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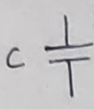
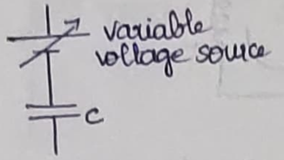
POWER ELECTRONICS

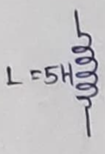
–||– ⇒ stores voltage in the form of electric charge
⇒ stores current in the form of magnetic field



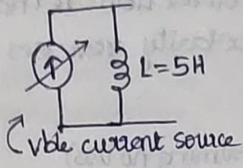
⟷ equivalent to



When no charge is stored in C, voltage source is at 0V.



⟷ equivalent to

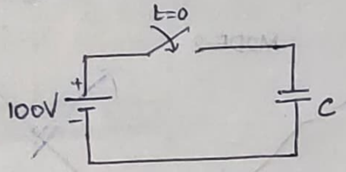


When inductor is not excited, current source gives 0A

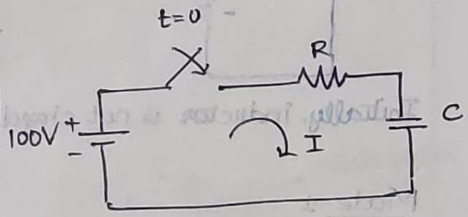
<u>Voltage source</u>: Voltage doesnot change even when it is open ckted.
<u>Current source</u>: Current doesnot change even when it is short-circuited.

x——x

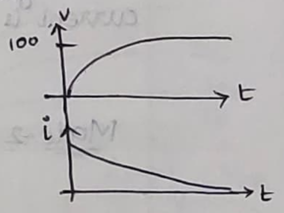
Time Constant



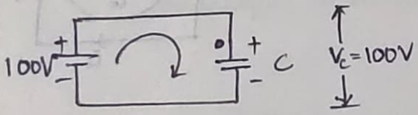
At $t=0$, $V_c = 100V$



At $t=0$, $V_c = (100 - IR)$ Volts
At $t=\infty$, $V_c = 100V$

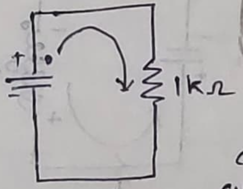


Charging



during charging, current enters through • side

Discharging

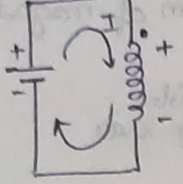


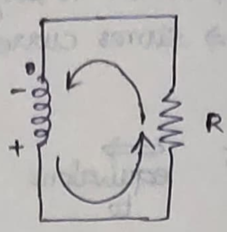
during discharging current leaves through • side

In capacitors,
during charging & discharging ⇒ current polarity changes
⇒ voltage polarity remains same

Inductors

Charging | Discharging





In inductors, during charging & discharging,

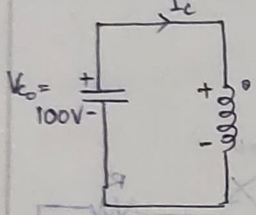
⇒ current direction remains same

⇒ voltage polarity reverses.

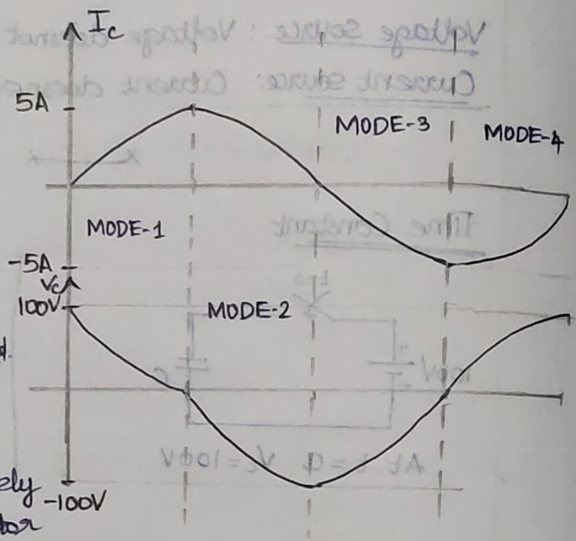
x———x

Tank-Ckt (assuming no loss)

Initially, cap is charged at 100V



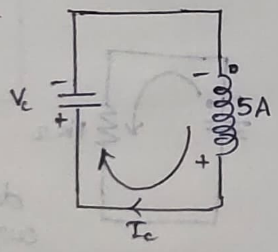
Initially, inductor is not charged.



Mode-1

When capacitor, is completely discharged, $V_c = 0$, the inductor current is at max. position

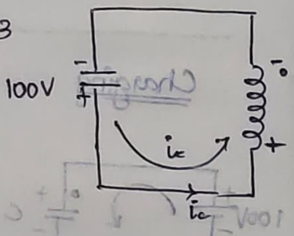
Mode-2



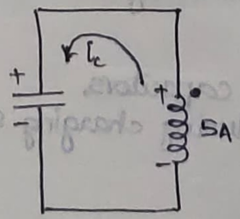
Inductor will charge the capacitor in reverse direction.

Once cap. voltage reaches 100V i_c will be zero

Mode-3



Mode-4



x———x

* Nowadays, in ICs Silicon wafer is not used
* Transistors ⇒ Building blocks of ICs

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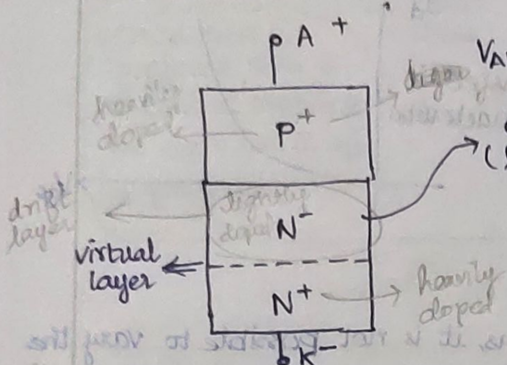
POWER DEVICES

(i) Power ~~Devices~~ diodes
(ii) Power BJT
(iii) IGBT ✓
(iv) MOSFET ✓
(v) SCR ✓
(vi) DIAC
(vii) TRIAC ⟶ doesnot comes under PE

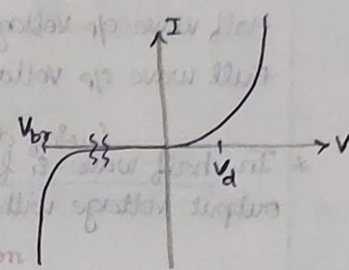
VI Characteristics
Working Principle
Diagram

POWER DIODE



$V_{AK} \Rightarrow +ve \Rightarrow$ diode is forward biased

drift region (lightly doped) ⇒ to increase reverse carrying ability

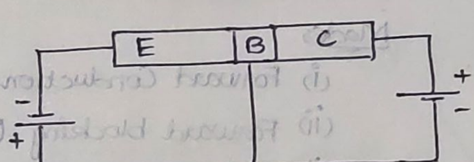


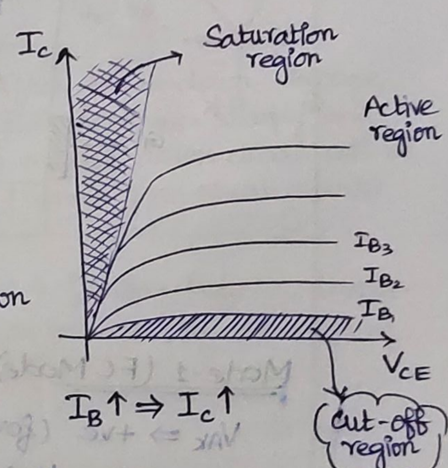
Working principle ⇒ same as normal diode

$V_f = 0.6 \Rightarrow$ for Si
$= 0.3 \Rightarrow$ for Ge

Width of N^- region (lightly doped region) is very large

POWER BJT



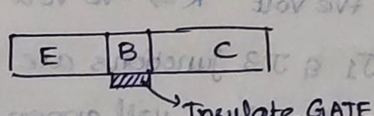


* acts as switch in saturation & cut-off region
  " amplifier in linear region

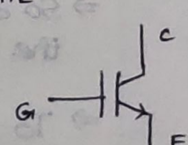
$I_B \uparrow \Rightarrow I_C \uparrow$

IGBT (IGB~~X~~T)

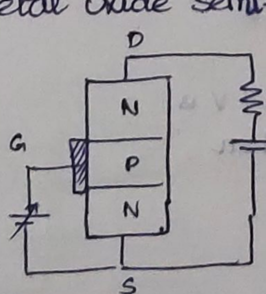
→ Insulated Gate BJT



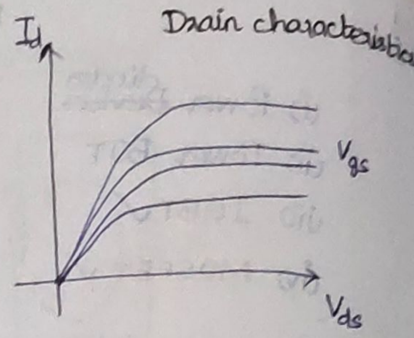
↳ takes very less current to turn on (Advantage) ↳ Power consumption is less



MOSFET - Metal Oxide Semi-conductor Field effect Transistor



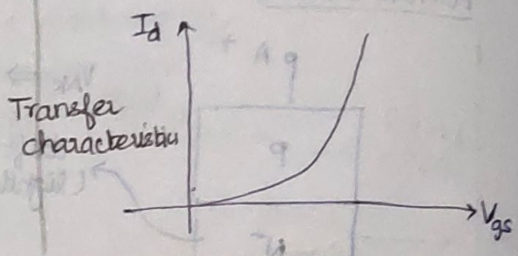
* enhancement type MOSFET
* depletion type MOSFET



SCR - Silicon Controlled Rectifier

Rectifiers already studied,

* Half Wave
* Full Wave
  * → Bridge circuit
  * → Centre-tapped trs



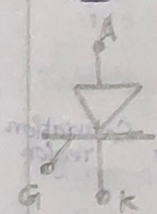
Half wave o/p voltage = V_m/π

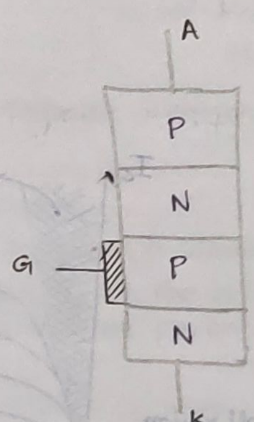
Full wave o/p voltage = $2V_m/\pi$

(using diodes)

* In half wave & full wave rectifiers, it is not possible to vary the output voltage without changing the i/p voltage ⇒ uncontrolled rectifiers

SCR





* three terminal device (A-Anode, K-cathode, G-Gate)

Working Principles

Modes

(i) Forward Conduction (FC)

(ii) Forward blocking (FB)

(iii) Reverse blocking (RB)

Mode-1 (FC Mode)

V_{AK} ⇒ +ve (forward bias)

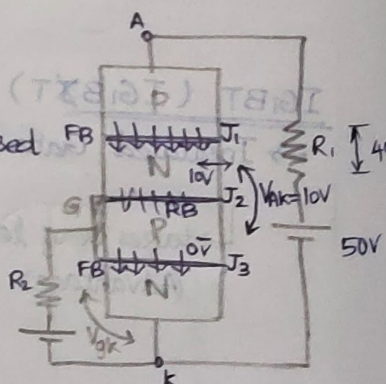
A ⇒ +ve Volt K ⇒ -ve volt

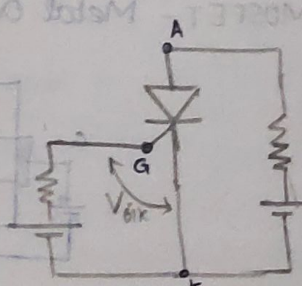
⇒ J1 & J3 junctions are forward biased

⇒ So all voltage will appear across the junction J2

⇒ To make the J2 region conduct, we have to give atleast 10.7V to make it forward biased for a very short time

⇒ For a very short time, if 10.7 V is given, J2 junction will be broken and SCR starts conducting.





* We can't stop the conduction by removing the gate voltage.

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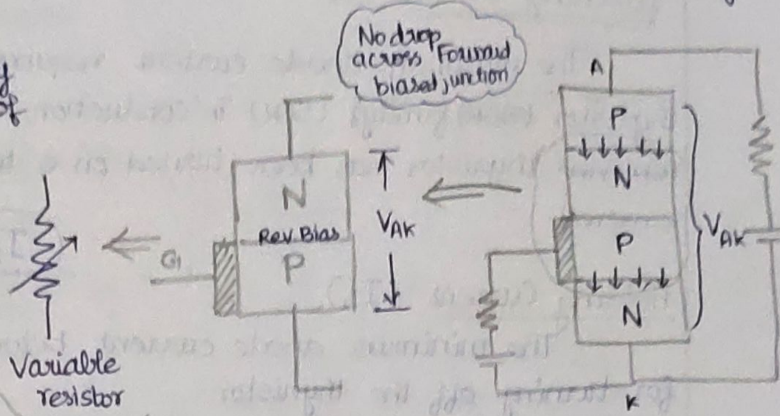
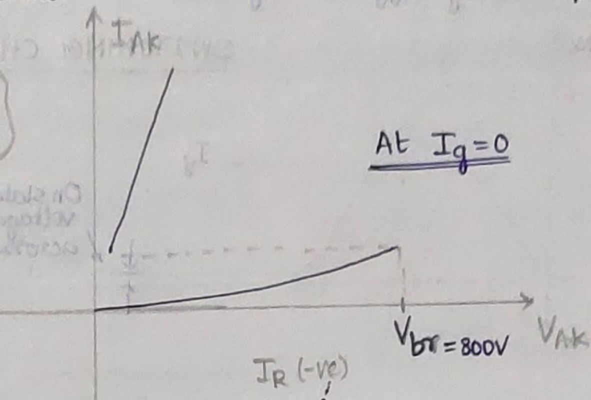
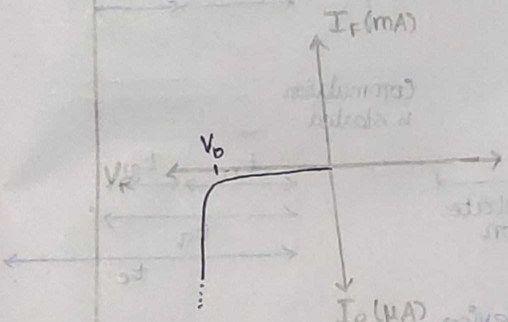
In rev. bias, very small amount of leakage current flows.

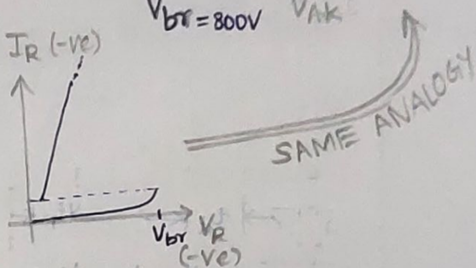


* Once SCR is triggered there is no control over SCR. We can't turn it off by giving gate voltage



<u>Reverse Characteristics of Diode</u>



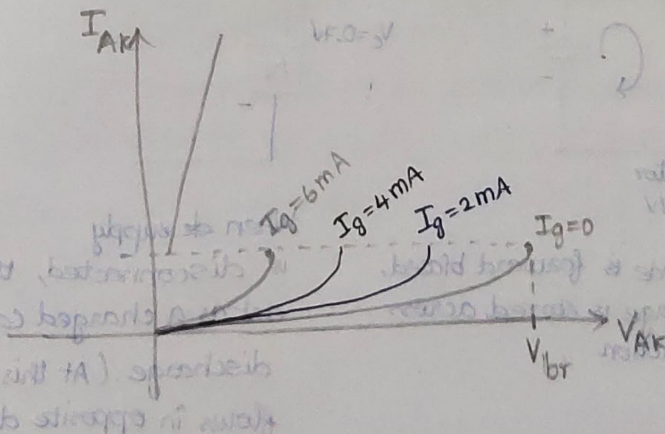


After breakdown voltage, the current increases sharply and again voltage across diode will be lesser (almost like short circuit)

* After the -ve voltage of diode is increased further beyond breakdown voltage, current increases sharply (as irreversible damage of diode occured)
* Before -ve voltage reaching V_b, current is in microamperes.

When I_g is increased, the junction J2 is slightly forward biased (I_g=2mA) ⇒ so lesser voltage across AK (V_{AK}) is required to turn on the reverse bias region.

$I_g \propto \frac{1}{V_{br}}$



Latching Current (I_L)

The minimum anode current required to maintain the thyristor ([illegible] family) (SCR) in conduction, immediately after ~~removing~~ thyristor has been turned on & the gate signal is removed.

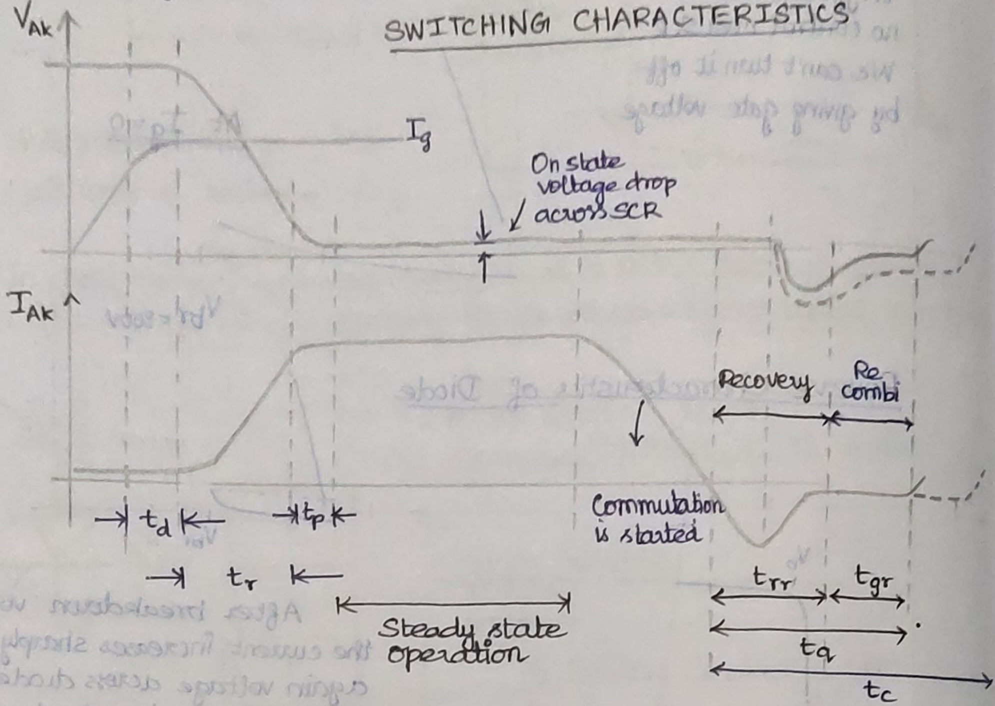
$\boxed{I_L > I_h}$

Holding Current (I_h)

The minimum anode current below which it must fall for turning off the thyristor

SWITCHING CHARACTERISTICS

Refer ppt



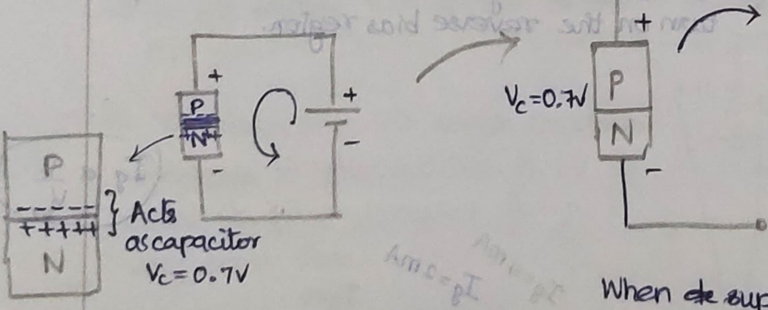
Commutation → turning off the device

t_d - delay time ; t_r - rise time ; t_p - peak time ; t_{rr} - reverse recovery time

t_{gr} - gate recovery time ; t_q - turn off time; t_c - ckt commutation time

Explanation for why at t_{rr}, i is negative?

