switch**

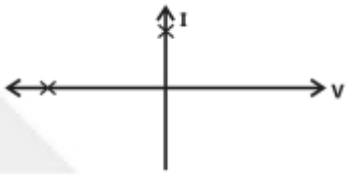
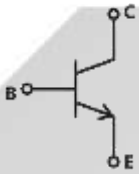
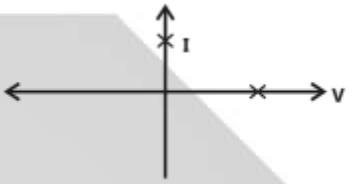
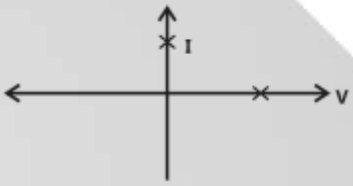
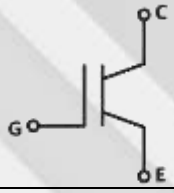
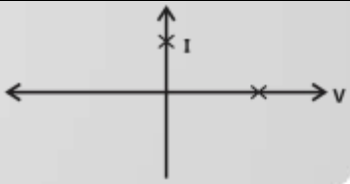
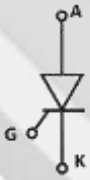
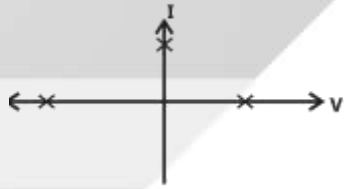
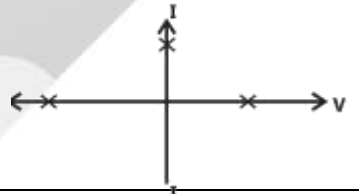
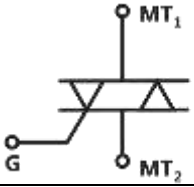
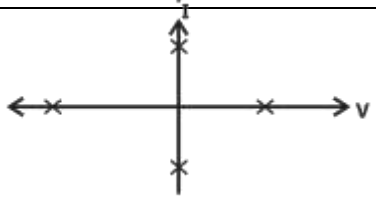
   This switch can carry current in only one direction when it is in conduction state.

4. **Bidirectional switch**

   This switch can carry current in both the directions when it is in conduction state.

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Ideal characteristics of power semiconductor switches

Device	Characteristic
Diode 	
BJT 	
MOSFET 	
IGBT 	
SCR 	
GTO 	
TRIAC 	

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Power loss in a switch

1) The average power has in a switch is given by

$$P = \frac{1}{T}\int_o^T vidt$$

Where v = instantaneous voltage

i = instantaneous current

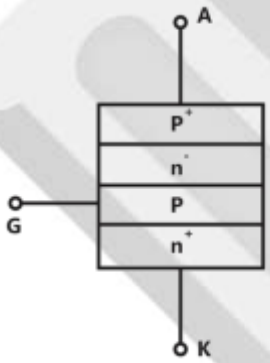
2) If the device is modeled as a resistance, as in case of a MOSFET

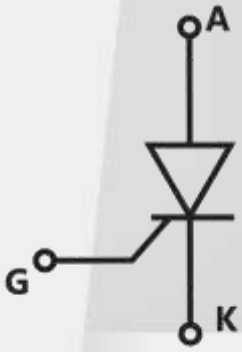
$$P = I_{rms}^2 R_{ON} = V_{rms}^2 / R_{ON}$$

3) If the device is modeled as a voltage source.

$$P = V I_{avg}$$

Silicon Controlled Rectifier





- In forward blocking mode, J_1, J_3 are forward biased and J_2 is reverse biased.
- In forward conduction mode, J_2 breakdown, J_1, J_3 are forward biased.
- In reverse blocking mode, J_1, J_3 are reverse biased & J_2 is forward biased.

Latching Current

This is the minimum value of anode current above which SCR turns ON. This is related to minimum gate pulse width requirement for SCR.

Holding current

Minimum value of anode current below which SCR turns OFF.

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Slope of characteristics = $\left(\frac{di}{dt}\right)$

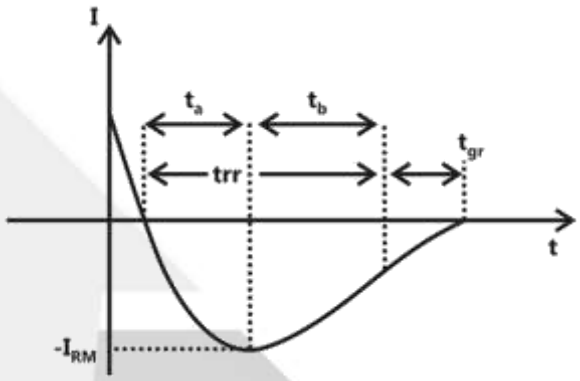
If $t_a \approx t_{rr}$

Area under the curve = Q_R

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

$$I_{RM} = \left(di/dt\right) t_{rr}$$

$$Q_R = \frac{1}{2}\left(di/dt\right)^2 t_{rr}$$



Device & Circuit Turn-off time

- Device turn off time, $t_q = t_{rr} + t_{gr}$
  t_{rr} = reverse recovery time
  t_{gr} = gate recovery time
- Circuit turn-off time (t_c) is the time period for which communication circuit applies reverse voltage across SCR after anode current becomes zero.
- For successful communication, $t_c > t_q$

Turn-ON methods of SCR

1) **Forward voltage triggering**
   If $V_{AK} > V_{BO}$, then J_2 breakdown & SCR conducts. This can damage the SCR.

2) $\frac{dV}{dt}$ **Triggering**
   $I_c = C_j \frac{dv}{dt}$, if $\frac{dv}{dt}$ is high, charging current increase and SCR conducts when $I_c > I_{latching}$.