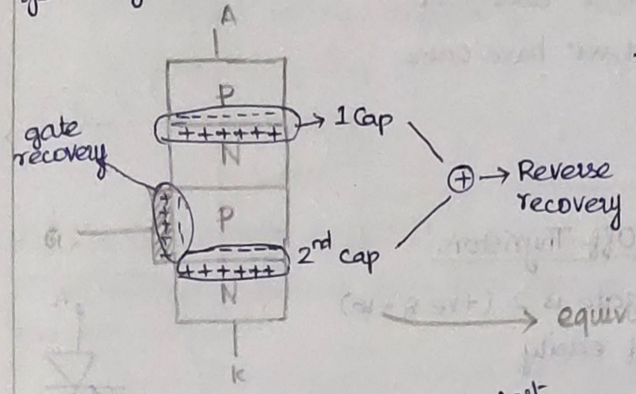
Consider,



When diode is forward biased, some charge is stored across the pn-junction

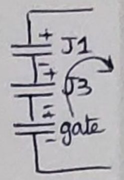
When ~~dc~~ supply is disconnected, the diode will act as a charged capacitor and discharge. (At this time, current flows in opposite direction)

Due to this discharging phenomena, at commutation time, we get negative current



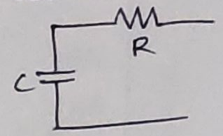
$\Rightarrow t_q$ (turn-off time)

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



→ equiv ckt at discharging time

To make this discharging process fast, high resistance is added so as the time constant increases



$\boxed{\text{Discharging time} = \text{Time Constant} = RC}$

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TURN OFF TIME

Initially, diode is forward biased, to turn off the diode, we need to give reverse bias for atleast 1 t_{rr}

Turn-off time
minimum time required to turn off the SCR

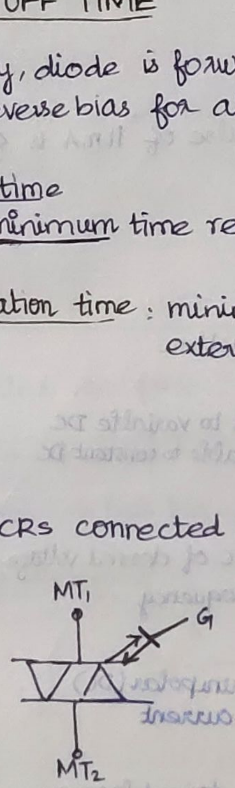
Commutation time: minimum time required to turn off SCR with external circuit.

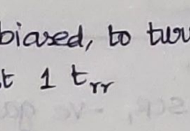
TRIAC

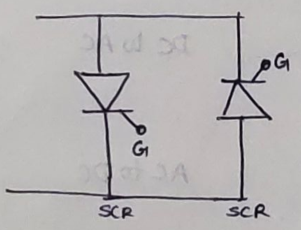
Equivalent circuit of TRIAC

* two SCRs connected ~~in~~ in anti-parallel fashion

Symbol

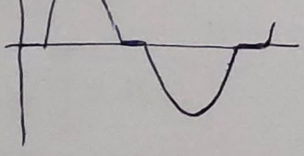




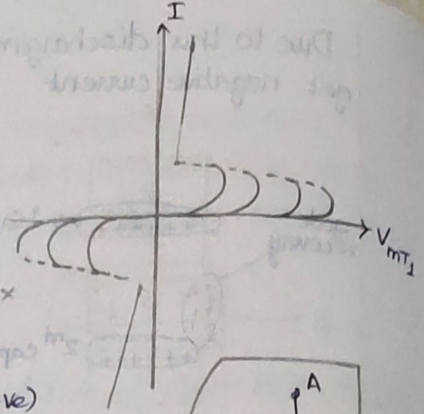


* Terminals can be interchangable.
* For AC supply given, any one SCR will conduct for +ve half cycle and another will conduct for -ve half cycle
* Gate voltage given to G terminal will be applied to the SCR that is conducting

Applications:- AC Voltage controllers



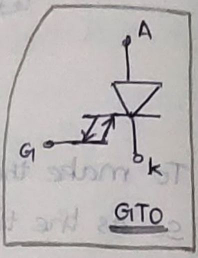
Characteristics of Triac



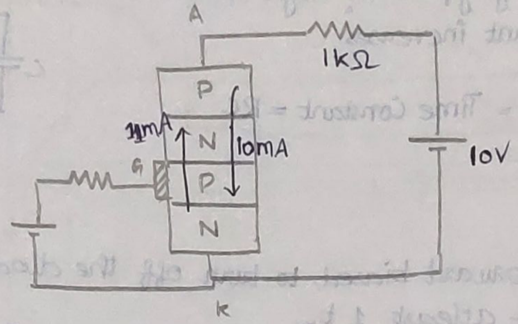
* Same as SCR in I^{st} Quadrant
* In III^{rd} quadrant, we have same characteristics

—— × —— × —— × —— ×

GTO ⇒ Gate Turn Off Thyristors

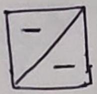
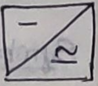
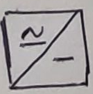
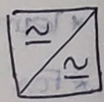


* Single SCR but gate is 2 (+ve & −ve)
* can be turned off easily
* To turn on the SCR, +ve gate pulse is given



* To turn off the SCR, −ve gate pulse of 11mA is given. It is turn off the SCR.

POWER CONVERTER TOPOLOGIES

Conversion	Name	Function	Symbol
DC to DC	Chopper	Constant to variable DC or variable to constant DC	
DC to AC	Inverter	DC to AC of desired voltage and frequency	
AC to DC	Rectifier	AC to unipolar (DC) current	
AC to AC	Cyclo converter, AC-PAC, Matrix converter	AC of desired frequency and/or magnitude from generally line AC	

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(i) Triggering methods (ii) Commutation of SCR
(iii) Protection of SCR

TRIGGERING METHODS

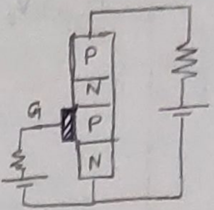
(a) Forward voltage triggering
(b) Gate triggering
(c) $\frac{dv}{dt}$ triggering
(d) Temperature triggering
(e) Light triggering

(a) Forward voltage triggering

* Applying voltage more than reverse breakdown voltage to make the SCR conduct.
* Irreversible damage occurs. SCR cannot be used again

(b) Gate triggering:-

* By applying gate voltage, the SCR is made to conduct. (seen earlier)



* Three types
  ① R triggering ② RC trig ③ UJT trigg

Commutation
(i) Natural commutation
(ii) Forced commutation
* voltage commutation (impulse) * load commutation (self commutation)
* current or resonant pulse * complementary * external pulse

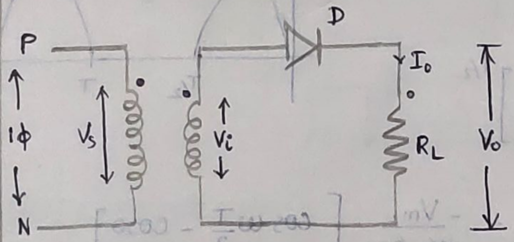
~~30/08/21~~
31/08/2021

HALF & FULL WAVE (UNCONTROLLED RECTIFIERS)

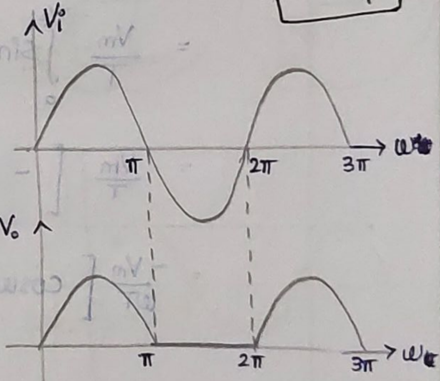
Uncontrolled Rectifiers
- → Half Wave Rectifiers
- → Full Wave rectifiers
  - → Centre-tapped transformer
  - → Bridge-type

$\boxed{\omega = \frac{2\pi}{T}}$

Half-wave rectifiers



$V_i = V_m \sin\omega t$



An method

$$V_{o\,avg} = \frac{\text{Area under the curve for one time period}}{\text{One time period}} = \frac{\text{Area}}{\text{Base}}$$

$$= \frac{\int_0^{2\pi} V_o\, d\omega}{2\pi} = \frac{\int_0^{\pi} V_m \sin(\omega t)\, d(\omega t) + \int_{\pi}^{2\pi} 0\, d(\omega t)}{2\pi}$$

$$V_{o\,avg} = \frac{1}{2\pi}\int_0^{\pi} V_m \sin(\omega t)\, d\omega$$

$$= \frac{V_m}{2\pi}\left[-\frac{\cos(\omega t)}{1}\right]_0^{\pi}$$

$$= \frac{-V_m}{2\pi}\left[+\cos\pi - \cos 0\right] = \frac{-V_m}{2\pi}\left[+(-1) - 1\right]$$

$$\boxed{V_{o\,avg} = \frac{V_m}{\pi}}$$ Half wave rectifier

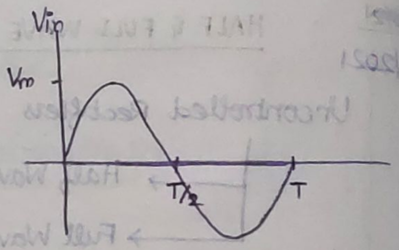
sir method $V_{o\,rms} = \sqrt{\dfrac{(\text{Area under the curve})^2}{\text{Base}}}$

$$= \sqrt{\frac{\int_0^{\pi} V_m^2 \sin^2(\omega t)\, d\omega}{2\pi}} = \sqrt{\frac{V_m^2}{2\pi}\int_0^{\pi}\sin^2 \omega t\, d\omega}$$

$$= \sqrt{\frac{V_m^2}{2\pi}\int_0^{\pi}\left(\frac{1}{2} - \frac{\cos 2\omega t}{2}\right) d\omega} = \frac{V_m}{2}$$

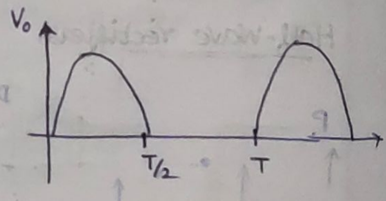
$$\boxed{V_{o\,rms} = \frac{V_m}{2}}$$ Half wave rectifi[er]

Average voltage of HWR (Uncontrolled)



$$V_{o\,avg} = \frac{\text{Area}}{\text{Base}} = \frac{\int_0^T V_o}{T}$$

$$= \frac{\int_0^{T/2} V_m \sin\omega t\, dt + \int_{T/2}^{T} 0}{T}$$



$$= \frac{V_m}{T}\int_0^{T/2}\sin\omega t\, dt$$

$$= \frac{V_m}{T}\left[-\frac{\cos\omega t}{\omega}\right]_0^{T/2}$$

$$= \frac{-V_m}{\omega T}\left[\cos\omega t\right]_0^{T/2} = \frac{-V_m}{\cancel{\omega}\times\left(\frac{2\pi}{\cancel{\omega}}\right)}\left[\cos\omega\frac{T}{2} - \cos 0\right]$$

$$= -\frac{V_m}{2\pi}\left[\cos\frac{2\pi}{\cancel{T}}\times\frac{\cancel{T}}{\cancel{2}} - \cos 0\right] = -\frac{V_m}{2\pi}\left[\cos\pi - \cos 0\right]$$

$$= \frac{-V_m}{2\pi}\left[-1 - 1\right] = \frac{V_m}{2\pi}(-(-2)) = \frac{V_m}{\pi}$$ ✓

RMS Voltage of HWR output Voltage:-

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T (v(t))^2\,dt}$$

$$\boxed{\sin^2 x = \frac{1-\cos 2x}{2}}$$

$$V_{o\,rms} = \sqrt{\frac{1}{T}\left(\int_0^{T/2} V_m^2 \sin^2\omega t\,dt + \int_{T/2}^{T} 0\right)}$$

$$= \sqrt{\frac{1}{T}\int_0^{T/2} V_m^2 \sin^2\omega t\,dt} = \sqrt{\frac{V_m^2}{T}\int_0^{T/2} \sin^2\omega t\,dt}$$

$$= \sqrt{\frac{V_m^2}{T}\int_0^{T/2} \frac{1-\cos 2\omega t}{2}\,dt} = \sqrt{\frac{V_m^2}{2T}\int_0^{T/2} (1-\cos 2\omega t)\,dt}$$

$\omega = \frac{2\pi}{T}$

$$= \sqrt{\frac{V_m^2}{2T}\left[t - \frac{\sin 2\omega t}{2\omega}\right]_0^{T/2}} = \sqrt{\frac{V_m^2}{2T}\left[\left(\frac{T}{2} - \frac{\sin 2\omega(\frac{T}{2})}{2\omega}\right) - (0-0)\right]}$$

$$= \sqrt{\frac{V_m^2}{2T}\left[\frac{T}{2} - \frac{\sin\omega T}{2\omega}\right]} = \sqrt{\frac{V_m^2}{2T}\left[\frac{T}{2} - \frac{\sin(\frac{2\pi}{T}\times T)}{2\times\frac{2\pi}{T}}\right]}$$

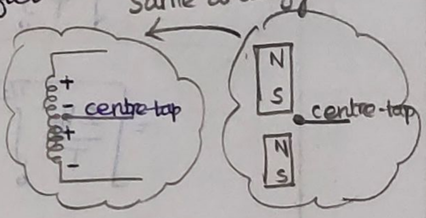
$$\boxed{\sin 2\pi = 0}$$

$$= \sqrt{\frac{V_m^2}{2T}\left[\frac{T}{2} - 0\right]} = \sqrt{\frac{V_m^2 \times \cancel{T}}{4\cancel{T}}}$$

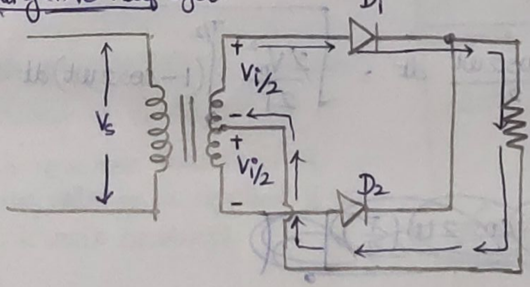
$$\boxed{V_{o\,rms} = \frac{V_m}{2}}$$

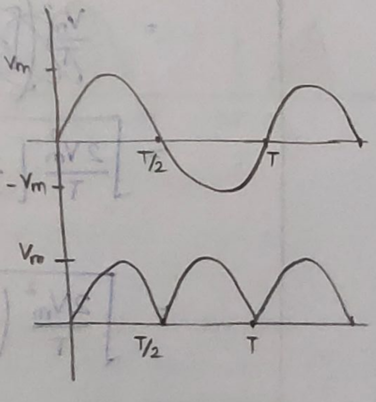
CENTER TAPPED TRANSFORMER – Full Wave Rectifier (Uncontrolled)

same analogy

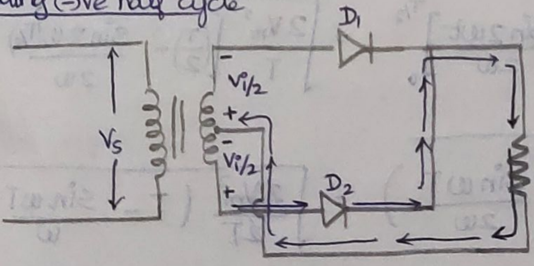


during (+)ve half cycle

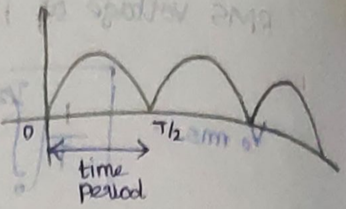




during (-)ve half cycle



$V_0\ avg \Rightarrow \dfrac{\int (V_0)\,dt}{\pi}$



V_0 avg - $\dfrac{\text{Area under one base}}{\text{Base}}$

Base ≡ Time period for which V_0 repeats

$$= \frac{\int_0^{T/2} V_m \sin\omega t}{\left(\frac{T}{2}\right)} = \frac{2V_m \int_0^{T/2} \sin\omega t}{T}$$

$$= \frac{2V_m}{T}\left[-\frac{\cos\omega t}{\omega}\right]_0^{T/2} = \frac{-2V_m}{\omega T}\left[\cos\omega t\right]_0^{T/2}$$

$$= -\frac{2V_m}{\left(\frac{2\pi}{T}\right)\times T}\left[\cos\omega\frac{T}{2} - \cos 0\right] = -\frac{2V_m}{2\pi}\left[\cos\frac{2\pi}{T}\times\frac{T}{2} - \cos 0\right]$$

$$= -\frac{2V_m}{2\pi}\left[\cos\pi - \cos 0\right] = -\frac{2V_m}{2\pi}(-1-1)$$

$$\boxed{V_0\ avg = \frac{2V_m}{\pi}}$$ Full Wave Uncontrolled rectifier

$$V_0\ rms = \sqrt{\frac{1}{\left(\frac{T}{2}\right)}\int_0^{T/2}(V_m \sin\omega t)^2\,dt}$$

$$V_{rms} = \sqrt{\frac{1}{T_0}\int (v(t))^2\,dt}$$

$$= \sqrt{\frac{2}{T}\int_0^{T/2} V_m^2 \sin^2\omega t\,dt} = \sqrt{\frac{2V_m^2}{T}\int_0^{T/2}\sin^2\omega t\,dt}$$

$$= \sqrt{\frac{2V_m^2}{T}\int_0^{T/2}\frac{1-\cos 2\omega t}{2}\,dt} = \sqrt{\frac{2V_m^2}{2T}\int_0^{T/2}(1-\cos 2\omega t)\,dt}$$

$$= \sqrt{\frac{2V_m^2}{T}\left[t - \frac{\sin 2\omega t}{2\omega}\right]_0^{T/2}} = \sqrt{\frac{2V_m^2}{T}\left[\left(\frac{T}{2}\right) - \frac{\sin 2\omega\left(\frac{T}{2}\right)}{2\omega} - (0-0)\right]}$$

$$= \sqrt{\frac{2V_m^2}{T}\left(\frac{T}{2} - \frac{\sin\omega T}{2\omega}\right)} = \sqrt{\frac{2V_m^2}{2T}\left(T - \frac{\sin\omega T}{\omega}\right)}$$

$$= \sqrt{\frac{V_m^2}{T}\left(T - \frac{\sin\frac{2\pi}{T}\times T}{\frac{2\pi}{T}}\right)} = \sqrt{\frac{V_m^2}{T}\times(T-0)} = \sqrt{\frac{V_m^2\times T}{T}}$$

$$= \frac{V_m}{\sqrt{2}}$$

03-09-2021

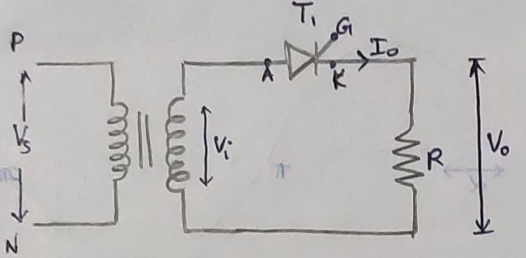
CONTROLLED RECTIFIERS (aka Converters)

- Half-wave rectifier
- Full-wave rectifiers
  - Center-tapped transf type
  - Bridge type
    - Half-controlled (aka semi-~~controlled~~ Converter)
    - Fully controlled (full converter)

X * <u>Half-controlled</u> is a full wave rectifier.