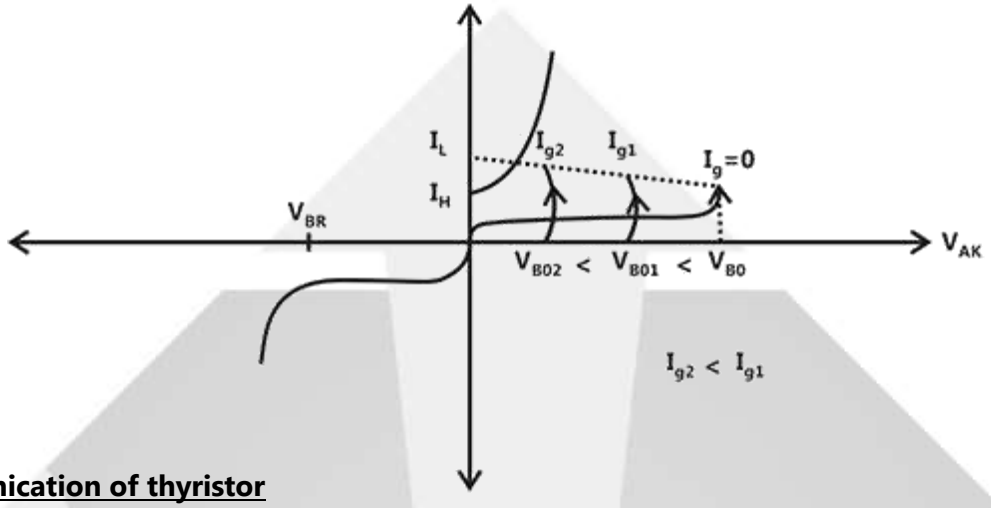
3) **Light Triggering**
   If light is incident on J_2, charge carriers are generated and J_2 starts conducting.

4) **Thermal Triggering**
   When temperature is increased then charge carriers are generated & SCR conducts.

5) **Gate Triggering**
   By applying gate pulse in SCR, V_{BO} is lowered and SCR can easily conduct.

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Static V-I characteristics of SCR



Communication of thyristor

Communication is defined as process of turning OFF the thyristor.

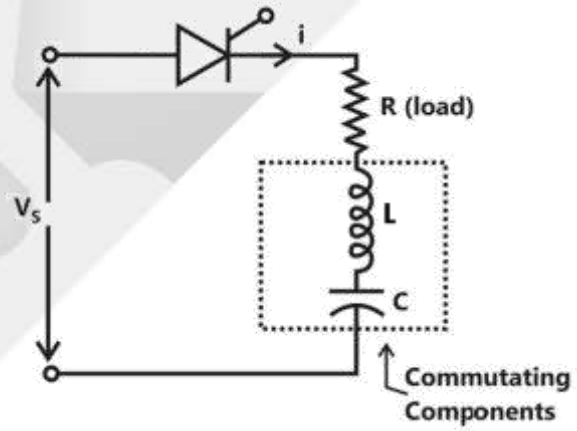
Types of Commutations:

1. **Natural or line communication**

   In this case nature of supply supports the commutation.
   E.g. Rectifier, AC voltage controllers, Step-down cyclo-converters.

2. **Forced Commutation**

1) **Class A commutation**



- Circuit should be under-damped.
- $R^2 < \frac{4L}{C}$ for damped oscillations.
- Ringing frequency, $\omega_r = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$
- Thyristor conducts for a period of = $\frac{\pi}{\omega_r}$

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2) **Class-B commutation or current commutation**

a) $(I_{TM})_{peak} = I_o$

b) $(I_{TA})_{peak} = V_s\sqrt{\frac{C}{L}} = I_P$

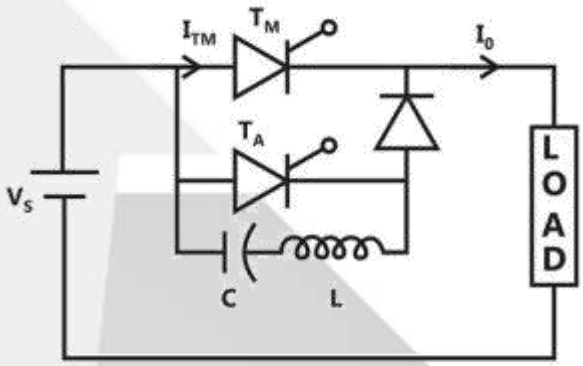
c) Time required to turn OFF T_M after T_A ON

$= \pi\sqrt{LC} + \sqrt{LC}\sin^{-1}\left(\frac{I_o}{I_p}\right)$

d) Conduction time of $T_A = \pi\sqrt{LC}$

e) $t_{CM} = \frac{CV_R}{I_o}$ = circuit turn off time

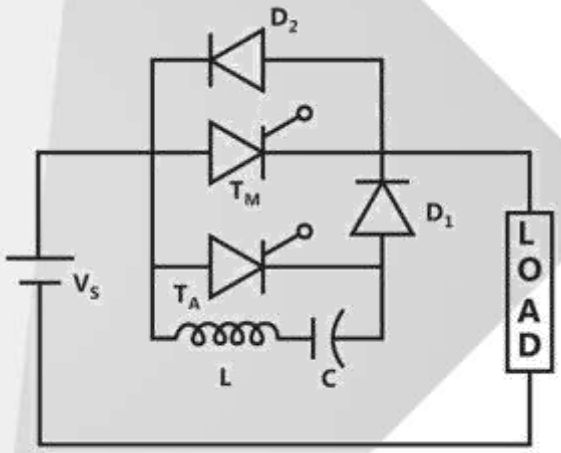
Where $V_R = V_S\cos\left\{\sin^{-1}\left(\frac{I_o}{I_p}\right)\right\}$



Other Implementation

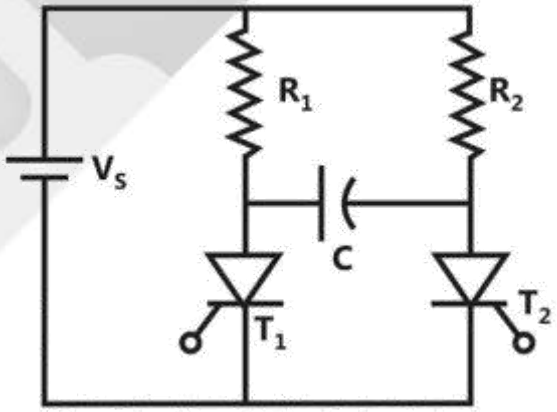
$t_{CM} = \left[\pi - 2\sin^{-1}\left(\frac{I_o}{I_p}\right)\right]\sqrt{LC}$

Rest all parameters remains same.