HALF WAVE CONTROLLED RECTIFIER (for R-load)

T_1 - Thyristor-1

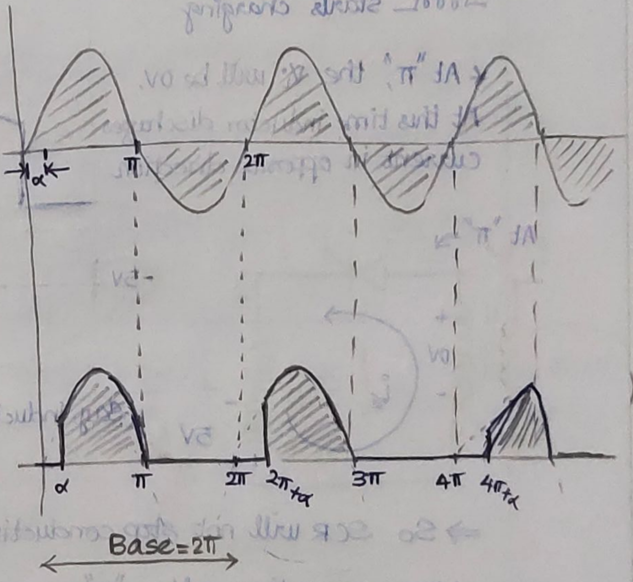


$V_i = V_m \sin \omega t$

* In 0 to π, SCR will conduct if SCR is triggered by gate pulse
* At α time period, gate pulse is applied
* At π to 2π, SCR is reverse biased ⇒ $V_o = 0V$

In reverse bias, even if gate voltage is applied, $V_o = 0V$ (SCR won't conduct)

* After (2π + α), gate pulse is given. SCR turns on



$$V_{o\,avg} = \frac{\text{Area}}{\text{Base}}$$

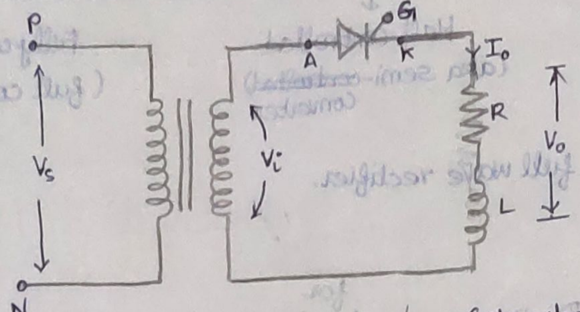
$$= \frac{1}{2\pi}\int_0^{2\pi} V_o(\omega t)\, d(\omega t) = \frac{1}{2\pi}\left\{ \int_0^{\alpha} 0 + \int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t) + \int_{\pi}^{2\pi} 0 \right\}$$

$$\frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin \omega t . d(\omega t) = \frac{V_m}{2\pi}\left[-\frac{\cos \omega t}{1} \right]_{\alpha}^{\pi}$$

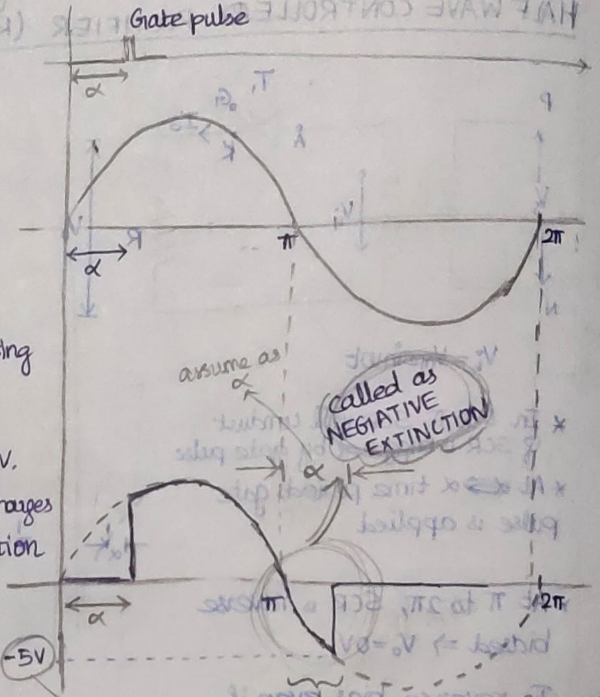
$$= -\frac{V_m}{2\pi}\left[\cos(\pi) - \cos\alpha\right] = \frac{-V_m}{2\pi}\left[(-1) - \cos\alpha\right]$$

$$\boxed{V_{o\,avg} = \frac{V_m}{2\pi}(1+\cos\alpha)}$$ HW controlled rectifier (for R-load)

Half-wave controlled Rectifier (RL load)



$V_i = V_m \sin\omega t$



* At α time period, gate pulse is applied.

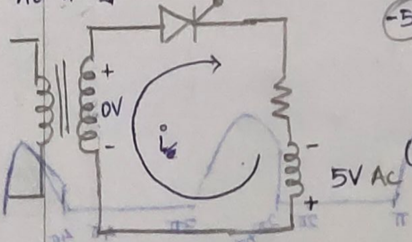
In +ve half cycle, SCR is on and it conducts

* After SCR starts conducting ⌇⌇⌇ starts charging

* At "π", the V_i will be 0V. At this time inductor discharges current in opposite direction

If inductance is high -ve voltage will also be high

At "π" →



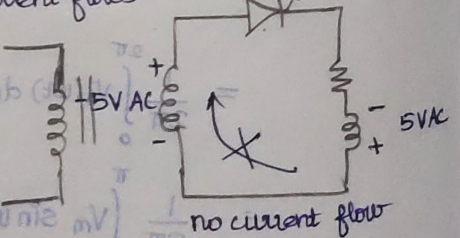
(Say, inductor stored 5V)

⇒ So SCR will not stop conducting. It will continuously conduct.

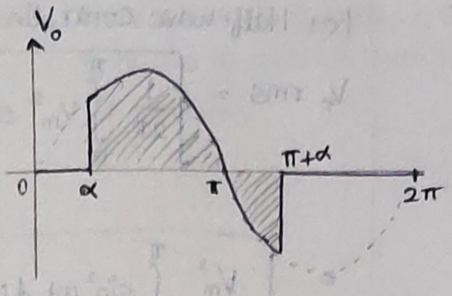
* After some time after "π", the V_i will also reverses its ~~direction~~ polarity (in -ve half cycle)

* When V_i is exactly -5V AC, no current flows so SCR will turn off

* Assume negative extinction time as α for easier calculation



$$V_o\ avg = \frac{Area}{Base} = \frac{Area}{2\pi}$$



$$= \frac{1}{2\pi}\left\{\int_0^{\alpha} 0 + \int_{\alpha}^{\pi+\alpha} V_m \sin\omega t\, d(\omega t) + \int_{\pi+\alpha}^{2\pi} 0\right\}$$

$$= \frac{1}{2\pi}\left\{ V_m \int_{\alpha}^{\pi+\alpha} \sin\omega t\, d(\omega t)\right\} = \frac{V_m}{2\pi}\left[-\frac{\cos\omega t}{1}\right]_{\alpha}^{\pi+\alpha}$$

$\cos(180+\theta) = -\cos\theta$

$$= -\frac{V_m}{2\pi}\left[\cos\omega t\right]_{\alpha}^{\pi+\alpha} = -\frac{V_m}{2\pi}\left[\cos(\pi+\alpha) - \cos(\alpha)\right]$$

$$= -\frac{V_m}{2\pi}\left[-\cos\alpha - \cos\alpha\right] = \frac{\cancel{-}V_m(\cancel{-}\cancel{2}\cos\alpha)}{\cancel{2}\pi}$$

$$\boxed{V_o\ avg = \frac{V_m}{\pi}\cos\alpha}$$

$$V_o\ rms = \sqrt{\frac{1}{2\pi}\int_0^{2\pi}(V_o(\omega t))^2\, d(\omega t)} \qquad V_{rms} = \sqrt{\frac{1}{T}\int_0^T v(t)^2\, dt}$$

$$= \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi+\alpha} V_m^2 \sin^2(\omega t)\, d(\omega t)} = \sqrt{\frac{V_m^2}{2\pi}\int_{\alpha}^{\pi+\alpha}\sin^2(\omega t)\, d(\omega t)}$$

$$= \sqrt{\frac{V_m^2}{2\pi}\int_{\alpha}^{\pi+\alpha}\frac{1-\cos 2\omega t}{2}\, d(\omega t)} = \sqrt{\frac{V_m^2}{2\times 2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi+\alpha}}$$

$$= \sqrt{\frac{V_m^2}{4\pi}\left[\left((\pi+\alpha) - \frac{\sin 2(\pi+\alpha)}{2}\right) - \left(\alpha - \frac{\sin 2(\alpha)}{2}\right)\right]}$$

$$= \sqrt{\frac{V_m^2}{4\pi}\left[\pi + \cancel{\alpha} - \cancel{\alpha} - \frac{\sin(2\pi+2\alpha)}{2} + \frac{\sin 2\alpha}{2}\right]}$$

$\sin(180+\theta) = -\sin\theta$

$$= \sqrt{\frac{V_m^2}{4\pi}\left[\pi - \left(-\frac{\sin 2\alpha}{2}\right) + \frac{\sin 2\alpha}{2}\right]}$$

$$= \sqrt{\frac{V_m^2}{4\pi}\left[\pi + \frac{\cancel{2}\sin 2\alpha}{\cancel{2}}\right]}$$

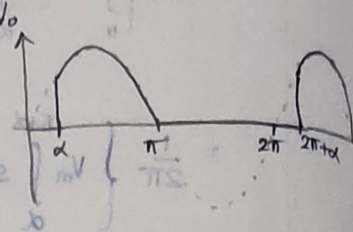
$$= \frac{V_m}{2}\sqrt{\frac{1}{\pi}(\pi + \sin 2\alpha)} = \cancel{\frac{V_m}{2}\sqrt{1 + \frac{\sin 2\alpha}{\pi}}}$$

$$\boxed{V_o\ rms = \frac{V_m}{2}}$$

For Half-wave controlled rectifier (R-load)

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v(t)^2\, dt}$$

$$V_o\ rms = \sqrt{\frac{1}{2\pi}\int_\alpha^\pi V_m^2 \sin^2 \omega t\, d(\omega t)}$$



$$= \sqrt{\frac{V_m^2}{2\pi}\int_\alpha^\pi \sin^2 \omega t\, d(\omega t)}$$

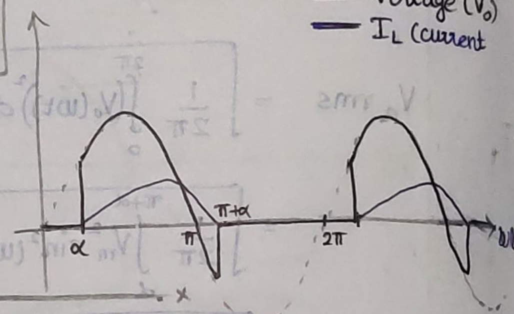
$$= \sqrt{\frac{V_m^2}{2\pi}\int_\alpha^\pi \frac{1-\cos 2\omega t}{2}\, d(\omega t)} = \sqrt{\frac{V_m^2}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_\alpha^\pi}$$

$$= \sqrt{\frac{V_m^2}{4\pi}\left[\pi - \frac{\sin 2\pi}{2} - \left(\alpha - \frac{\sin 2\alpha}{2}\right)\right]} = \frac{V_m}{2}\sqrt{\frac{1}{\pi}\left[\pi - \cancel{0} - \alpha + \frac{\sin 2\alpha}{2}\right]}$$

$$\boxed{V_o\ rms = \frac{V_m}{2\sqrt{\pi}}\sqrt{\pi - \alpha + \frac{\sin 2\alpha}{2}}}$$

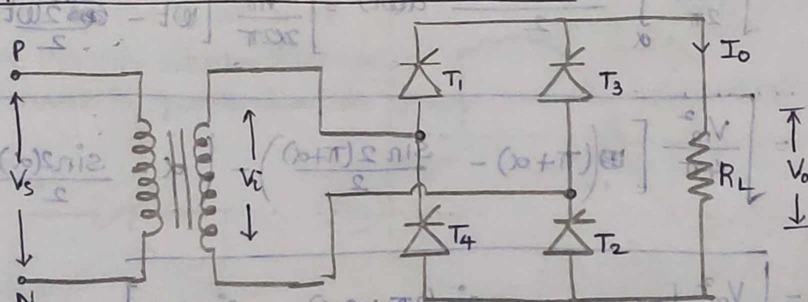
06-09-2021

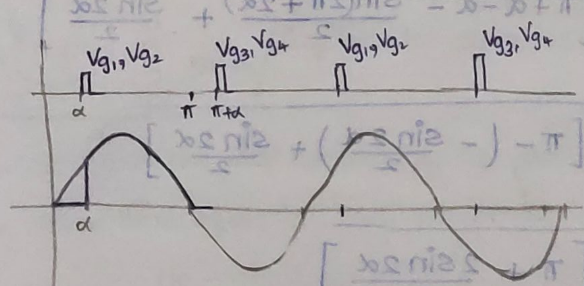
Half-wave controlled rectifier output for RL load $\Longrightarrow\Longrightarrow$



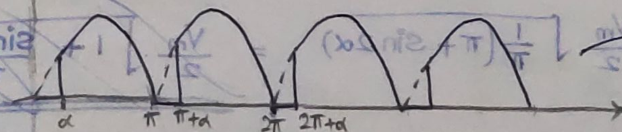
1 Φ FULL CONVERTER WITH 'R' LOAD

Bridge circuit

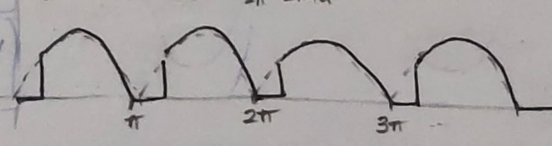




* In +ve half cycle, T_1 and T_2 conducts
* So in +ve half cycle, apply gate pulse for T_1 and T_2

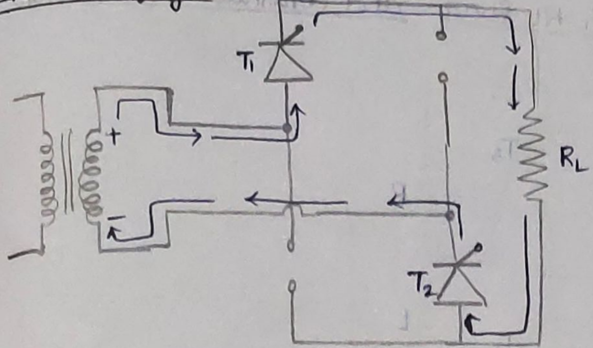


$\longrightarrow$ voltage waveform



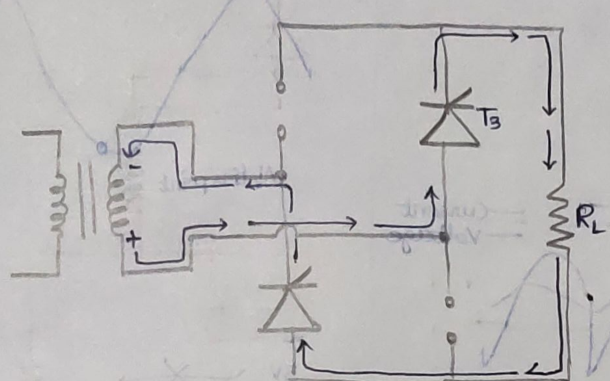
$\longrightarrow$ Current waveform

In +ve half cycle



* During +ve half cycle, it is of no use if pulse is given to T_3 and T_4

In -ve half cycle



$$I_o = \frac{V_o}{R}$$

Since, here we have purely resistive load, current & voltage will have same waveform

Here, the output repeats itself for every π

$$V_o\ avg = \frac{Area}{Base} = \frac{1}{\pi}\int_0^{\pi} V_o\, d(\omega t) = \frac{1}{\pi}\int_\alpha^{\pi} V_m \sin\omega t\, d(\omega t)$$

$$= \frac{V_m}{\pi}\int_\alpha^{\pi} \sin\omega t . d(\omega t) = \frac{V_m}{\pi}\left[\frac{-\cos\omega t}{1}\right]_\alpha^{\pi}$$

$$= -\frac{V_m}{\pi}\left[\cos(\pi) - \cos(\alpha)\right] = -\frac{V_m}{\pi}\left[-1 - \cos\alpha\right]$$

$$\boxed{V_o\ avg = \frac{V_m}{\pi}\left[1 + \cos\alpha\right]} \Rightarrow \boxed{I_o\ avg = \frac{V_m}{\pi}\left[1+\cos\alpha\right] \times \frac{1}{R}}$$

(or)

$$V_o\ rms = \sqrt{\frac{1}{\pi}\int_\alpha^{\pi} V_m^2 \sin^2\omega t\, d(\omega t)} = \sqrt{\frac{V_m^2}{\pi}\int_\alpha^{\pi} \frac{1-\cos 2\omega t}{2}\, d(\omega t)}$$

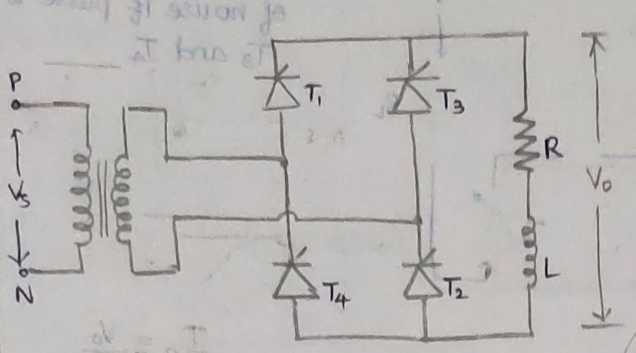
$$= \sqrt{\frac{V_m^2}{2\pi}\int_\alpha^{\pi}(1 - \cos 2\omega t)\, d(\omega t)} = \sqrt{\frac{V_m^2}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_\alpha^{\pi}}$$

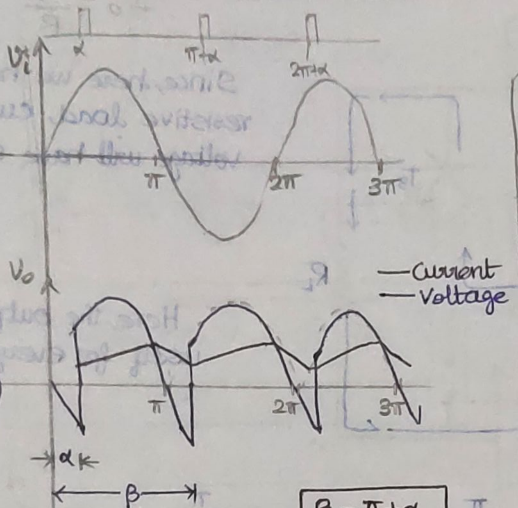
$$= \sqrt{\frac{V_m^2}{2\pi}\left[\pi - \frac{\sin 2\pi}{2} - \left(\alpha - \frac{\sin 2\alpha}{2}\right)\right]}$$

$$= \sqrt{\frac{V_m^2}{2\pi}\left(\pi - \alpha + 0 + \frac{\sin 2\alpha}{2}\right)} = \frac{V_m}{\sqrt{2\pi}}\sqrt{\pi - \alpha + \frac{\sin 2\alpha}{2}}$$

$$\boxed{V_o\ rms = \frac{V_m}{\sqrt{2\pi}}\sqrt{\pi - \alpha + \frac{\sin 2\alpha}{2}}} \Rightarrow \boxed{I_o\ rms = \frac{V_m}{\sqrt{2\pi}(R)}\sqrt{\pi - \alpha + \frac{\sin 2\alpha}{2}}}$$

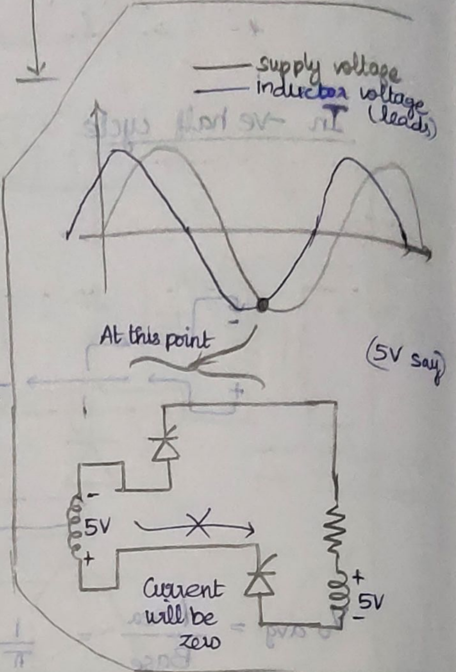
1ϕ Full Converter with RL load and Continuous Conduction





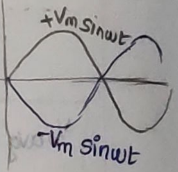
β- extinction angle

$\boxed{\beta = \pi + \alpha}$



* At -5V, SCR stops conducting.
* To avoid that, below -5V, gate pulse is given

* At any point, the current will not be zero.
* The SCR is triggered before I becomes zero to make the SCR continuously conduct.



$$V_{o\,avg} = \frac{1}{\pi}\left[\int_0^{\alpha} -V_m \sin\omega t \, d(\omega t) + \int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t)\right]$$

(or)

$$V_{o\,avg} = \frac{1}{\pi}\left[\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d(\omega t)\right]$$

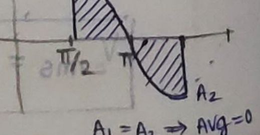
$$= \frac{V_m}{\pi}\int_{\alpha}^{\pi+\alpha} \sin\omega t \, d(\omega t) = \frac{V_m}{\pi}\left[-\frac{\cos\omega t}{1}\right]_{\alpha}^{\pi+\alpha}$$

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

$$\boxed{V_{o\,avg} = \frac{2V_m \cos\alpha}{\pi}}$$

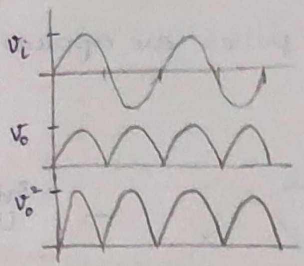
(When $\alpha = \frac{\pi}{2}$, $V_o\,avg = 0$

$\boxed{\alpha = 90^\circ}$

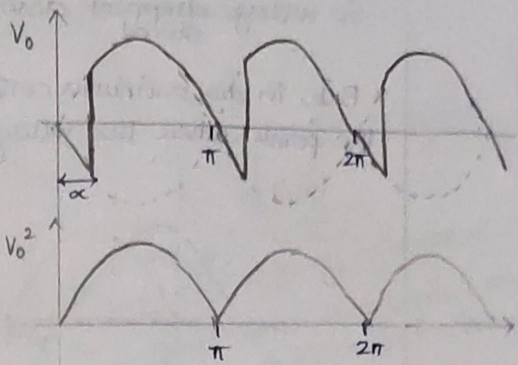


$A_1 = A_2 \Rightarrow Avg = 0$

* V_o^2 is Same as the V_o^2 of full wave uncontrolled rectifier



full wave uncontroller rectifier



$\therefore V_{o\,rms} = V_{o\,rms}$ of full-wave uncontroller rectifier.

$$\boxed{V_{o\,rms} = \frac{V_m}{\sqrt{2}}}$$

$80\,deg \times \frac{\pi\ rad}{180\ \cancel{deg}}$ $1\ rad = 180\ deg$

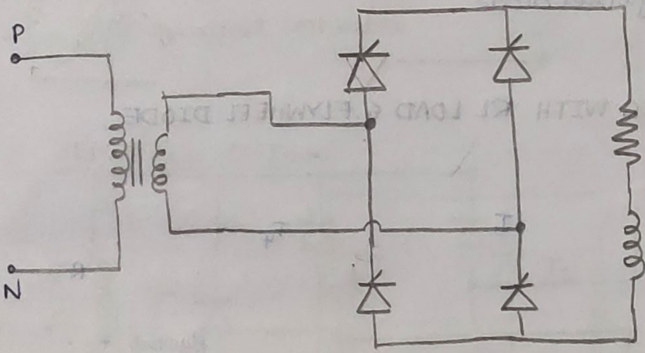
$\frac{\pi\ rad}{180\ deg} = 1$

08-09-2021

1φ FULL CONVERTER

- R-load
- RL-load
  - RL with flywheel drive
  - Continuous conduction — At any time, current is not equal to zero
  - disconti. conduction

1φ FULL CONVERTER WITH RL LOAD - discontinuous conduction

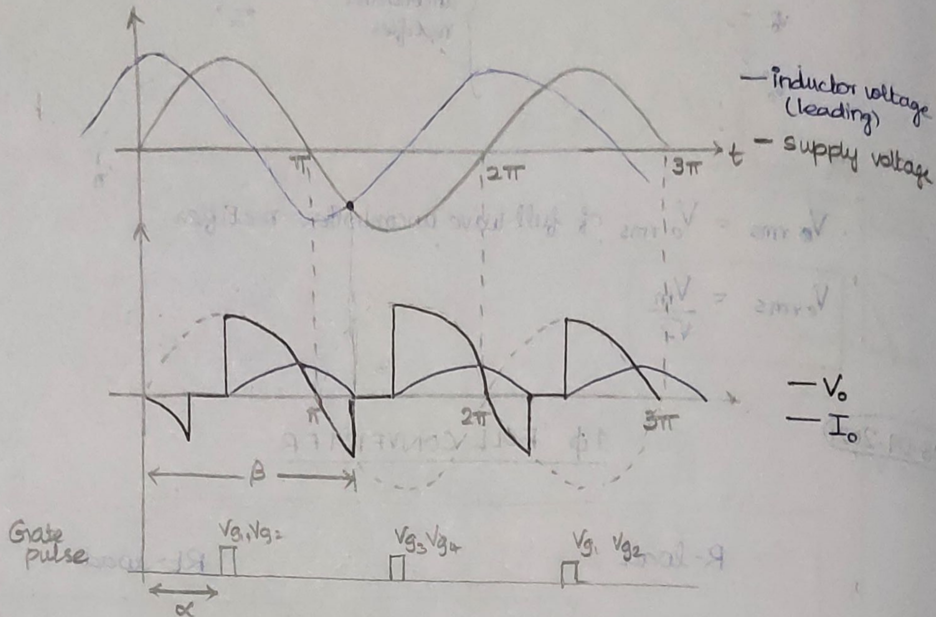


Consider the same ckt as for 1φ full converter with RL load (continuous conduction).

* In continuous conduction mode, at any point I should not be zero
* In continuous conduction, when -ve half cycle voltage and inductor voltage are same, I will become zero.
* To avoid that respective gate pulses (T_1, T_3 / T_2, T_4) is given before the point where two voltages are same
* So current will keep flowing in the circuit.

* But in discontinuous conduction, the inductance value is less, So voltage ~~dropped~~ stored across it is also less.

* But, in discontinuous conduction, gate pulses are applied after the points where two voltages are equal.

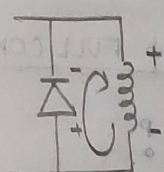


In discontinuous conduction, $\beta < \pi + \alpha$

x———x

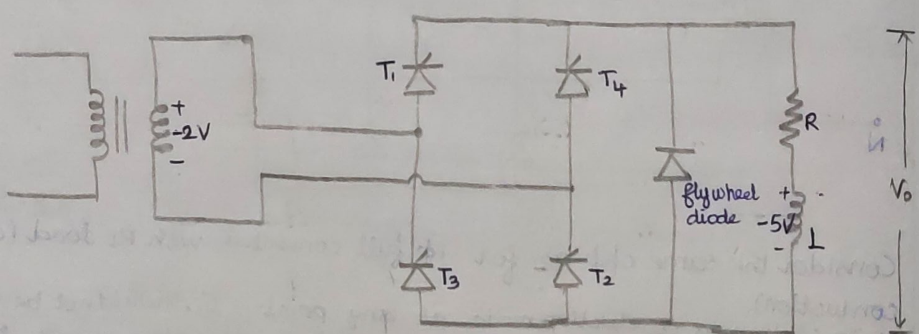
Flywheel diode

⟹ stored energy in the inductor is bypassed ~~by~~ through the flywheel diode.



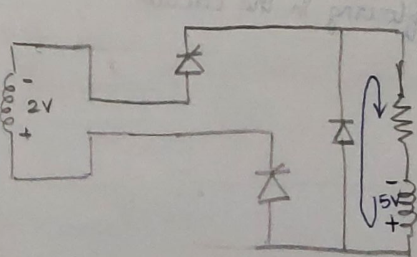
x————x

1ϕ- FULL CONVERTER WITH RL LOAD & FLYWHEEL DIODE



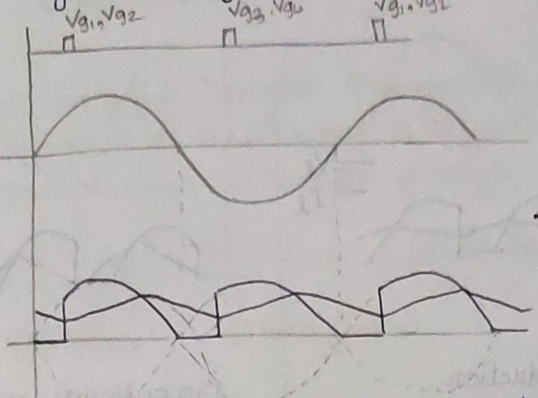
* In +ve half cycle, some voltage will be stored in the inductor.
* During negative half cycle, the inductor will discharge in opposite direction

(Negative inductance voltage) > (Negative supply voltage)
$-5V$ $\quad$ -2



When diode is on, it will act like a short circuit

* The diode will be in ON state in the -ve half cycle
* So, in negative half cycle, $V_o = 0V \Rightarrow$ No negative extinction

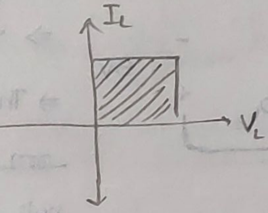


— V_o voltage
— I_o $\Longrightarrow$ Continuous conduction in flywheel-D ckt (heavy inductance)

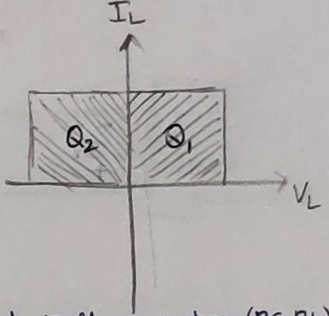
* Current is not zero (Short circuit current flows when diode is on)
  At this time, V_o is zero

* In flywheel diode, based on the value of inductance, we can get
  ① Continuous conduction (or) ② Discontinuous conduction

1ϕ
* Full-converter with flywheel
  - $\Rightarrow$ voltage cannot be -ve
  - $\Rightarrow$ current will be positive or zero



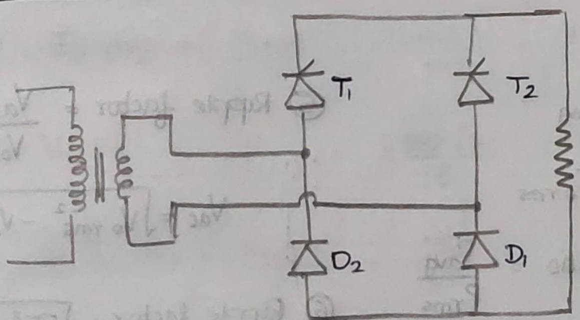
One-quadrant converter



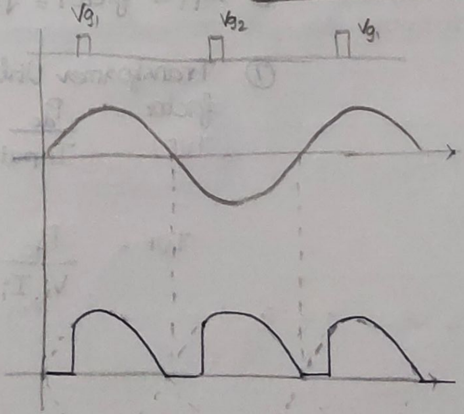
1ϕ-Full converter (R & RL)
- $\Rightarrow$ voltage (V_o) is +ve & -ve
- $\Rightarrow$ but I_o is always positive or zero

Two-quadrant conductor

1ϕ- SEMI CONVERTER



There will be one controlled device (SCR) and uncontrolled device (diode) in each paths (forward & backward)



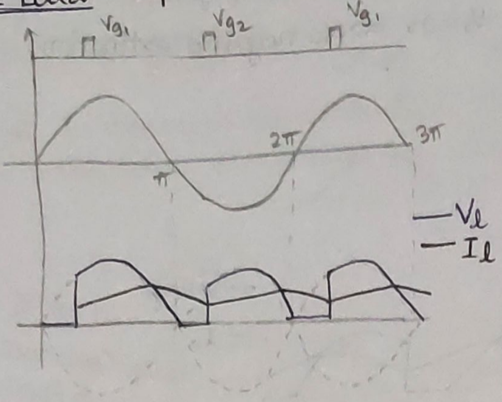
$$V_o\ avg = \frac{V_m}{\pi}[1+\cos\alpha]$$

$$V_o\ rms = \frac{V_m}{\sqrt{2\pi}\ R}\sqrt{\pi-\alpha+\frac{\sin\alpha}{2}}$$

V_o avg, V_o rms as same as 1ϕ-full converter

~~(Inductance is high)~~

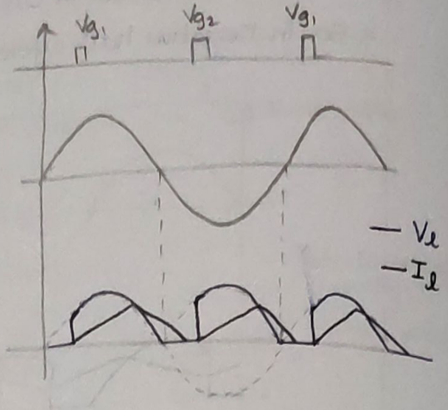
RL Load - 1ϕ - semi-converter



Continuous conduction
(Inductance is very high)

Voltage waveform same

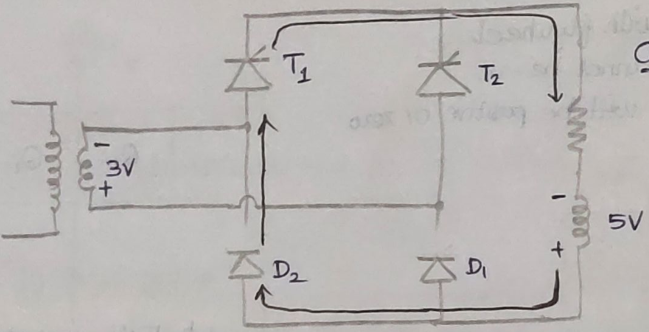
Current > 0 always



Discontinuous conduction
(Inductance is low)

voltage waveform same

Current > 0 & at some times current = 0



Consider (-)ve half cycle

⇒ T_1 was already conducting

⇒ T_2 was off

⇒ The shortest path is

-ooo- ⇒ D_2 ⇒ T_1 ⇒ -ooo-

not

-ooo- ⇒ D_1 → -ooo- → T_1 ⇒ -ooo-

~~In -ve half cycle,~~ ⇒ Negative extinction = 0V

[Voltage across T_1 and D_2 in on state = 0V]

⇒ acts as flywheel diode

14/09/2021

① $P_{dc} = V_{o\,avg} \times I_{o\,avg}$

② $P_{o\,rms} = V_{o\,rms} \times I_{o\,rms}$

③ η = rectification ratio = $\dfrac{P_{avg}}{P_{rms}}$

④ Form factor (FF) = $\dfrac{V_{o\,rms}}{V_{o\,avg}}$

⑤ Ripple factor = $\dfrac{V_{ac}}{V_{o\,avg}}$

$$V_{ac} = \sqrt{V_{o\,rms}^2 - V_{o\,avg}^2}$$

⑥ Ripple factor = $\sqrt{FF^2 - 1}$

⑦ Transformer Utilization factor (TUF) = $\dfrac{P_{dc}}{\text{Input VA}}$

$$TUF = \frac{P_{dc}}{V_{i\,rms} I_{i\,rms}}$$

⑧ Displacement factor

DF = $\cos\phi$

⑨ $PF = \dfrac{P_{ac}}{V_{irms}\, I_{irms}} = \dfrac{P_{ac}}{\text{Input VA}}$

① A single phase full converter is supplied from 230V, 50 Hz source. The load consists of R = 20Ω and a large inductance so as to make the load current constant. The firing angle (α) is 45°.

Find (a) $V_{o\,avg}$ (b) $I_{o\,avg}$ (c) I_{orms} (d) average value of thyristor current

(e) $V_{o\,rms}$ (f) Form factor.

Soln

Given $\alpha = 45°$

↳ The given voltage is rms voltage. $V_{rms} = 230\,V \Rightarrow V_m = 230\sqrt{2}\,V$

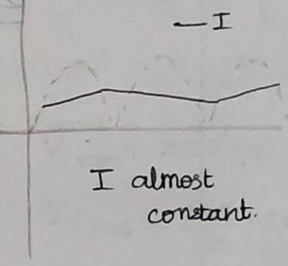
↳ The inductance is very high (L is very high)

⇒ Time constant $T = \dfrac{L}{R}$ is very high

↳ Charging & discharging is slow

↳ Continuous conduction mode

⇒ Current is almost constant



Also,

since $I_{inductor} \simeq 0 \Rightarrow L\dfrac{di}{dt} \simeq 0$

Voltage across inductor = 0 V

Soln

(a) $V_{o\,avg} = \dfrac{2V_m \cos\alpha}{\pi} = \dfrac{2\times(230\sqrt{2})}{\pi}\cos(45°)$

$= 146.42\,V$

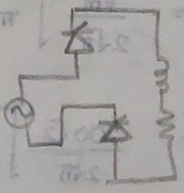
(b) $I_{o\,avg} = \dfrac{V_{o\,avg}}{R} = \dfrac{146.42}{20} = 7.32\,A$

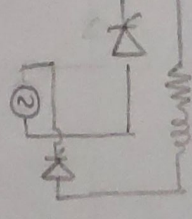
(e) $V_{o\,rms} = \dfrac{V_m}{\sqrt{2}} = \dfrac{230\sqrt{2}}{\sqrt{2}} = 230\,V$

(c) $I_{o\,rms} = \dfrac{V_{o\,rms}}{R} = \dfrac{230}{20} = 11.5\,A$

(d) Average value of thyristor current

$I_T = I_{o\,avg}$





$\boxed{I_T = \dfrac{I_{o\,avg}}{2}}$??

(f) Form factor :- $\frac{V_{o\,rms}}{V_{o\,avg}} = 1.5708$

② A single phase full converter is connected to 'R' load. The source voltage is of 230 V, 50 Hz. The average load current is of 20 A. Find the firing angle. For $R = 10\,\Omega$

1φ full converter
R-load

$$V_{o\,avg} = \frac{V_m}{\pi}[1+\cos\alpha]$$

Also $I_{o\,avg} = \frac{V_{o\,avg}}{R} \Rightarrow \frac{V_{o\,avg}}{R} = 20$

$$\Rightarrow V_{o\,avg} = 20 \times R$$

$$V_{o\,avg} = 200$$

$$\frac{230\sqrt{2}}{\pi}[1+\cos\alpha] = 200 \Rightarrow 1+\cos\alpha = 1.931$$

$$\cos\alpha = 0.931 \Rightarrow \alpha = 0.3736 \text{ rad}$$

$$\boxed{\alpha = 21.40^\circ}$$

③ A single phase HW controlled rectifier is operated from 200 V, 50 Hz supply. If the R_L is $100\,\Omega$ and average output voltage is 50 V. Find (a) α (b) $V_{o\,rms}$, (c) $I_{o\,rms}$ (d) FF (e) RF (f) TUF

Soln

(a) $V_{o\,avg} = \frac{V_m}{2\pi}[1+\cos\alpha]$ Given $V_{o\,avg} = 50$ V, $V_m = 200\sqrt{2}$

$$\Rightarrow \overset{1}{\cancel{50}} = \frac{\overset{4}{\cancel{200}}\sqrt{2}}{2\pi}[1+\cos\alpha]$$

$$\left(\frac{2\pi}{4\sqrt{2}} - 1\right) = \cos\alpha \Rightarrow \alpha = \cos^{-1}(0.1107)$$

$$\boxed{\alpha = 83.64^\circ} \qquad \alpha = 1.459 \text{ rad}$$

(b) $V_{rms} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\pi - \alpha + \frac{\sin 2\alpha}{2}}$

3.14 (rad) α in radians

$$= \frac{200\sqrt{2}}{2\sqrt{\pi}}\sqrt{\pi - (1.459) + \frac{\sin(2\times 1.459)}{2}}$$

$$= \frac{200\sqrt{2}}{2\sqrt{\pi}}\sqrt{3.14 - 1.459 + \frac{0.22}{2}}$$

RAD mode
sin(2×1.459) = 0.22

DEG MODE
sin(2×83.64) = 0.22

$$V_{orms} = \frac{200\sqrt{2}}{2\sqrt{\pi}}\sqrt{1.791}$$

$$= \frac{100\sqrt{2}}{\sqrt{\pi}} \times 1.3382$$

$$\boxed{V_{orms} = 106.772\,V}$$

π radians = $180°$

deg to radians conversion

$$\text{rad} = \frac{(\text{deg})}{180°\,\text{deg}} \times 3.14\ \text{rad}$$

(c) $$I_{o\,rms} = \frac{V_{o\,rms}}{R} = \frac{106.772}{100} = 1.0677\,A$$

(d) $$FF = \frac{V_{o\,rms}}{V_{o\,avg}} = \frac{106.772}{50} = 2.13544$$

(e) $$\text{Rectification factor} = \frac{P_{avg}}{P_{rms}} = \frac{V_{avg}\ I_{avg}}{V_{rms}\ I_{rms}} = \frac{50 \times \left(\frac{50}{100}\right)}{106.772 \times 1.0677}$$

$$= \frac{25}{114.0025} = 0.2192$$

(f) $$TUF = \frac{P_{dc}}{V_{irms}\ I_{irms}} = \frac{V_{o\,avg} \times I_{o\,avg}}{200 \times 2}$$

$V_{i\,rms} = 200\,V$ (ac)

$I_{i\,rms} = \frac{200}{100} = 2\,A$ (ac)

$$= \cancel{\frac{V_{o\,avg} \times I_{o\,avg}}{106.772 \times 1.06772}}$$

$$= \frac{50 \times \left(\frac{50}{100}\right)}{200 \times 2} = \frac{25}{400} = 0.0625$$

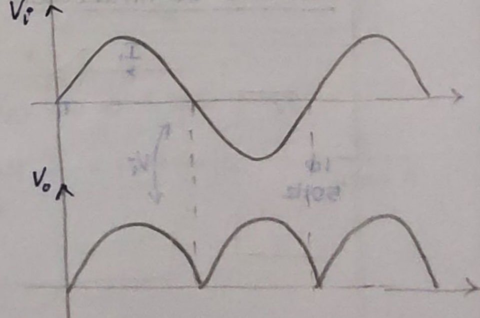
④ In a single phase full converter all thyristors are given constant dc voltage. The load is of 'R' type. Draw output voltage and find $V_{o\,avg}$.