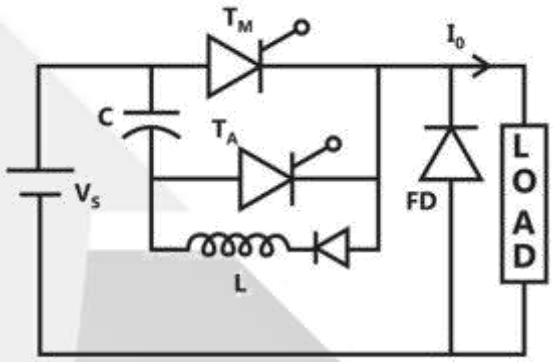
3) **Class-C commutation or Impulse commutation**

- $(I_{T1})_{peak} = \left(\frac{V_S}{R_1} + \frac{2V_S}{R_2}\right)$
- $(I_{T2})_{peak} = \left(\frac{V_S}{R_2} + \frac{2V_S}{R_1}\right)$
- $t_{C1} = R_1(\ln 2)$
- $t_{C2} = R_2(\ln 2)$



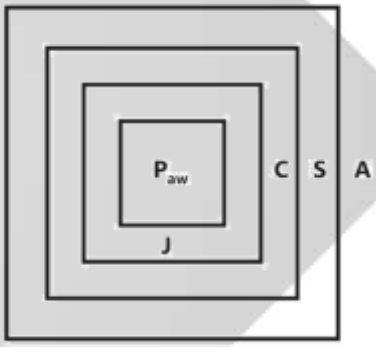
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Class-D commutation or voltage commutation



- $(I_{TM})_{peak} = I_o + V_S\sqrt{\frac{C}{L}}$
- $(I_{TA})_{peak} = I_o$
- $(T_{ON})_{min}$ for $T_M = \pi\sqrt{LC}$
- $t_{CM} = \frac{CV_s}{I_o}$
- Conduction time of $T_A = 2t_{CM} = \frac{2CV_s}{I_o}$
- $(V_O)_{avg} = \frac{V_S}{T}(T_{ON} + 2t_{CM})$, T = Switching internal

Thermal Protection of SCR



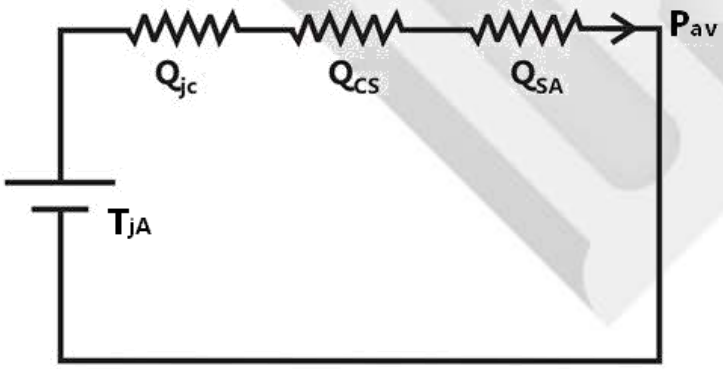
θ_{jc} = Thermal resistance b/w J & C

θ_{CS} = Thermal resistance b/w C & S

θ_{SA} = Thermal resistance b/w S & A

Unit of $\theta = {}^0C/w$

In electrical circuit representation



T_{jA} = Temperature difference b/w J & A

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Phase Controlled converter

Form factor

$$FF = \frac{V_{or}}{V_o}$$

V_{or} : rms value of output voltage.

V_o : Average value of output voltage.

Ripple Factor

$$RF = \sqrt{FF^2 - 1}$$

Distortion factor

$$DF = \frac{V_{01}}{V_{or}}$$

V_{01} : rms value of fundamental components of V_o

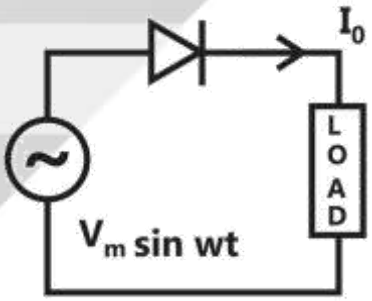
V_{or} : rms value of output voltage.

Total harmonic Distortion

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

Single phase half wave uncontrolled rectifier

	R – load	RL – Load	L – Load
V_O	$\frac{V_m}{\pi}$	$\frac{V_m}{2\pi}(1-\cos\beta)$	0
I_O	$\frac{V_m}{\pi R}$	$\frac{V_m}{2\pi R}(1-\cos\beta)$	$\frac{V_m}{\omega L}$
Y	π	$(\beta > \pi)$	2π
$I_O\,(max)$	$\pi/2$	$(\pi/2, \pi)$	π



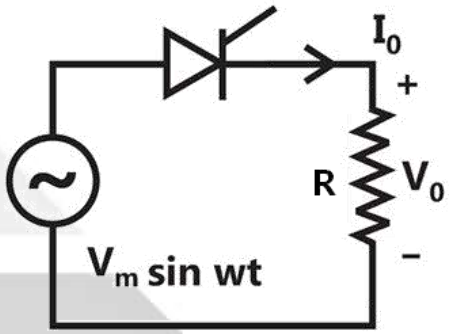
β = Extinction angle, Angle at which ω goes to zero.

- If a free-wheeling diode is connected across the load (RL) that behaves as R-load as output voltage goes to zero after $\omega t = \pi$ when FD conducts.

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Single phase half wave controlled rectifier

i) R – load

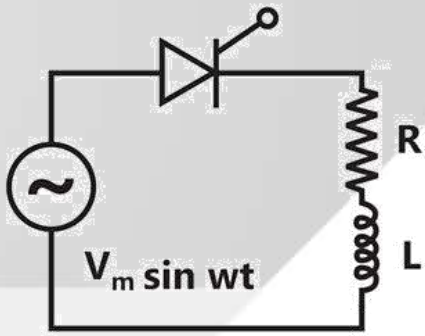


- $V_{O(avg)} = \frac{V_m}{2\pi}(1+\cos\alpha)$
- $I_{O(avg)} = \frac{V_m}{2\pi R}(1+\cos\alpha)$
- $V_{or} = \sqrt{\frac{V_m^2}{4\pi}\left((\pi-\alpha)-\frac{\sin 2\alpha}{2}\right)}$
- Input power factor = $\frac{V_{or}^2/R}{V_S I_S} = \frac{V_{or}}{V_S}$

$$V_S = V_m/\sqrt{2}$$

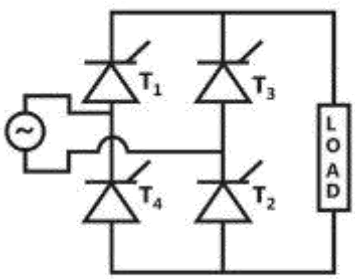
- α = firing angle

ii) R – L load

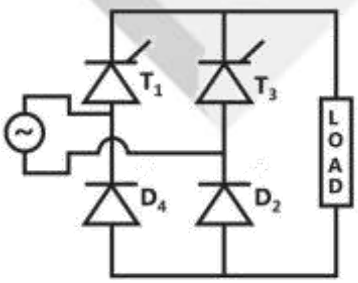


- $V_{o(avg)} = \frac{V_m}{2\pi}(\cos\alpha - \cos\beta)$
- $I_{o(avg)} = \frac{V_m}{2\pi R}(\cos\alpha - \cos\beta)$
- $V_{or} = \frac{V_m}{2\sqrt{\pi}}\sqrt{(\beta-\alpha)+\frac{1}{2}(\sin 2\alpha - \sin 2\beta)}$
- Circuit turn off time, $t_c = \frac{(2\pi-\beta)}{\omega}$

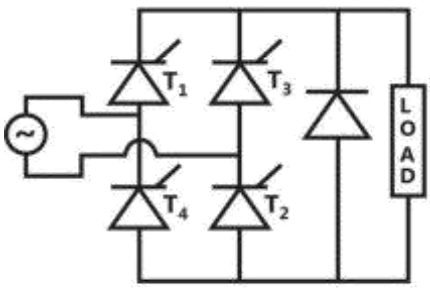
Single phase full – wave rectifier



Fully Controlled



Semi-Controlled



Semi-Controlled

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	$1-\phi$ full converter	$1-\phi$ Semi converter
V_O	$\frac{2V_m}{\pi}\cos\alpha$	$\frac{V_m}{\pi}(1+\cos\alpha)$
I_{S1}	$\frac{2\sqrt{2}}{\pi}I_o$	$\frac{2\sqrt{2}}{\pi}I_O\cos\alpha/2$
I_S	I_o	$I_O\sqrt{\frac{\pi-\alpha}{\pi}}$
DF	$\frac{2\sqrt{2}}{\pi}$	$\frac{2\sqrt{2}}{\sqrt{\pi(\pi-\alpha)}}\cos\alpha/2$
DPF	$\cos\alpha$	$\cos\alpha/2$
IPF	$\frac{2\sqrt{2}}{\pi}\cos\alpha$	$\sqrt{\frac{2}{\pi(\pi-\alpha)}}(1+\cos\alpha)$

DPF: Displacement power factor = $\cos(\text{angle b/w } V_S \text{ \& } I_{S1})$

I_{S1} = fundamental components of I_S

IPF: Input power factor

IPF = DPF x DF

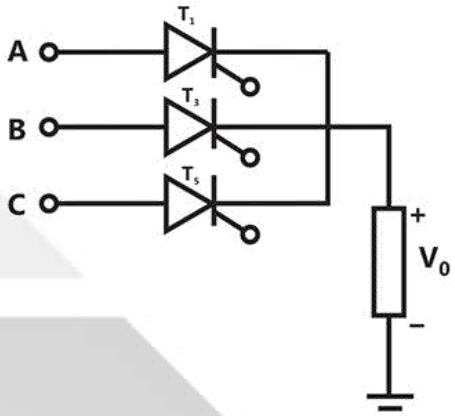
DF: Distortion factor

In case of continuous conductions, outgoing thyristors stop conduction before incoming thyristor start

Load	$1-\phi$ Full converter	$1-\phi$ Semi – converter
R – load	$V_o=\frac{V_m}{\pi}(1+\cos\alpha)$	$V_o=\frac{V_m}{\pi}(1+\cos\alpha)$
R – L load	$V_o=\frac{V_m}{\pi}(\cos\alpha-\cos\beta)$	$V_o=\frac{V_m}{\pi}(1+\cos\alpha)$
RLE – load	$V_o=\left[\frac{V_m}{\pi}(\cos\alpha-\cos\beta)+E(\pi+\alpha-\beta)\right]$	$V_o=\frac{1}{\pi}\left[V_m(1+\cos\alpha)+E(\pi+\alpha-\beta)\right]$

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Three phase half wave controlled rectifier



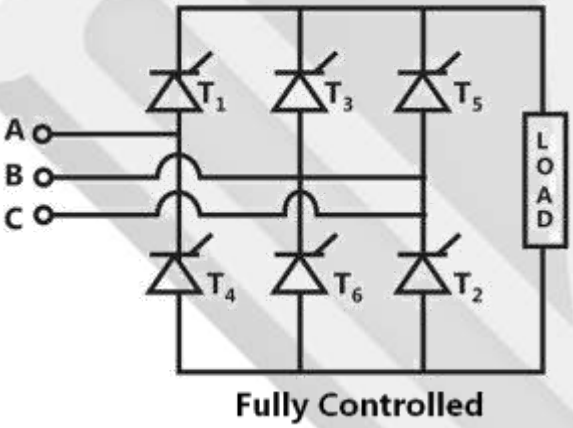
$$V_o = \frac{3V_{ml}}{2\pi}\cos\alpha$$

V_{ml} : Peak value of line voltage

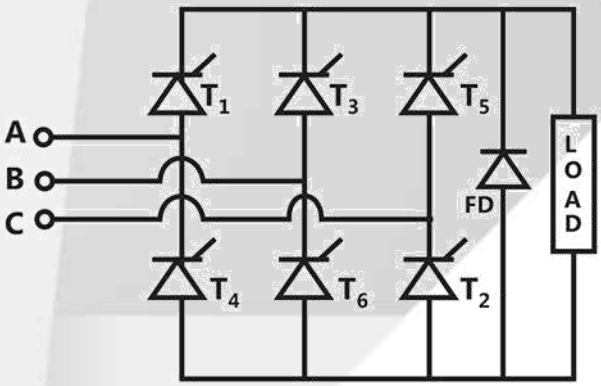
$$V_{or} = V_{mp}\left[\frac{1}{2} + \frac{3\sqrt{3}}{8\pi}\cos 2\alpha\right]^{1/2}$$