Soln

When constant dc voltage is given to thyristor (gate of thyristor), then all thyristors will be on when they are forward biased.

Then α will be zero

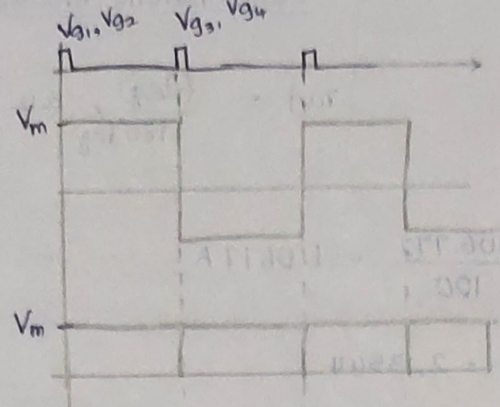
The output voltage will be like the output voltage of uncontroller full wave rectifier



(5) In a full converter with 'R' load the thyristor is triggered at $\alpha = 0$ and input is a square wave. Find V_o?

1ϕ

The output is a dc waveform



Aug 25 2021

(1ϕ)

(6) In a full converter when $\alpha = 0°$, the output voltage is 300 V. The load is RL type and continuous conduction. ~~$V_i = 230V$~~. Find V_o avg for $\alpha = 60°$

In assn

(7) A 1ϕ HWR is fired at α. If the peak value of the instantaneous output equals 230V. Find α when $V_i = 230V$.

Aug 23

COMMUTATION CIRCUIT

The process of turning off the conducting SCR (thyristor) is called commutation.

Commutation

(i) Natural commutation (for ac supply)

(ii) Forced commutation (for dc supply)

(a) Load commutation (or) self commutation (or) resonant

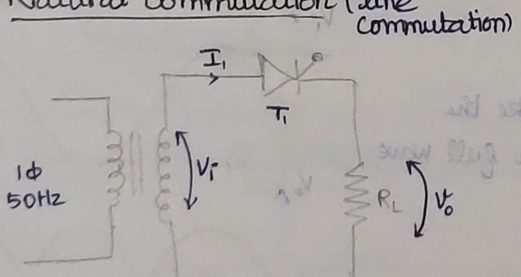
(b) current (or) resonant pulse.

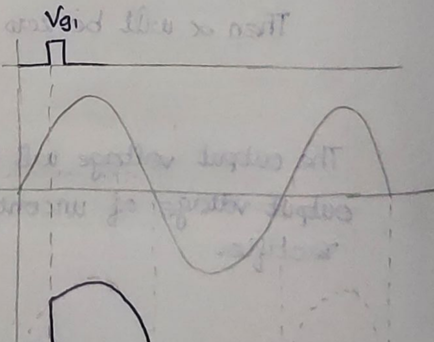
(c) complementary

(d) Voltage (or) impulse

(e) External pulse commutation

Natural commutation (line commutation)



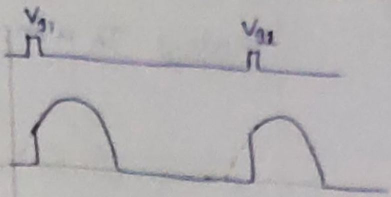


In AC supply SCR will turn off by itself when it is reverse biased (by -ve half cycle)

SCR turned off by itself due to rev. bias

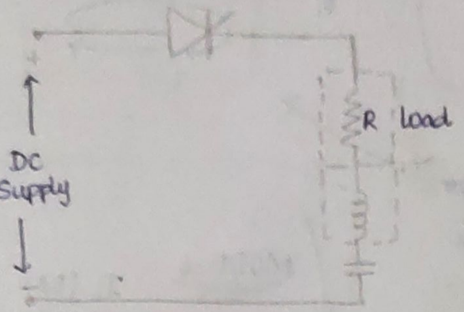
* No external commutation circuit is needed.

* If gate pulse is applied periodically.
* for each cycle, diode needs to be triggered in ac supply

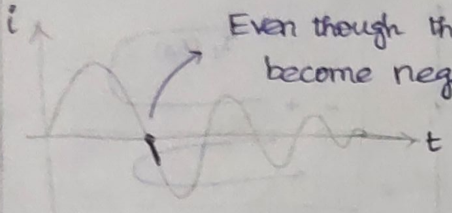


Aug 25 2021

Load Commutation (or) resonant commutation (or) Self commutation

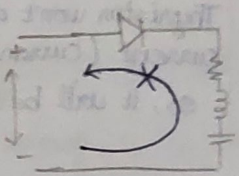


* R and L are the load
* L and C are the commutating components
* In RLC circuit, when $X_L < X_C$. We get underdamped response

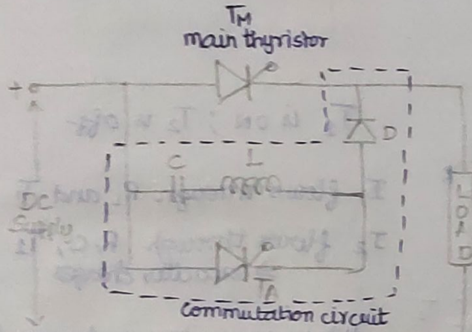


Even though the supply is dc, the current will become negative due to the underdamped response

* When current becomes -ve, the SCR will turn-off

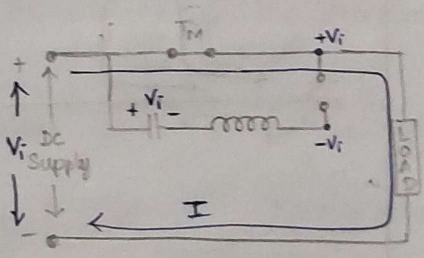


Current Commutation (Class B commutation)



T_A - auxillary thyristor

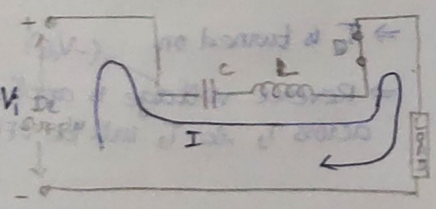
Mode-2 T_M is on ; T_A is off



$V_{AK} < 0 \Rightarrow$ Diode is off

Now I is constant $I = \frac{V_i}{\text{Load } R}$

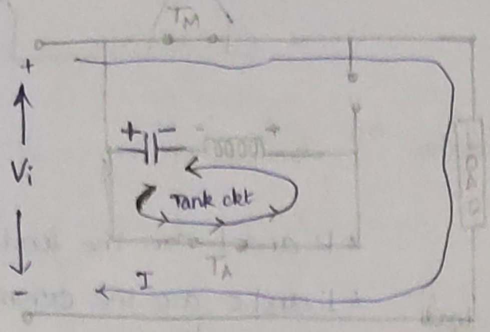
Mode-1 T_M is Off ; T_A is off

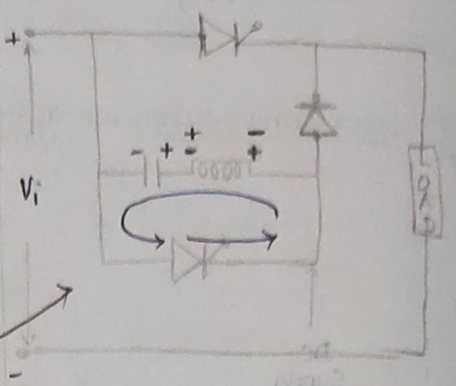


Capacitor will start charging to V_i volts.

After capacitor starts, I becomes zero

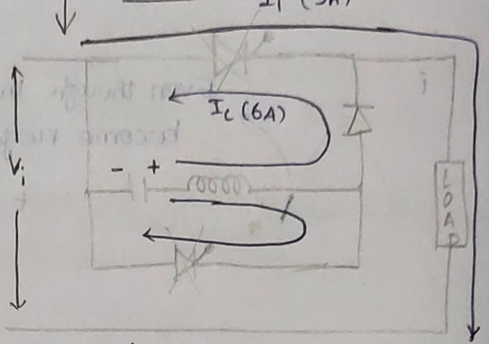
Mode-3 T_A is on; T_M is ON





* Capacitor will charge inductor. Inductor will again charge the capacitor

MODE-4

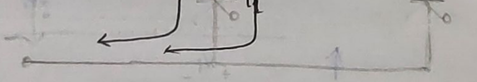


Net current through T_M
$= 5A - 6A$
$= -1A$

Thyristor won't allow negative current (current from k to A)
so, it will be turned off

⊣⊢$^{+}$ ⇒ capacitor current will turn off both T_M and T_A. Hence Commutation is performed.

Complementary Commutation

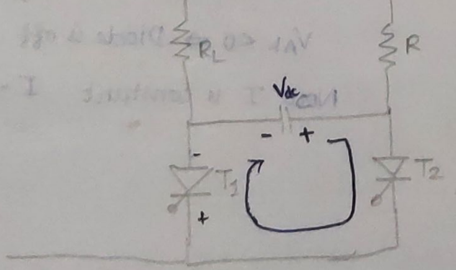


T_1 is ON ; T_2 is off

I_1 flows through R_L and T_1

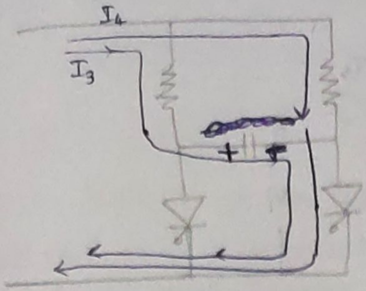
I_2 flows through R, C, T_1
⇒ capacitor charges

When capacitor is charged
$V_c = V_{dc} \Rightarrow I_2 = 0$



⇒ T_2 is turned on

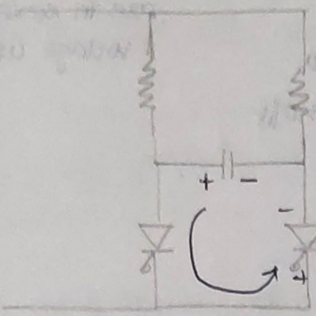
⇒ Reverse voltage $(-V_{dc})$ is applied across T_1 so T_1 will be OFFed.



Capacitor charges in opposite direction

$R_L \to C \to T_2 \Rightarrow I_3$

$R \to T_2 \Rightarrow I_4$



Turn on $T_1 \Rightarrow T_2$ will be turned off (due to reverse voltage)

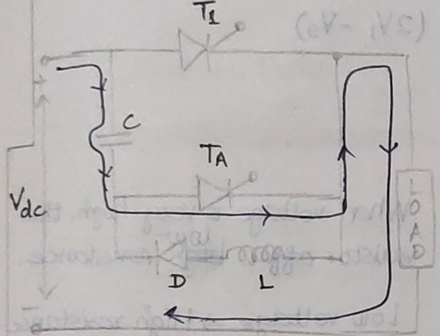
To turn off T_2, turn on T_1

To turn off T_1, turn off T_2

$\Downarrow$

Complementary commutation

VOLTAGE COMMUTATION $\Leftrightarrow$ $\boxed{\text{Sudden reverse voltage across SCR is applied} \Rightarrow \text{SCR will turn off}}$



Mode-1

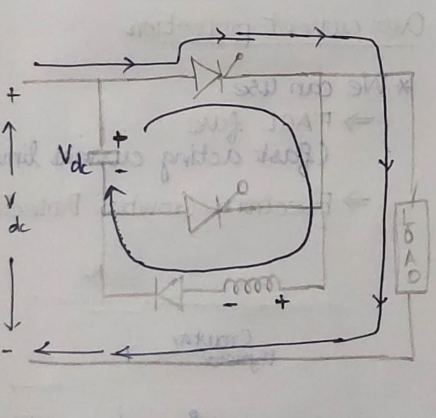
T_A is on. T_1 is off

$\Rightarrow$ Current flows through C, T_A, Load.

$\Rightarrow$ This current charges the capacitor C.

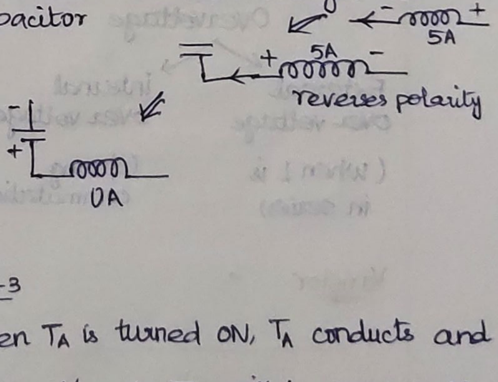
When $V_c = V_{dc}$ (capacitor charged),

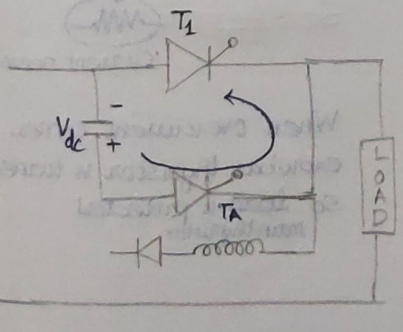
$I = 0 \Rightarrow T_A$ will turn off



Mode-2 (T_A is in off condition)

* T_1 is turned on by giving gate pulse
* The capacitor charges the inductor (Tank circuit)
* Next time inductor charges the capacitor



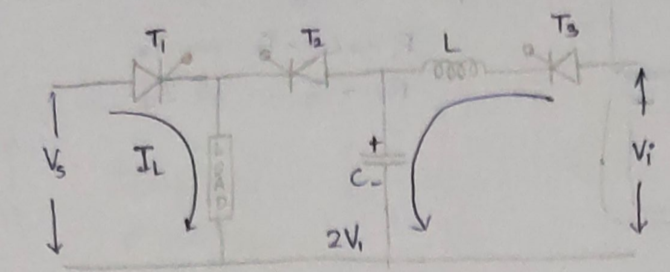


Mode-3

* When T_A is turned ON, T_A conducts and

$V_{AK} = -V_{dc} \Rightarrow T_1$ will be turned off

EXTERNAL PULSE COMMUTATION (CLASS-E)



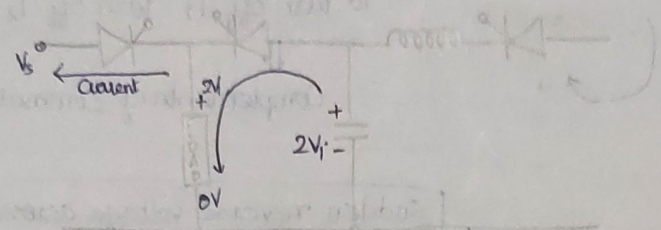
When & are in series, voltage will be doubled.

Step-I > Turn on T_1 and T_3

once capacitor is charged, I becomes zero,

T_3 turns off

$2V_1 > V_s$



Step-II : To turn off T_1, turn ~~off~~ on T_2

~~Current flows~~ V_{AK} of $T_1 = (2V_1 - V_s)$

$V_{AK} > 0 \Rightarrow T_1$ will be OFFed.

THYRISTOR PROTECTION

(1) Over voltage protection

(2) Over current protection

(3) $\frac{dv}{dt}$ protection

(4) $\frac{di}{dt}$ protection

(5) Gate protection

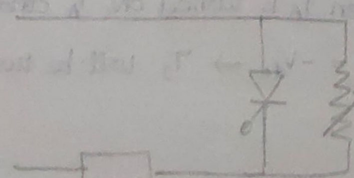
① Overvoltage Protection

Overvoltage

External over voltage (when L is in series)

internal over voltage (during commutation)

Varistor

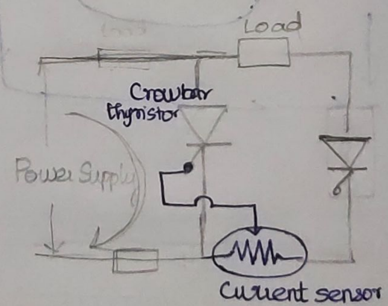


When voltage is very high, the varistor offers ~~high~~ low resistance.

Low voltage ⇒ High resistance

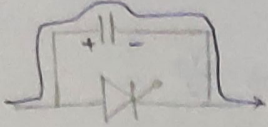
② Over current protection

* We can use
  ⇒ FACL fuse (fast acting current limiter)
  ⇒ Electronic Crowbar Protection



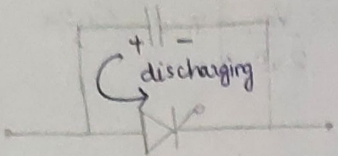
When overcurrent comes, crowbar thyristor is turned on.
So ~~load~~ main thyristor is protected

③ $\frac{dv}{dt}$ protection

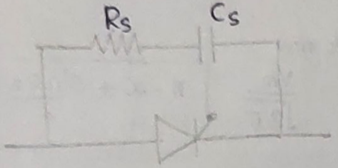


When high $\frac{dv}{dt}$ comes, capacitor will act as a short circuit and also it will start charging.