V_{mp} : Peak value of phase voltage

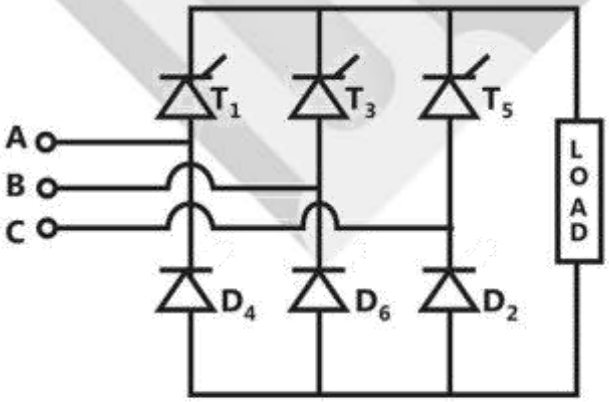
Three phase full wave rectifier



Fully Controlled



Semi-Controlled



Semi-Controlled

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	$3-\phi$ Full converter	$3-\phi$ Semi converter
V_o	$\frac{3V_{ml}}{\pi}\cos\alpha$	$\frac{3V_{ml}}{2\pi}(1+\cos\alpha)$
V_{or}	$V_{ml}\sqrt{\frac{1}{2}+\frac{3\sqrt{3}}{4\pi}\cos 2\alpha}$	Expression varies for $\alpha<60^0$ & $\alpha>60^0$ For $\alpha>60^0$, it becomes 3-pulse converter.
I_{S1}	$\frac{\sqrt{6}}{\pi}I_o$	$\frac{\sqrt{6}}{\pi}I_o\cos\left(\alpha/2\right)$
I_S	$\sqrt{\frac{2}{3}}I_o$	$I_o\sqrt{\frac{\pi-\alpha}{\pi}}$
DF	$\frac{3}{\pi}$	$\sqrt{\frac{6}{\pi(\pi-\alpha)}}\cos\alpha/2$
DPF	$\cos\alpha$	$\cos\alpha/2$
IPF	$\frac{3}{\pi}\cos\alpha$	$\sqrt{\frac{6}{\pi(\pi-x)}}\cos^2\alpha/2$

I_{S1} : Fundamental rms value of source current

I_S : rms value of source current

Effect of source inductance

Assuming source inductance equal to L_S.

Due to source inductance, there is an overlap b/w incoming and outgoing thyristor, given by overlap angle (μ).

For 2-pulse converter

$$V_O=\frac{2V_m}{\pi}\cos\alpha-\frac{\omega L_S}{\pi}I_O$$

$$V_O=\frac{V_m}{\pi}\left[\cos\alpha+\cos(\alpha+\mu)\right]$$

Displacement power factor = $\cos\left(\alpha+\mu/2\right)$

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For 6 – pulse converter

$$V_O = \frac{3V_m}{\pi}\cos\alpha - \frac{3\omega L_S}{\pi} I_O$$

$$V_O = \frac{3V_m}{2\pi}\left[\cos\alpha + \cos(\alpha + \mu)\right]$$

Displacement power factor $= \cos\left(\alpha + \mu/2\right)$

Chopper



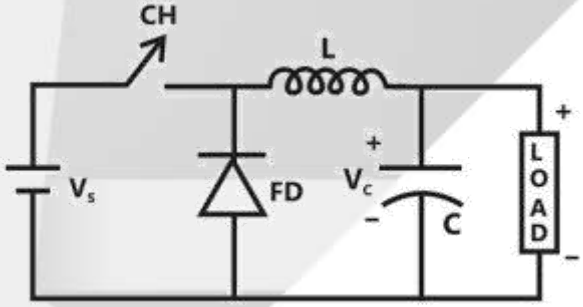
Buck Converter

When CH is ON $(o < t < DT)$

Voltage across inductor $V_L = (V_S - V_O)$

When CH is OFF (DT < t < T)

Voltage across inductor $V_L = V_O$



Applying volt-sec balance across inductor

$$(V_S - V_O) \times DT + (-V_O)[T - DT] = 0$$

$$(V_S - V_O)D - V_O(1 - D) = 0$$

$$\boxed{V_O = DV_S}$$

D = duty cycle = $\frac{T_{ON}}{T}$

Where T = switching period = $1/f$

f = switching frequency

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- Average output voltage = DV_S
- rms output voltage = $\sqrt{D}V_S$
- Average source current = DI_O
- Average current of FD = $(1-D)I_O$

Ripple in output current

When CH is ON $(0 < t < DT)$

$V_L = V_S - V_O = (1-D)V_S$

During this period, since voltage is positive current increase from minimum value to maximum value.

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

$$\Delta t = DT - 0 = DT$$

$$L \times \frac{(\Delta i)}{DT} = (1-D)V_S$$

$$\boxed{\Delta i = \frac{D(1-D)V_S}{fL}}$$

- This formula gives approximate value of output ripple current for maximum ripple, D = 0.5

$$\boxed{(\Delta i)_{max} = \frac{V_S}{4fL}}$$

- $I_{max} = I_O + \frac{\Delta I_L}{2}$
- $I_{min} = I_O - \frac{\Delta I_L}{2}$

Critical Inductance (L_C)

Value of inductance at which inductor voltage waveform is just discontinuous.

$$\boxed{L_c = \frac{(1-D)R}{2f}}$$

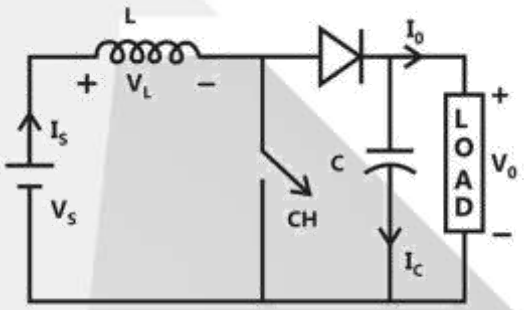
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Critical Capacitance (C_C)