Then it will discharge after the high dv/dt goes



To avoid this, we have a resistor in discharge path



"Snubber Protection"

Uncontrolled rectifiers

Half-wave $\quad V_{o\,avg} = \frac{V_m}{\pi} \quad V_{o\,rms} = \frac{V_m}{2}$

Full-wave $\quad V_{o\,avg} = \frac{2V_m}{\pi} \quad V_{o\,rms} = \frac{V_m}{\sqrt{2}}$

Controlled rectifiers

Half-wave (R load) $\quad V_{o\,avg} = \frac{V_m}{2\pi}(1+\cos\alpha) \quad V_{o\,rms} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\pi-\alpha+\frac{\sin 2\alpha}{2}}$

Half-wave (RL-load) $\quad V_{o\,avg} = \frac{V_m}{\pi}(\cos\alpha) \quad V_{o\,rms} = \cancel{\frac{V_m}{2}\sqrt{1+\frac{\sin 2\alpha}{\pi}}}$

Full-wave (R-load) $\quad V_{o\,avg} = \frac{V_m}{\pi}[1+\cos\alpha] \quad V_{o\,rms} = \frac{V_m}{\sqrt{2\pi}}\sqrt{\pi-\alpha+\frac{\sin 2\alpha}{2}}$

Full-wave (RL-load) $\quad V_{o\,avg} = \frac{2V_m}{\pi}\cos\alpha \quad V_{o\,rms} = \frac{V_m}{\sqrt{2}}$

1. $P_{dc} = I_{avg} \times V_{avg}$
2. $P_{o\,rms} = V_{rms} \times I_{rms}$
3. Rectification ratio $= \eta = \frac{P_{avg}}{P_{rms}}$
4. Form factor $= \frac{V_{rms}}{V_{avg}}$
5. Ripple factor $= \frac{V_{ac}}{V_{avg}}$

   $V_{ac} = \sqrt{V_{rms}^2 - V_{avg}^2}$

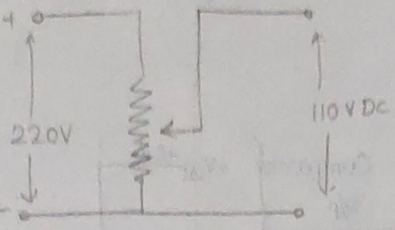
6. Ripple factor $= \sqrt{FF^2 - 1}$
7. $TUF = \frac{P_{dc}}{\text{Input VA}} = \frac{P_{dc}}{V_{rms}\, I_{rms}}$
8. Displacement factor $= \cos\phi$
9. $PF = \frac{P_{ac}}{\text{Input VA}}$

Oct 4

DC - DC Converter (DC chopper)

* Converts fixed DC to variable DC
* also known as DC transformer
* a conventional fixed DC - variable DC converter is a voltage divider (rheostat)

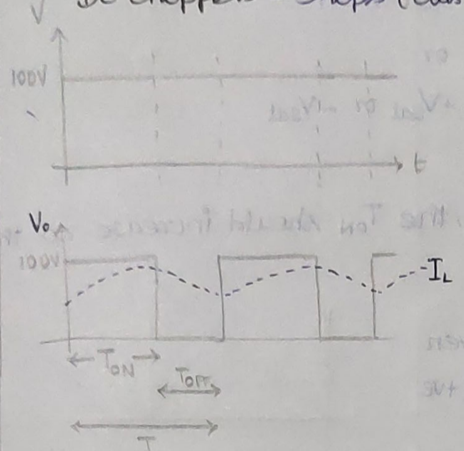
Application:- Traction motor control, marine hoists, mine haulers



Disadvantage of potential divider:

* Wastage of electrical energy

DC choppers - Chops (cuts the DC Waveform)



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

* Due to inductance present in the load, current will be continuous (similar to triangular wave)
* Power consumed during T_{OFF} time $= V_o \times I_L = 0\,W$

$$\boxed{\text{Duty cycle } K = \frac{T_{ON}}{T}}$$

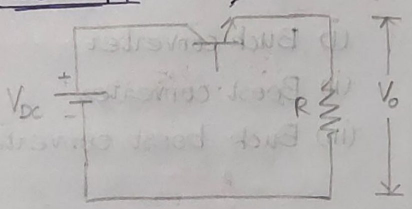
in some books α is duty cycle

* Power electronics devices are energy efficient (very low or no wastage of energy)

Oct 5 [offline]

Basic Chopper

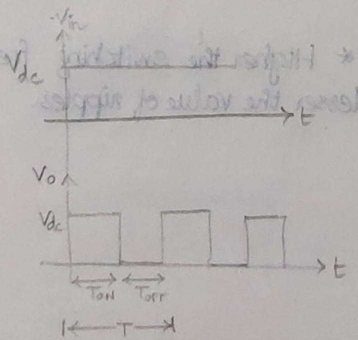
Transistor will operate only on saturation region (ON) or cut-off region (OFF)



$$V_{avg} = \frac{\text{Area}}{\text{Base}} = \frac{V_{dc} \times T_{ON}}{T}$$

$$\boxed{V_{avg} = \alpha V_{dc}}$$

since $\boxed{\alpha = \frac{T_{ON}}{T}}$ duty cycle



$$V_{rms} = \sqrt{\frac{V_{dc}^2 \times T_{ON}}{T}} = \sqrt{\alpha}\, V_{dc}$$

$$\boxed{V_{rms} = \sqrt{\alpha}\, V_{dc}}$$

effective i/p resistance $= \boxed{R_i = \frac{R}{\alpha}}$

$\boxed{\text{T-chopping Frequency}}$

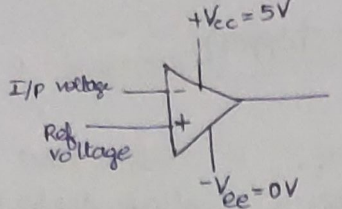
Modes of Control

(i) Constant frequency control (T is constant; T_{ON} or T_{OFF} is varied)

(ii) Variable frequency control (T is not constant; T_{ON} or T_{OFF} is constant)

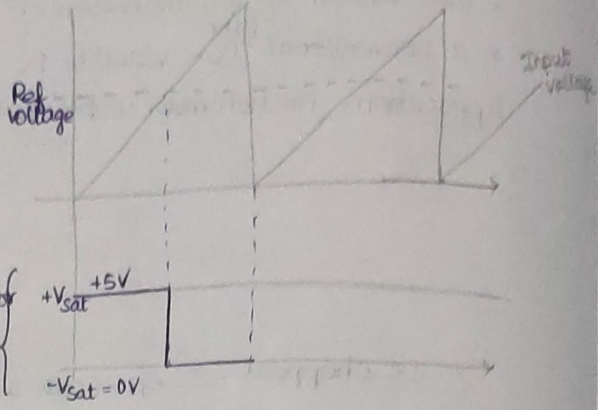
Width of pulse is varied
⇒ pulse width modulation

frequency modulation
⇒ generate unpredictable harmonics (filter design is difficult)



Comparator

⇒ Compatible for digital devices



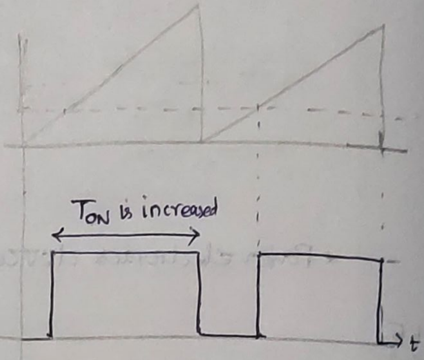
Comparator o/p voltage

$= (V^+ - V^-) \times A_{OL}$

But when the o/p exceeds, $+V_{sat}$ or $-V_{sat}$, then o/p voltage will be $+V_{sat}$ or $-V_{sat}$

If we increase the ref. voltage, the T_{ON} should increase so that V_{avg} increases.

So, ref. voltage should be given to -ve terminal & i/p voltage to +ve terminal



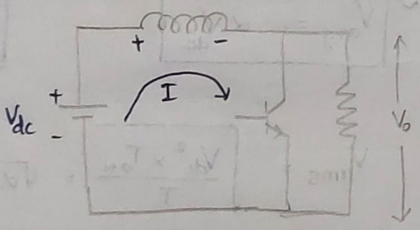
Types of Converters (Choppers)

(i) Step-up ~~converter~~ chopper $\Rightarrow V_o > V_{in} \Rightarrow$

(ii) Step-down chopper
$\Rightarrow V_o < V_{in} \Rightarrow \alpha < 0.99$

(i) Buck converter
(ii) Boost converter
(iii) Buck boost converter

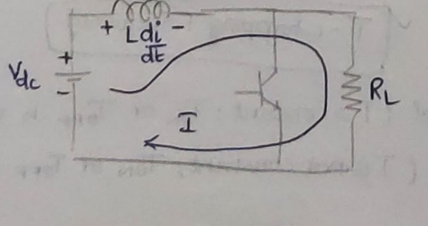
Step-up chopper



* Higher the switching frequency, lesser the value of ripples.

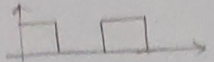
Inductor charges when Transistor is on $\Rightarrow V_o = 0V$

When transistor turns off

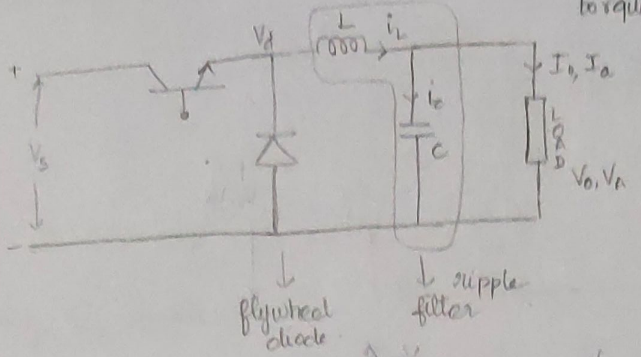


$$V_o = V_{dc} + L\frac{di}{dt} \text{ Volts}$$

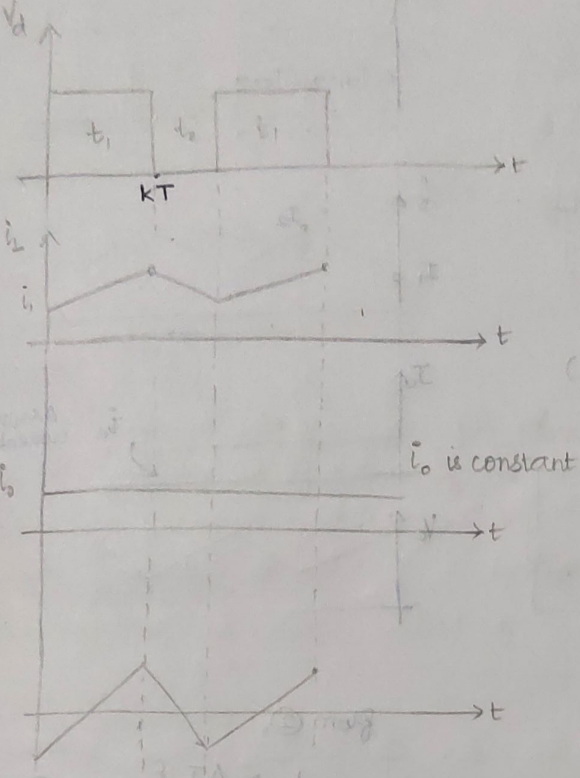
Buck Converter

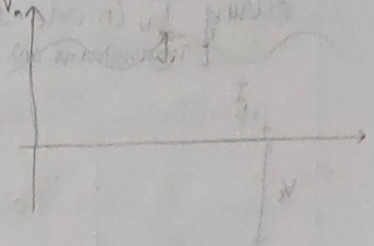


→ If the voltage is given to motor, it will have fluctuating torque, to avoid that, the voltage must be flattened



k-duty cycle





$$\frac{t_1(V_s - V_a)}{L} = \frac{t_2 V_a}{L}$$

$$t_1 V_s - t_1 V_a = t_2 V_a$$

$$t_1 V_s = (t_1 + t_2) V_a$$

$$e_L = L \, di/dt$$

$$V_s - V_a = \frac{L(I_2 - I_1)}{t_1}$$

$$= \frac{L \Delta I}{t_1}$$

$$t_1 = \frac{\Delta I . L}{V_s - V_a} \rightarrow (A)$$

$$\boxed{\Delta I = \frac{t_1(V_s - V_A)}{L}} \rightarrow (1)$$

I_L falls at t_2

$$0 - V_a = \frac{L(I_1 - I_2)}{t_2}$$

$$\boxed{t_2 = \frac{\Delta I . L}{V_a}} \rightarrow (B)$$

$$\Delta I = \frac{t_2 V_a}{L} \rightarrow (2)$$

equating (1) & (2),

$$V_a = \frac{V_s . t_1}{T} = k V_s$$

$$T = t_1 + t_2 = \frac{\Delta I . V_s}{V_a(V_s - V_a)}$$

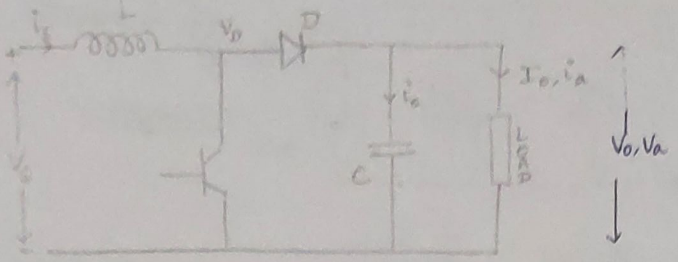
$$L = \frac{V_s . k(1-k)}{\Delta I . f} \quad (\because f = \tfrac{1}{T})$$

$$\Delta V_c = \frac{1}{C} \int_0^{T/2} \Delta I/4 \, dt$$

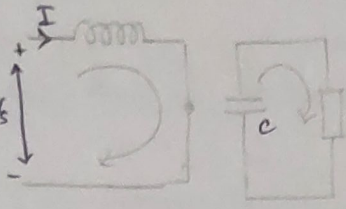
$$\boxed{C = \frac{\Delta I}{\Delta V_c . 8f}}$$

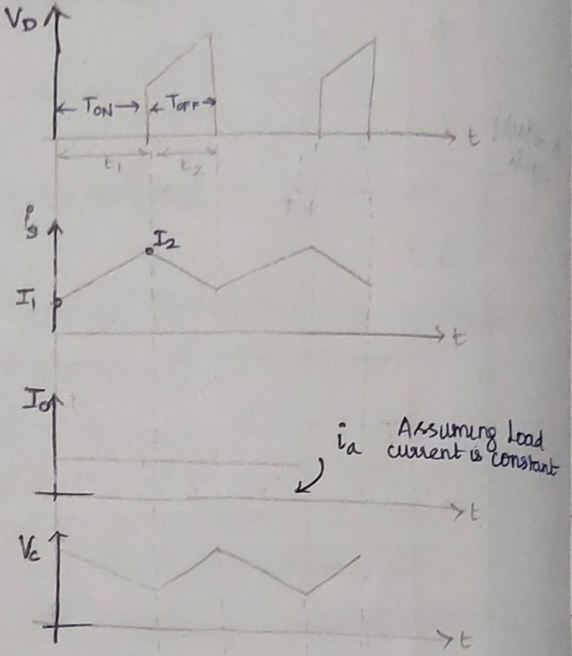
October 7
Offline

II Boost Converter

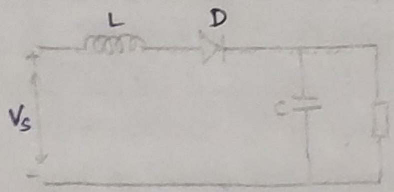


during T_{ON} (mode-I)
[Transistor is on)





during T_{off} (mode-II)



$$e = L\frac{dI}{dt}$$

during T_{ON}

$$V_s = \frac{L(I_2-I_1)}{t_1} \Rightarrow \boxed{t_1 = \frac{\Delta I . L}{V_s}} \rightarrow (A)$$

$$V_s = \frac{L\Delta I}{t_1} \Rightarrow \boxed{\Delta I = \frac{V_s t_1}{L}} \rightarrow (1)$$

during t_2 (T_{off})

$$V_s - V_a = -\frac{L\Delta I}{t_2} \Rightarrow t_2 = \frac{\Delta I . L}{V_a - V_s}$$

$$\boxed{\Delta I = \frac{t_2(V_a - V_s)}{L}} \rightarrow (2)$$

Comparing (1) & (2),

$$\boxed{V_a = \frac{V_s T}{t_2} = \frac{V_s}{1-k}} \rightarrow (3)$$

from (2),

$$L = \frac{\Delta I . f}{V_s k} \rightarrow (4)$$

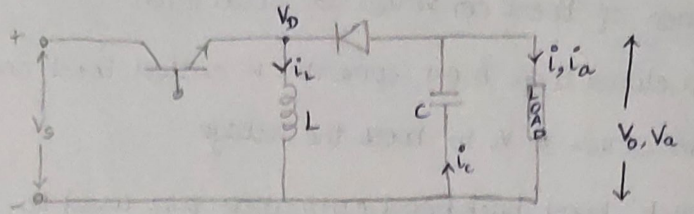
$\because f = \frac{1}{T} = \frac{1}{t_1+t_2}$

$$\Delta V_c = \frac{1}{c}\int_0^{t_1} I_c . dt$$

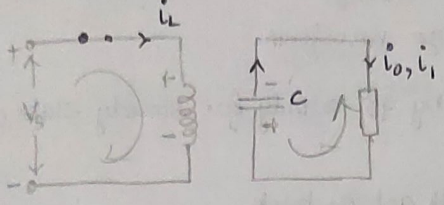
$$= \frac{1}{c} I_a t_1$$

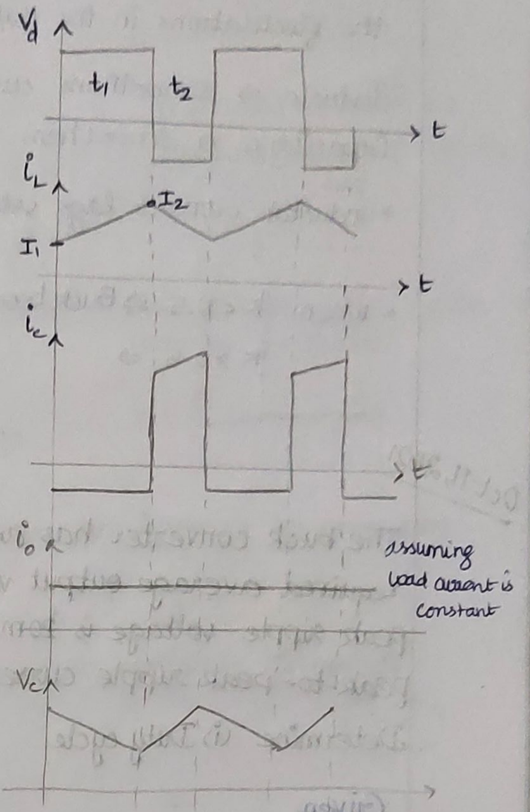
$$\boxed{C = \frac{f . \Delta V_c}{I_a k}} \rightarrow (5)$$

III Buck-Boost Converter:-

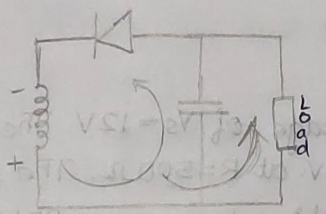


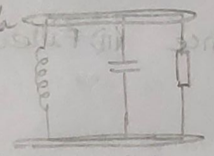
during T_{ON} (mode-I)





during T_{OFF} (mode-II)





during t_1

$$V_s = L\frac{\Delta I}{t_1} \Rightarrow \boxed{t_1 = \frac{\Delta I . L}{V_s}} \rightarrow (A)$$

$$\boxed{\Delta I = \frac{V_s . t_1}{L}} \rightarrow (1)$$

during t_2

$$V_a = -L.\frac{\Delta I}{t_2}$$

$$\boxed{t_2 = \frac{-\Delta I . L}{V_a}} \rightarrow (B)$$

$$\boxed{\Delta I = -\frac{V_a t_2}{L}} \rightarrow (2)$$

from (1) & (2)

$$\boxed{V_a = \frac{V_s . k}{1-k}}$$

$$\boxed{L = \frac{V_s . k}{\Delta I . f}}$$

$$\boxed{C = \frac{f . \Delta V_c}{I_a . k}}$$

* Solar panel is a current source. Voltage will not be constant due to variation in sunlight.

Main application of Boost converter ⇒ Solar Panel

* If there is a closed loop, boost converter is called boost controller.

* Inductor is in series to V_s to boost the voltage.

* L & C in buck, boost, buck boost converters are used to filter out the fluctuations in the output power.

Inductor ⇒ smoothens current waveform

Capacitance ⇒ smoothens voltage waveform

* Pure inductor current lags voltage by 90° ⇒ only for steady state conditions

* when $k < 0.5$ ⇒ Buck boost will act as buck

  $k > 0.5$ ⇒ act as boost

5×2 = 10 ⇒ Under

2×10 = 20 ⇒ Apply

Oct 11, 2021

The buck converter has an input voltage of $V_s = 12V$. The required average output voltage is 5V. at $R = 500\Omega$. The peak to peak ripple voltage is 20mV. The switching frequency is 25kHz. If the peak-to-peak ripple current of inductor is limited to 0.8 A. Determine (i) Duty cycle (ii) Filter inductance (iii) Filter Capacitance

Given

$V_s = 12V$; $V_o = 5V$ DC ; $\Delta V = 20mV$; $\Delta I_o = 0.8A$; $R = 500\Omega$; $f = 25$ kHz

Buck Converter,

* $V_o = kV_s \Rightarrow k = \frac{V_o}{V_s} = \frac{5}{12} = 0.416 \Rightarrow \boxed{k = 0.416}$

* $L = \frac{V_s k(1-k)}{\Delta I . f} = \frac{12 \times 0.416(1-0.416)}{0.8 \times 25000} = \frac{2.9153}{20,000}$

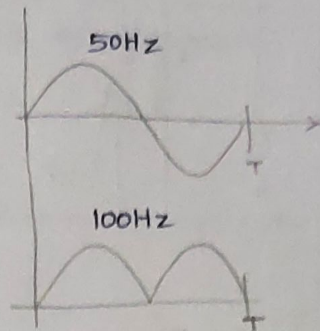
$= 1.457 \times 10^{-4} \times \frac{10}{10}$ $\boxed{L = 0.1457 \text{ mH}} = 145.7 \mu H$

* $C = \frac{\Delta I}{\Delta V \times 8f} = \frac{2 \times 10^{-4} \times 10}{10} = 0.2 \text{ mF} = 200 \mu F$

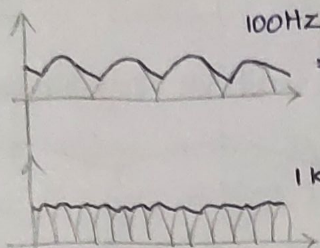
$= \frac{0.8}{(20 \times 10^{-3}) \times 8(25000)} = 200 \mu F \Rightarrow \boxed{C = 200 \mu F}$

SWITCHING MODE POWER SUPPLY

* AC to DC converter
* used in CPU
*
$$f = \frac{1}{2\pi\sqrt{LC}}$$

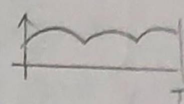


* If frequency is high, less values of L and C is needed to filter out the pulsating dc.

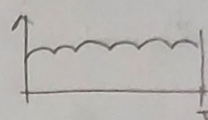


⇒ more ripple

3-ϕ semi-converter is a 3 pulse converter $f = 150$ Hz



3-ϕ full converter is 6-pulse converter $f = 300$ Hz



* Large inductance will require large size inductors
* In laptops we cant have large size inductors (transformers) for converting AC to DC.

* Silicon Carbide (SiC) & Gallium Nitrite (GAN) are now used instead of silicon wafer ⇒ ~~t_{rr}~~ t_{rr}

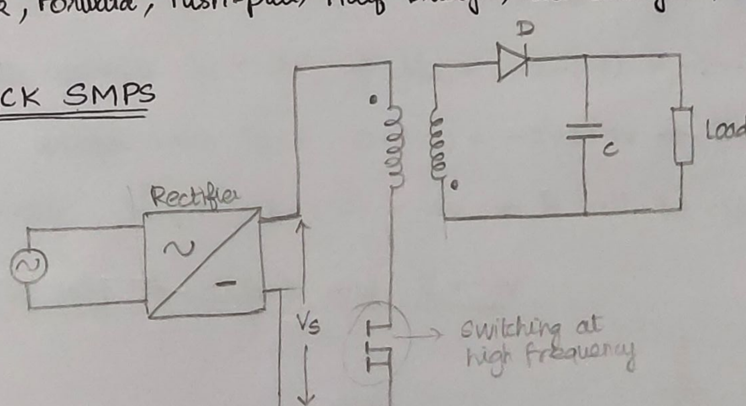
SiC ⇒ t_{rr} = 1 nano second

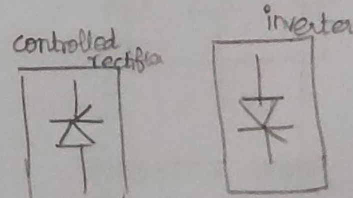
GaN ⇒ t_{rr} = 10 pico second

⇒ So SiC and GaN can be used in fast switching devices.

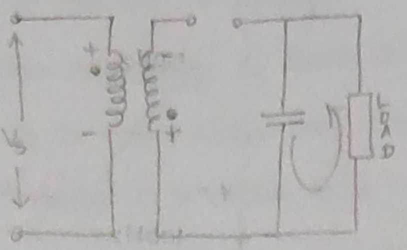
⇒ Flyback, Forward, Push-pull, Half bridge, Full-bridge ⇒ types of SMPS

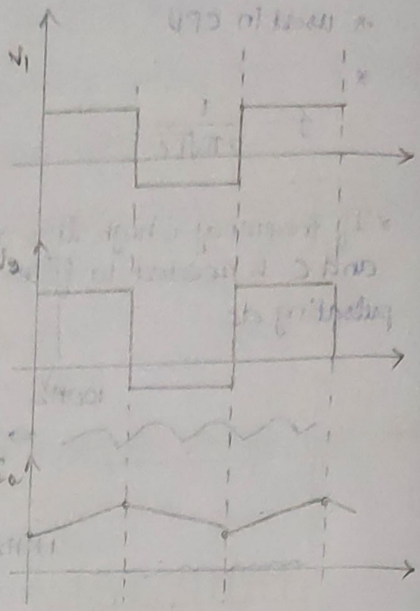
FLYBACK SMPS



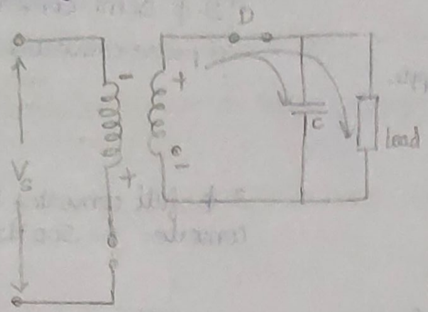


During T_{ON}





During T_{OFF}



$V_1 \quad V_2 \Rightarrow = V_1 + V_2$

$V_1 \quad V_2 \Rightarrow V_1 - V_2$

Forward

3 windings are magnetically coupling

Tertiary winding is for reset.

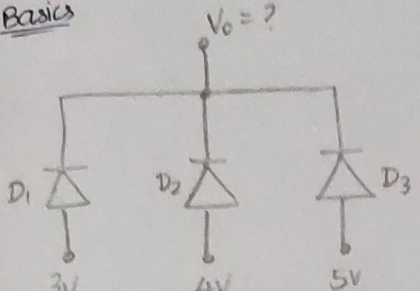
PE Sept 28

THREE PHASE CONVERTER

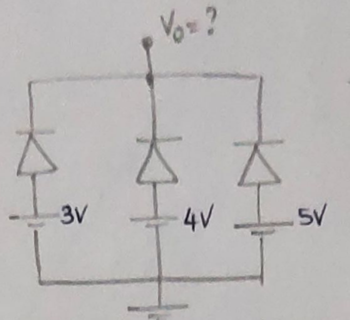
3 ϕ full converter

3 ϕ semi converter

Basics



$\Rightarrow$

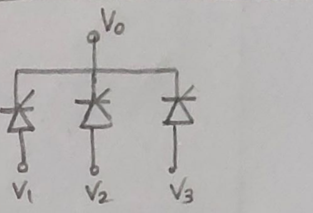


The anode voltages of diodes are different, hence these diodes are not connected in parallel.

* Assume first 3V diode D_1 starts conducting, then $V_o \simeq 3V$
* Now voltage across $D_2 = (4-3)V \Rightarrow$ So D_2 will start to conduct
* Now $V_o \simeq 4V$. $\Rightarrow$ Now D_1 becomes rev. biased.
* Voltage across $D_3 = V_{AK_3} = (5-4)V \Rightarrow$ D_3 starts conducting. $\Rightarrow$ D_2 rev bias

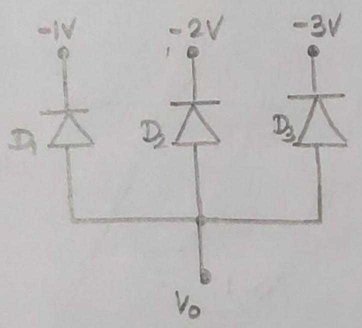
Hence $\boxed{V_o \simeq 5V}$ This is the final value of V_o

Only diode D_3 will conduct.



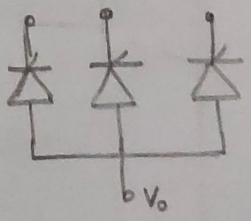
V_o = most positive of V_1, V_2, V_3

~~MOST~~ POSITIVE GROUP THYRISTORS



* Assuming initially D_1 conducts, $V_o = -1V \Rightarrow$ Voltage across D_2 is $V_{AK_2} = -1-(-2) = -1+2 = 1V \Rightarrow D_2$ starts conducting.
* As D_2 conducts $V_o = -2V \Rightarrow V_{AK_1} = -2-(-1) = -2+1 = -1V \Rightarrow D_1$ off
* Now voltage across $D_3 = -2-(-3) = -2+3 = 1V \Rightarrow D_3$ starts conducting
* $V_o = -3V$ $V_{AK_3} = -3-(-2) = -1V \Rightarrow D_2$ will be off

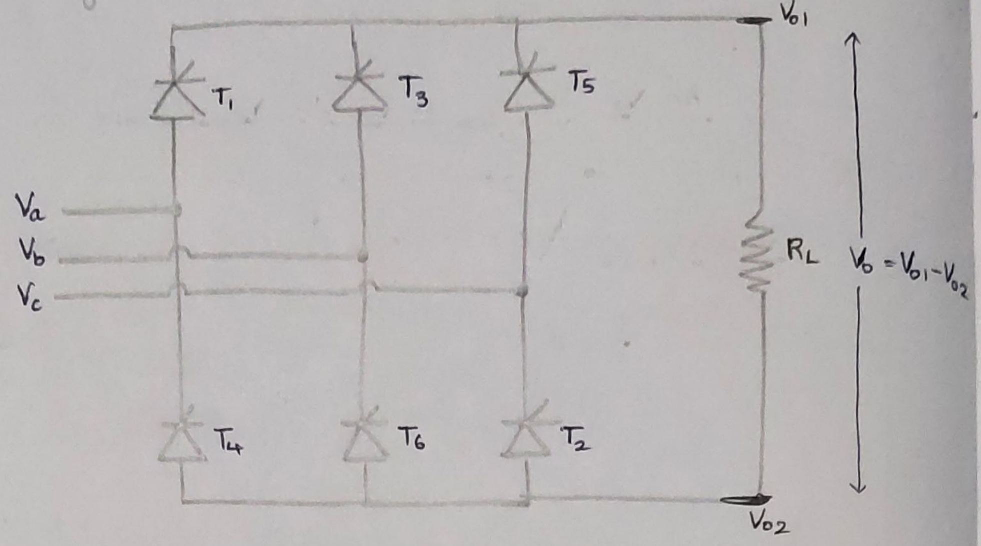
Finally only D_3 conducts and $V_o = -3V$



NEGATIVE GROUP THYRISTORS

V_o = most negative i/p

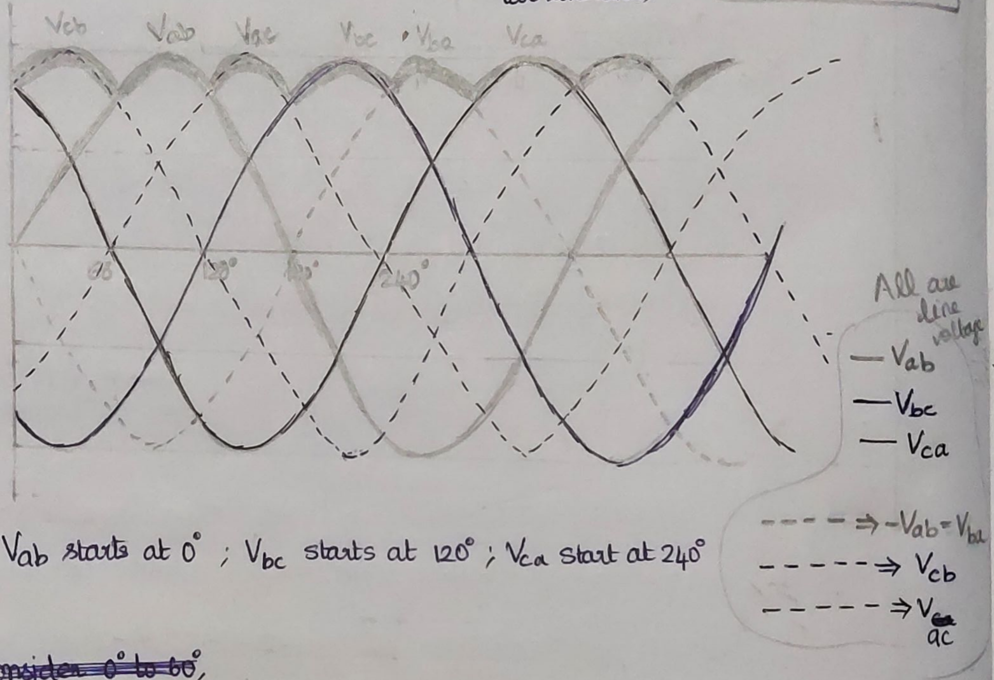
Assuming $\alpha = 0^\circ$ (firing angle)



Hence V_o = (most positive) − (most negative)

Thyristor with firing angle $\alpha = 0^\circ$ is a diode

* At any time, o/p voltage is line voltage (voltage between any two live lines)



* V_{ab} starts at 0° ; V_{bc} starts at 120° ; V_{ca} start at 240°

~~Consider 0° to 60°~~,

~~V_{o1} = most positive line voltage~~ =

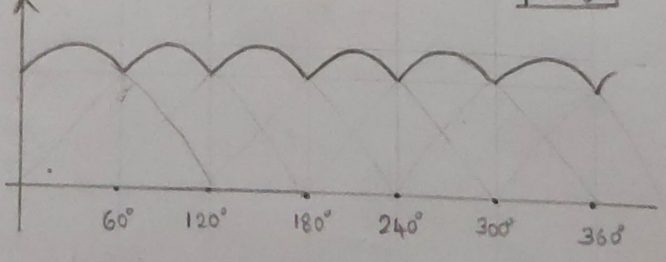
V_o = most positive −(most negative)

= most most positive

So from 0° to 60°, o/p voltage = V_{cb}

o/p voltage of 3-ϕ full converter

$\boxed{\alpha = 0^\circ}$



(1) For O/P = V_{cb}, (0° to 60°) T_5 is the +ve group thyristor that conducts
T_6 is the -ve group thyristor that conducts.

$\alpha = 0°$

	0° V_{cb} 60°	V_{ab} 120°	V_{ac} 180°	V_{bc} 240°	V_{ba} 300°	V_{ca} 360°
	T_5	T_1	T_1	T_3	T_3	T_5
-ve group thyristors	T_6	T_6	T_2	T_2	T_4	T_4

⇒ Conduction table diagram

⇒ Each thyristor should conduct for 120°.

Initially, only one thyristor should be conducting (say T_1)

T_1 conducts ⇒ After 60° T_2 conducts ⇒ After 60° T_3 conducts, . . .

When firing angle is $\alpha = 60°$,

0° – 60°	60° – 120°	120° – 180°	180° – 240°	240° – 300°	300° – 360°
T_5	T_5	T_1	T_1	T_3	T_3
T_4	T_6	T_6	T_2	T_2	T_4
V_{ca}	V_{cb}	V_{ab}	V_{ac}	V_{bc}	V_{ba}

Sept 30

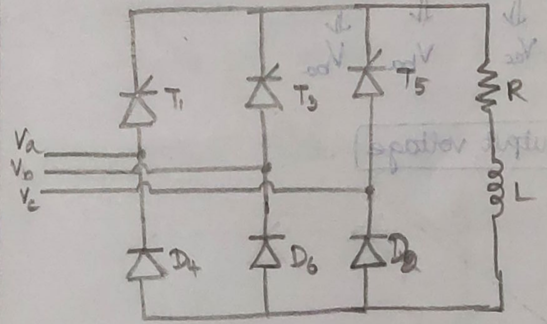
For a 3-φ full converter $\boxed{V_{o\,avg} = \frac{3V_{mL}}{\pi} \cos\alpha}$

V_{mL} ⇒ maximum of line to line voltage

3-φ 440 V
line to line RMS voltage

$\Rightarrow V_{ml} = 440 \times \sqrt{2}$

3-φ semi converter



For $\alpha = 0°$, o/p voltage of 3-φ full converter & 3-φ semi-converter remains the same

$\alpha = 0$

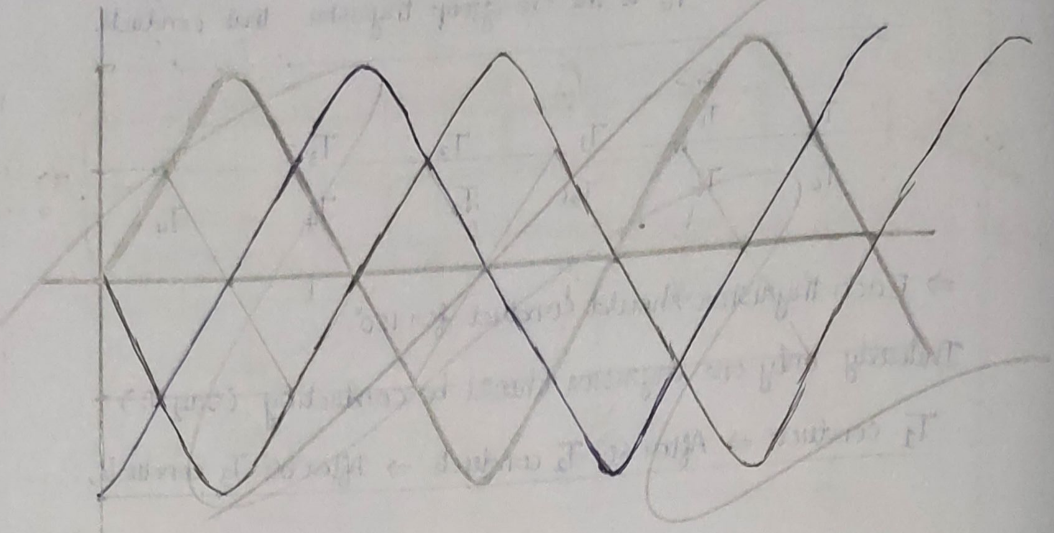
0° V_{cb} 60°	V_{ab} 120°	V_{ac} 180°	V_{bc} 240°	V_{ba} 300°	V_{ca} 360°
T_5	T_1	T_1	T_3	T_3	T_5
D_6	D_6	D_2	D_2	D_4	D_4

$\alpha = 60°$

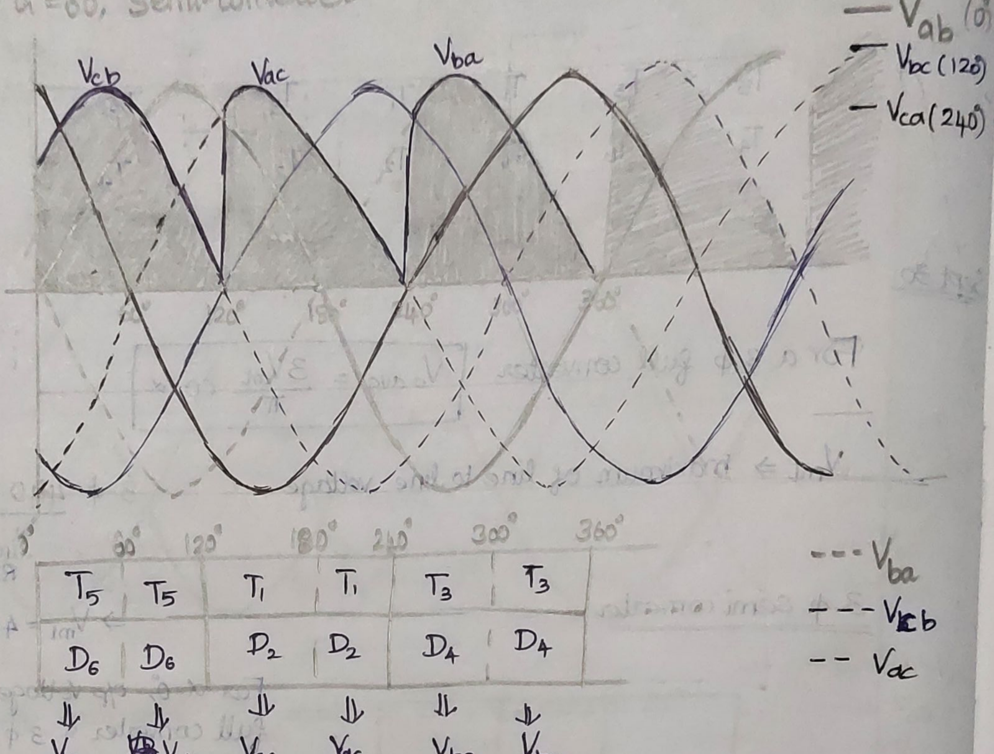
0° – 60°	60° – 120°	120° – 180°	180° – 240°	240° – 300°	300° – 360°
T_5	T_5	T_1	T_1	T_3	T_3
D_6	D_6	D_2	D_2	D_4	D_4
V_{cb}	V_{cb}	V_{ac}	V_{ac}	V_{ba}	V_{ba}