Value of capacitance at which capacitor voltage waveform is just discontinuous.

$$C_C = \frac{1}{8fR}$$

Step-up chopper (Boost converter)



when CH is ON $(0 < t < DT)$, $V_L = V_S$

when CH is OFF $(DT < t < T)$, $V_L = (V_S - V_O)$

Applying volt-sec balance across inductor

$$V_S(DT) + (V_S - V_O)(1-D)T = 0$$

$$V_O = \frac{V_S}{(1-D)}$$

- Since $D < 1$, $V_O > V_S$
- when CH is ON $(0 < t < DT)$, $I_C = -I_O$

  when CH is OFF $(DT < t < T)$, $I_C = -I_L - I_O$

  Applying Ampere – sec balance across capacitor

  $$-I_O(DT) + (I_L - I_O)(1-D)T = 0$$

  $$I_L = \frac{I_O}{(1-D)}$$

Ripple in inductor current

When CH is ON $(0 < t < DT)$, current increase from I_{min} to I_{max}

$$L\frac{\Delta i_L}{DT} = V_S \Rightarrow \Delta i_L = \frac{V_S(DT)}{L} = \frac{DV_S}{fL}$$

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Ripple in output voltage

when CH is ON , $I_C = -I_O$

$$C.\frac{\Delta V_C}{DT} = -I_O$$

$$\Delta V_O = \Delta V_C = \frac{-I_O\,(DT)}{C}$$

-ve sign indicates voltage decrease

$$\therefore \boxed{\Delta V_O = \frac{I_O\,(DT)}{C}}$$

Critical Inductance (L_c)

$$I_L = \frac{\Delta I_L}{2}$$

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

Critical Capacitance (C_c)

$$V_O = \frac{\Delta V_O}{2}$$

$$\boxed{C_C = \frac{D}{2fR}}$$

If inductor also has an internal resistance, then

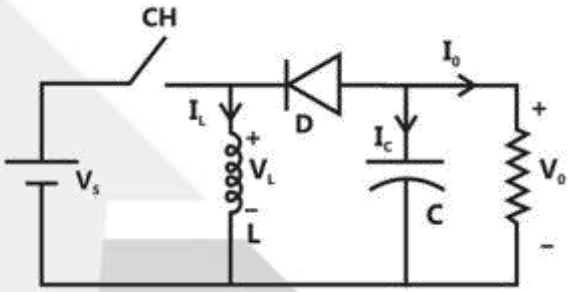
$$V_O = V_S\left[\frac{(1-D)}{r/R + (1-D)^2}\right]$$

r = internal resistance of inductor

R = load resistance

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Buck-Boost Converter



When CH is ON (O < t < DT)

$$V_L = V_S$$

$$I_C = -I_O$$

When CH is OFF (DT < t < T)

$$V_L = V_O$$

$$I_C = -(I_L + I_O)$$

Applying volt-sec balance across inductor

$$V_S(DT) + V_O(1-D)T = 0$$

$$\boxed{V_O = \frac{-DV_S}{(1-D)}}$$

Applying Ampere-sec balance across inductor

$$-I_O(DT) - (I_L + I_O)(1-D)T = 0$$

$$\boxed{I_L = \frac{-I_O}{(1-D)}}$$

$$I_L = \frac{-V_O}{R(1-D)} = \frac{DV_S}{R(1-D)^2}$$

Ripple in inductor current

When CH is ON (O < t < DT)

Inductor current increase from I_{min} to I_{max}

$$L \times \frac{\Delta I_L}{DT} = V_S$$

$$\boxed{\Delta I_L = \frac{DV_S}{fL}}$$

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Ripple in output voltage

When CH is ON (O < t < DT)

Capacitor discharge & voltage decrease from V_{max} to V_{min}

$$\frac{C\Delta V_O}{DT} = -I_O$$

$$\boxed{\Delta V_O = \frac{DI_O}{fC}}$$

Critical inductance (L_c)

$$I_L = \frac{\Delta I_L}{2}$$

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

Critical capacitance (C_c)

$$V_O = \frac{\Delta V_O}{2}$$

$$\boxed{C_C = \frac{I_O(1-D)T}{2V_S}}$$

If internal resistance (r) of inductor is also considered then

$$V_O = \left[\frac{D(1-D)}{r/R + (1-D)^2}\right] V_S$$

R = load resistance

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Inverters

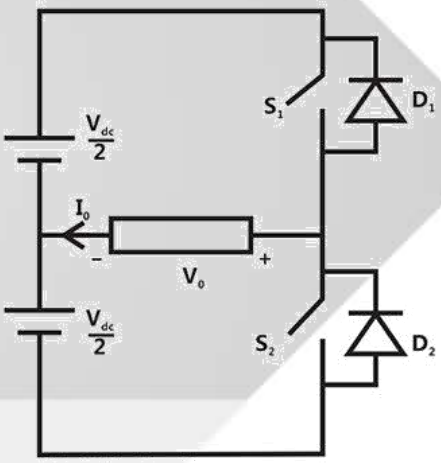
Inverters circuits will convert DC power to AC power at required voltage & required frequency.

Classification

1) **Voltage source Inverter**
   - Input source is a voltage source.
   - Switching device is bidirectional & unipolar.
   - Load voltage depends on source voltage & load current depends on load parameters.

2) **Current source Inverters**
   - Input source is a current source.
   - Switching device is bidirectional & bipolar
   - Load voltage depends on source current & load voltage on load parameters.

Single phase half bridge VSI



When S_1 is ON, $V_O > 0, I_O > 0$

When S_2 is ON, $V_O < 0, I_O < 0$

When D_1 is ON, $V_O > 0, I_O < 0$

When D_2 is ON, $V_O < 0, I_O > 0$

- The output voltage is a square wave of amplitude $\frac{V_{dc}}{2}$
- The fourier series of output voltage is given by

$$V_O = \sum_{n=1,3,5}^{\infty} \frac{2V_{dc}}{n\pi} \sin(n\omega t)$$

- rms value of fundamental components is given by

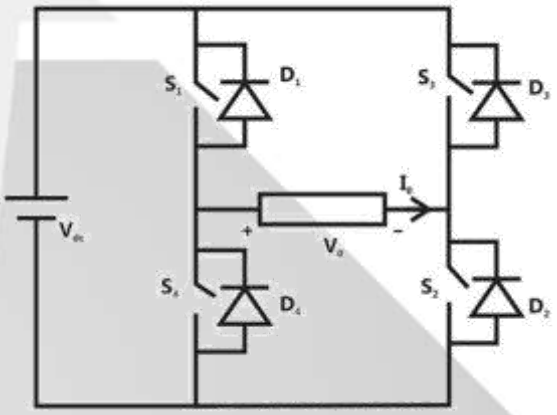
$$V_{or1} = \left(\frac{2V_{dc}}{\pi}\right) \times \frac{1}{\sqrt{2}} = \frac{\sqrt{2}}{\pi} V_{dc}$$

- rms value of output voltage $V_{or} = \frac{V_{dc}}{2}$
- Distortion Factor(DF) = $\frac{V_{or1}}{V_{or}} = \frac{2\sqrt{2}}{\pi}$
- % Total Harmonic Distortion $THD = \sqrt{\frac{1}{DF^2} - 1} = 48.43\%$

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- If load power factor is lagging, then it requires forced commutation.
- If load power factor is leading, then natural commutation occurs.

Single phase Full Bridge VSI



When S_1, S_2 conduct $V_O > 0, I_O > 0$

When D_1, D_2 conduct, $V_O > 0, I_O < 0$

When S_3, S_4 conduct, $V_O < 0, I_O < 0$

When D_3, D_4 conduct, $V_O < 0, I_O > 0$

- The output voltage is a square wave of amplitude V_{dc}
- The fourier series of output voltage is given by

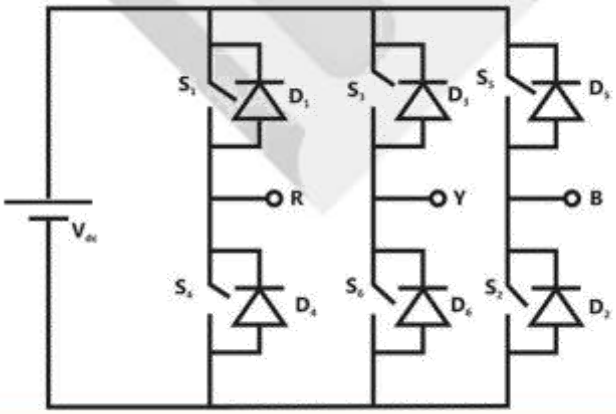
$$V_O = \sum_{n=1,3,5}^{\infty} \frac{4V_{dc}}{n\pi} \sin(n\omega t)$$

- rms value of fundamental components is given by

$$V_{or1} = \frac{\sqrt{2}}{\pi} V_{dc}$$

- rms value of output voltage $V_{or} = V_{dc}$
- Distortion Factor(DF) = $\frac{V_{or1}}{V_{or}} = \frac{2\sqrt{2}}{\pi}$
- % Total Harmonic Distortion $THD = \sqrt{\frac{1}{DF^2} - 1} = 48.43\%$

Three phase full bridge VSI



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180^0conduction mode

In this mode, each switch will conduct for a period of 180^0 and phase displacement between any two poles is 120^0

- Phase voltage

$$\left(V_{ph}\right)_{rms} = \frac{\sqrt{2}}{3}V_{dc}$$

$$V_{RN} = \sum_{n=6k\pm1}^{\infty} \frac{2V_{dc}}{n\pi}\sin\left(n\omega t\right)$$

$\left(V_{R1}\right)$ = rms value of fundamental component of V_{RN}

$$V_{R1} = \frac{\sqrt{2}V_{dc}}{\pi}$$

Distortion factor, $DF = \frac{V_{R1}}{V_{ph,rms}} = \frac{3}{\pi}$

$$THD = \sqrt{\frac{1}{DF^2} - 1} \times 100 = 31\%$$

- Line voltage

$$\left(V_{L-L}\right)_{rms} = \sqrt{\frac{2}{3}}V_{dc}$$

$$V_{RY} = \sum_{n=6k\pm1}^{\infty} \frac{4V_{dc}}{n\pi}\sin\left(n\pi/3\right)\sin\left\{n\left(\omega t + \pi/6\right)\right\}$$

$\left(V_{RY}\right)_1$ = rms value of fundamental component of $V_{RY} = \left(V_{RY}\right)_1 = \frac{\sqrt{6}}{\pi}$

Distortion factor = $3/\pi$

In each phase, each switch conducts for 180^0 out of 360^0

$$\therefore I_{r.rms} = \frac{I_{o,rms}}{\sqrt{2}} = \frac{\sqrt{2}V_{dc}}{3R \times \sqrt{2}} = \frac{V_{dc}}{3R}$$, Where R = load resistance

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Voltage	Total RMS	Fundamental RMS
Phase	$\frac{\sqrt{2}}{3}V_{dc}$	$\frac{\sqrt{2}}{\pi}V_{dc}$
Line	$\sqrt{\frac{2}{3}}V_{dc}$	$\sqrt{6}/\pi\ V_{dc}$

- This conversion from total rms to fundamental rms can be performed by multiplication of $3/\pi = DF$.
- This conversion from phase to line voltage can be performed by multiplication of $\sqrt{3}$.

120^0conduction mode

For each thyristor, conduction angle is 120^0 & last 60^0 for commutation.

- Phase Voltage

$$\left(V_{ph}\right)_{rms} = \frac{V_{dc}}{\sqrt{6}}$$

$$V_{RN} = \sum_{n=6k\pm1}^{\infty} \frac{2V_{dc}}{n\pi}\sin\left(n\pi/3\right)\sin\left(n\omega t + n\pi/6\right)$$

$$V_{R1} = \frac{\sqrt{6}}{\pi}V_{dc}$$

Distortion factor, $DF = 3/\pi$

THD = 31%

- Line Voltage

$$\left(V_{L}\right)_{RMS} = \frac{V_{dc}}{\sqrt{2}}$$

$$\left(V_{RY}\right) = \sum_{n=6k\pm1}^{\infty} \frac{3V_{dc}}{n\pi}\sin\left(n\left(\omega t + \pi/3\right)\right)$$

$$\left(V_{RY}\right)_1 = \frac{3}{\sqrt{2}\pi}V_{dc}$$

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Distortion factor, = $3/\pi$; THD = 31%

In each, phase each switch conducts for 120^0 out of 360^0

$$I_{T,\,rms} = \frac{I_{o,\,rms}}{\sqrt{3}} = \frac{V_{dc}}{\sqrt{2}R}$$

R = load resistance

Voltage	Total RMS	Fundamental RMS
Phase	$\frac{V_{dc}}{\sqrt{6}}$	$\frac{\sqrt{6}}{\pi}V_{dc}$
Line	$\frac{V_{dc}}{\sqrt{2}}$	$\frac{3}{\sqrt{2}\pi}V_{dc}$

- The conversion factor remain same as in 180^0 conduction mode.
- In both 120^0 & 180^0 conduction mode both phase & line voltages are free from even & triplen harmonics.

Voltage control using PWM techniques

1) Single PWM techniques

In this case, width of positive & negative cycle is not π but rather equal to 2d.

$$V_o = \sum_{n=1,3,5}^{\infty} \frac{4V_s}{n\pi}\sin\left(n\pi/2\right)\sin(nd)\sin(n\omega t)$$

To eliminate n^{th} harmonics

Sin (nd) = 0

$d = \pi/n$

Pulse width, $2d = 2\pi/n, 4\pi/n, 6\pi/n, \ldots\ldots\ldots\ldots$

but $2d \le \pi$

To eliminate 3^{rd} harmonics

$3d = \pi$; $d = \pi/3$; $2d = 2\pi/3$

So pulse width of 120^0 is required.

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2) Multiple PWM techniques

Here a single pulse of '2d' width is divided into 'n' pulses each of width $\frac{2d}{n}$.

$$n = \frac{f_c}{2f_r}$$

f_c = carrier signal frequency
f_r = reference signal frequency

AC - AC Converters

These circuits control AC power. They are of 2 types:

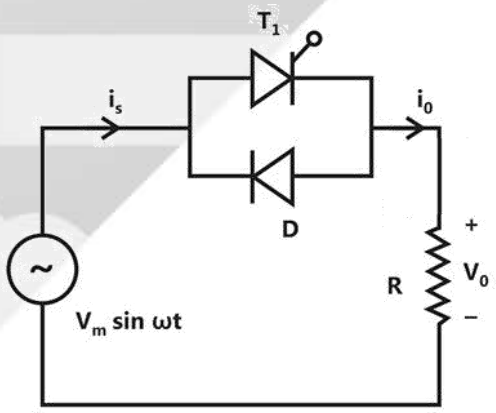
1) AC voltage regulator

2) Cyclo-converter

AC voltage regulator

These transfer AC power from 1 circuit to another by controlling output voltage & fixed frequency.

Single phase half wave ACVR



- $V_{O(avg)} = \frac{V_m}{2\pi}(\cos\alpha - 1)$

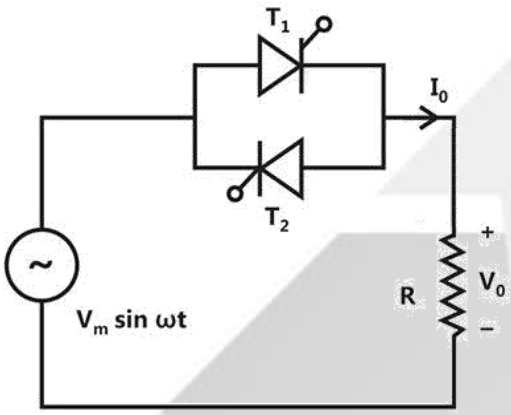
  $I_{O(avg)} = \frac{V_m}{2\pi R}(\cos\alpha - 1)$

- $V_{O(rms)} = \frac{V_m}{2\sqrt{\pi}}\left[(2\pi - \alpha) + \frac{1}{2}\sin 2\alpha\right]^{\frac{1}{2}}$

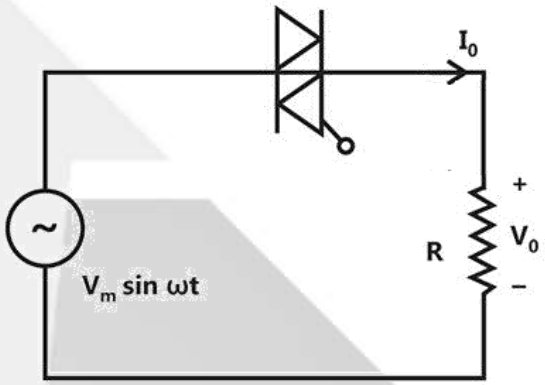
- $pf = \frac{V_{or}}{V_{sr}} = \frac{1}{\sqrt{2\pi}}\left\{(2\pi - \alpha) + \frac{1}{2}\sin 2\alpha\right\}^{\frac{1}{2}}$

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Single phase fully controlled ACVR



High power applications



Low power applications

- $V_{o(avg)} = 0$
- $V_{o(rms)} = \frac{V_m}{\sqrt{2\pi}}\left\{(\pi - \alpha) + \frac{1}{2}\sin 2\alpha\right\}^{\frac{1}{2}}$
- If R – L load is used, then in steady state I_o lags V_o by an angle ϕ

$$\phi = \tan^{-1}\left(\frac{wL}{R}\right)$$

- If $r > \phi$, then above formulas remain valid & output voltage is controllable by controlling α.
- If $r < \phi$, output voltage is not controllable & $\boxed{V_{or} = V_{sr}}$

So, range of firing angle is $\phi < \alpha < 180^0$

Integral cycle control (ON/OFF) control

If in fully controlled ACVR, thyristors conduct for m cycle & are OFF for n cycle then

$$(V_o)_{rms} = V_{sr}\left(\frac{m}{m+n}\right)^{\frac{1}{2}}$$

For R – load, $pf = \frac{V_{or}}{V_{sr}} = \left(\frac{m}{m+n}\right)^{\frac{1}{2}}$

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$$I_{T1(avg)} = \frac{V_m}{\pi R}\left(\frac{m}{m+n}\right)$$

$$I_{T1(rms)} = \frac{V_m}{2R}\left(\frac{m}{m+n}\right)^{\frac{1}{2}}$$

R = load resistance ; V_m is maximum value of V_S

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