⇒ Thyristors are shifted by 60°

⇒ Diodes remain same



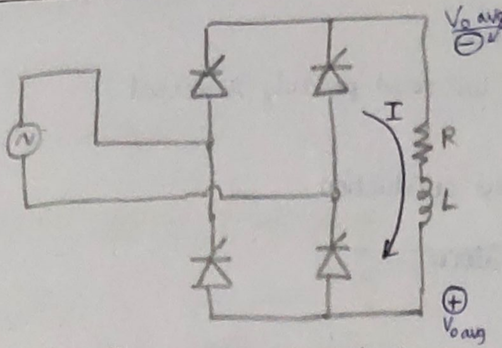
For $\alpha = 60°$, semi-converter

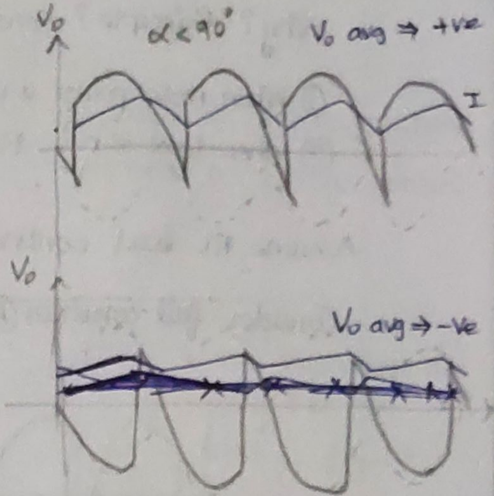


0°–60°	60°–120°	120°–180°	180°–240°	240°–300°	300°–360°
T_5	T_5	T_1	T_1	T_3	T_3
D_6	D_6	D_2	D_2	D_4	D_4
$\Downarrow$	$\Downarrow$	$\Downarrow$	$\Downarrow$	$\Downarrow$	$\Downarrow$
V_{cb}	V_{cb}	V_{ac}	V_{ac}	V_{ba}	V_{ba}

$\Rightarrow$ $\boxed{\text{Shaded region} \Rightarrow \text{output voltage}}$

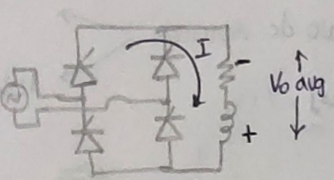
Line Commutated Inverter



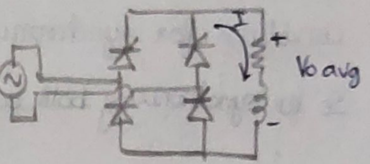


1 φ full converter with RL load

* When α > 90°, the V_o avg becomes negative ⇒ voltage polarity reverses
* But current direction remains same.

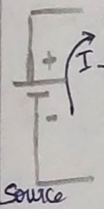


α > 90°



α < 90°

Current enters through -ve terminal
Current leaves through +ve terminal



The load acts as a DC Source

Current enters through +ve terminal.

Load is acting as a load

If a rectifier is operated as an inverter, then ac line voltage commutates the device and no commutation device is required

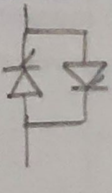
$\boxed{DC \rightarrow AC \Rightarrow \text{Inverter}}$

Hence it is called line commutated inverter

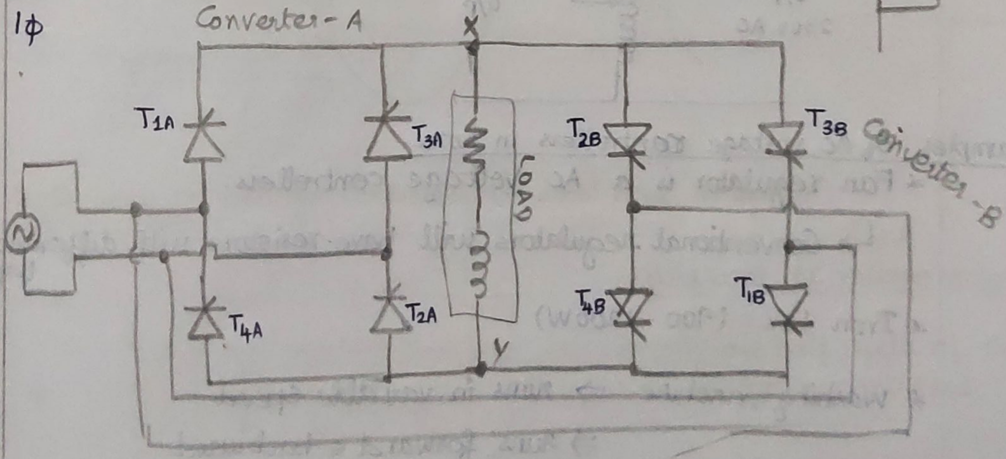
Line commutated inverter:-

⇒ 1φ full converter with RL load with continuous conduction & α > 90°

Dual Converters (Back to back converters) $\xrightarrow{\text{similar to}}$



1φ



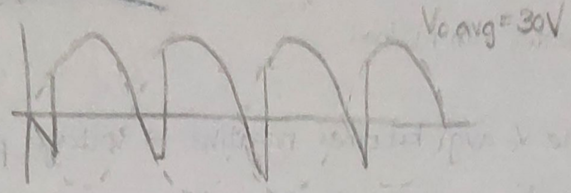
Why? Principle? Conditions?

① When more power is needed.

② When load is not RL, we need polarity reversal

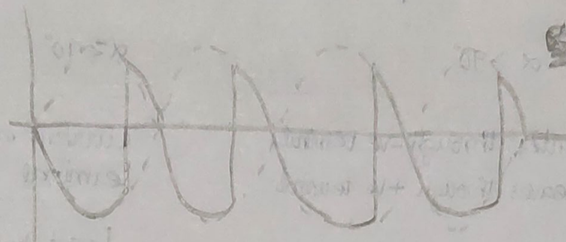
Assume RL load, continuous conduction

Consider full-converter Ⓐ alone, $\alpha_A = 30°$



Conditions for synchronizing two dc sources → Magnitude must be equal; → Polarity must be

So for synchronizing both converters,



$\alpha_B = 180 - 30°$

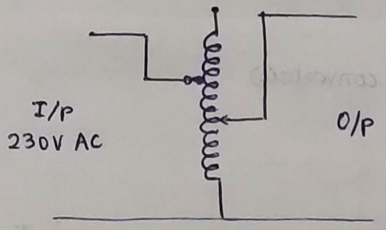
$V_{o\,avg} = -30V$

October 25

AC Voltage Controllers

Constant AC supply → [AC Voltage Controllers] → Variable AC supply

Example:- Variac



230V AC → Variac → (2-270V) AC variable

Examples of AC voltage controllers in home

* Fan regulator is a AC voltage controllers.
  ↳ Conventional regulators will have resistors with different tappings
* Iron box (900 – 1200W)
* Washing machine ⇒ runs in variable speed
  ⇒ runs forward & backward

Control Types

(a) Phase control

(b) Integral cycle control

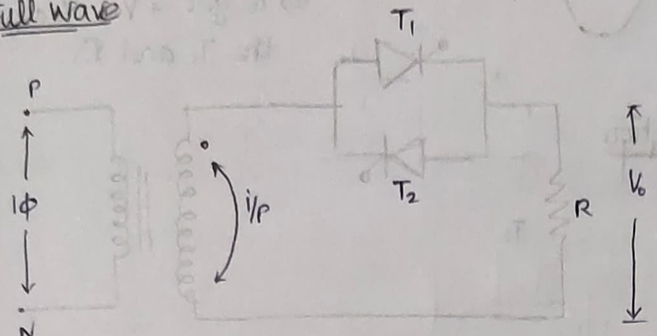
Types

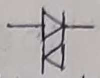
(1) Half-wave AC voltage control

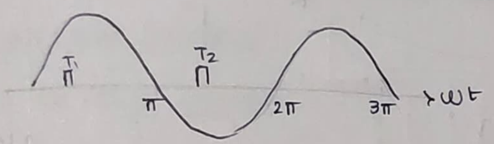
(2) Full-wave AC voltage control

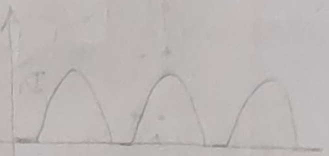
Basic AC voltage Controllers

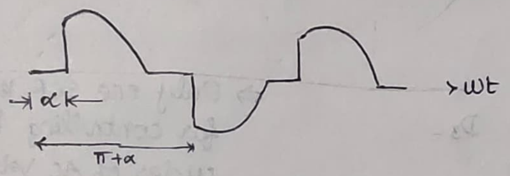
Full wave



* Two thyristors are needed or one triac  is needed to control two half cycles of AC voltage





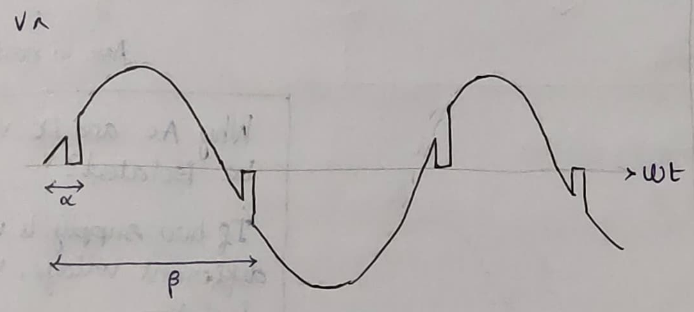


V_o^2 will be the same as V_o^2 of 1ϕ full converter with R load.

$$\Rightarrow V_{o\,rms} = \frac{V_m}{\sqrt{2\pi}}\sqrt{\pi-\alpha+\frac{\sin 2\alpha}{2}}$$

$$\Rightarrow V_{o\,avg} = 0\,V$$

Full wave with RL load

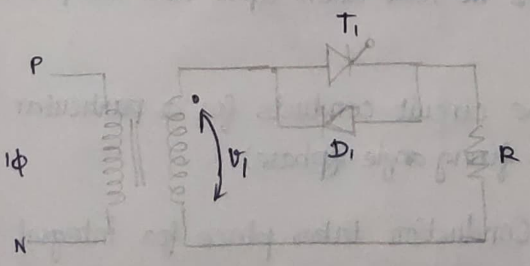


Types based on connections

(a) Series connection

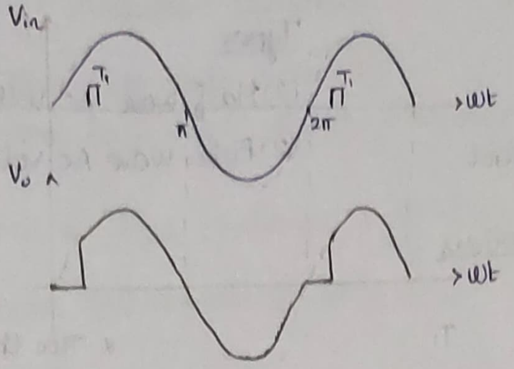
(b) Bridge connection

Half-wave AC voltage controller (R load and RL load)



Half wave AC voltage controller

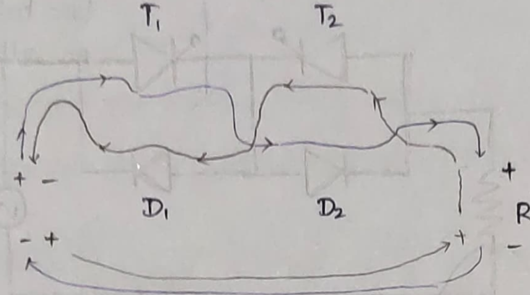
⇒ Only one half cycle of the AC voltage is controlled.



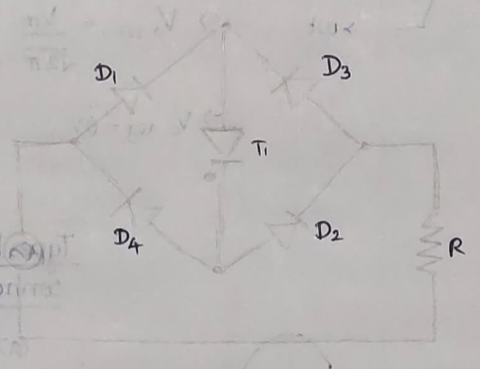
⇒ V_o avg will be negative

⇒ to get +Ve V_o avg, interchange the T_1 and D_1

(a) Series Connection



(b) Bridge Connection



⇒ Only one SCR is used for controlling both half cycles of AC voltage

Ask in next class

Why AC and DC voltage should be isolated?

If two supply is with different voltage, we need isolation.

The AC voltage controllers we have seen upto now are phase control AC controllers.

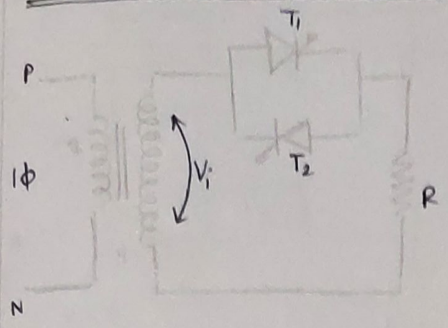
In each half cycle, the circuit conducts for a particular part starting from some firing angle (phase)

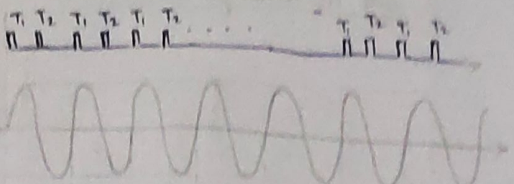
Integral Cycle Control: Conduction takes place for integral number of ~~times~~ full cycles and turn off for further number of cycles.

→ Used in systems with larger time constants.

October 26

INTEGRAL CYCLE CONTROL

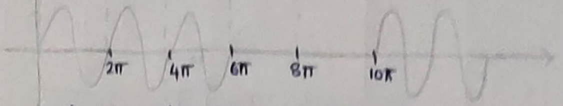




$$V_{o\,rms} = \sqrt{\frac{\int_0^{6\pi} V_m^2 \sin^2\omega t \, d(\omega t)}{10\pi}}$$

$$= \sqrt{\frac{6\int_0^{\pi} V_m^2 \sin^2\omega t \, d(\omega t)}{10\pi}}$$

$=$



⇒ 3 cycles ON, 2 cycles off

Base is 10π

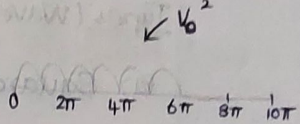
$N \rightarrow$ on cycles

$M \rightarrow$ no. of off cycles

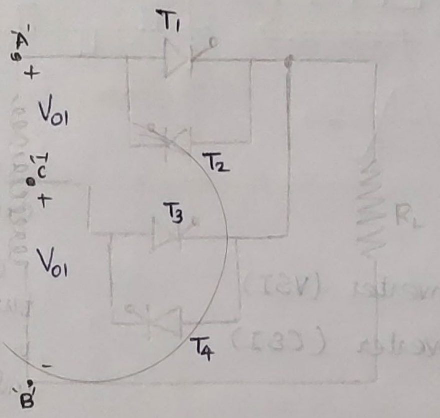
$$\boxed{V_{o\,rms} = \sqrt{\frac{N}{N+M}\int_0^{2\pi} V_m^2 \sin^2\omega t \, d(\omega t)}}$$

SEQUENTIAL CONTROL

There are many types of sequential control



(a) Two stage sequential control



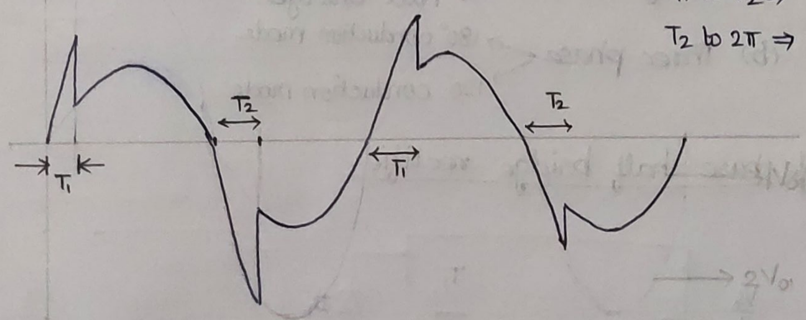
$V_{AB} = 2V_{01}$; $V_{AC} = V_{CB} = V_{01}$

0 to T_1 ⇒ T_1 thyristor on

T_1 to π ⇒ T_3 thyristor on

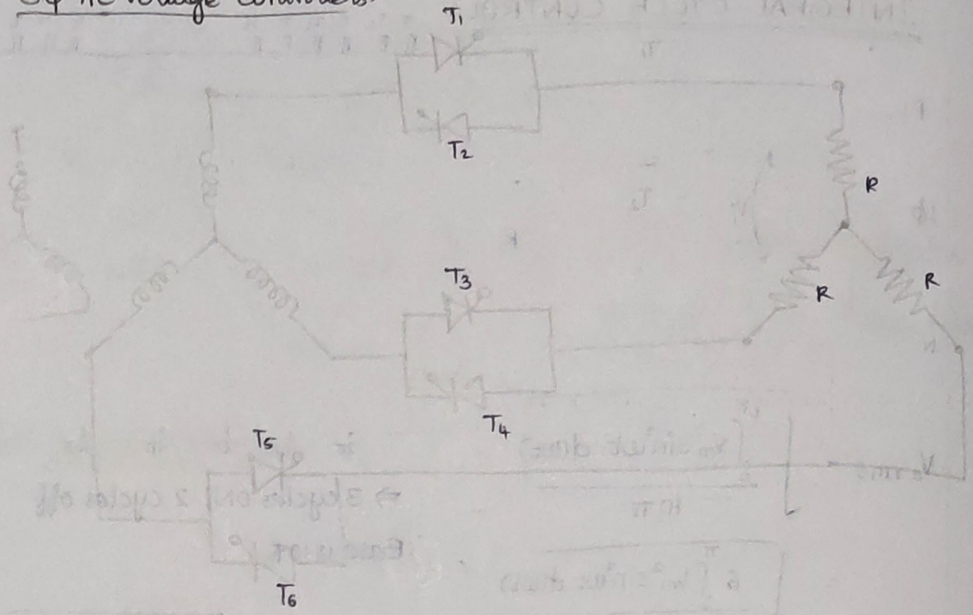
π to T_2 ⇒ T_2 thy is on

T_2 to 2π ⇒ T_4 is on



We can get different wave shapes based on which thyristors we are firing.

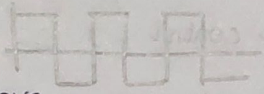
3φ AC Voltage controllers:-

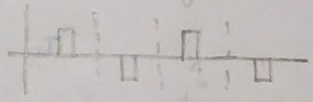


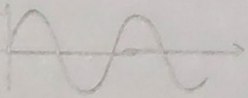
October 29

Inverter (DC to AC)

Types (Wave shapes)

(a) Square wave 

(b) Quasi square wave ⟹ 

(c) Sine wave 

UPS is needed for critical loads.

Computer will turn off even if there is a power cut for milli seconds,

UPS will turn ~~off~~ on immediately after power cut

Types (source)

(a) Voltage source Inverter (VSI)

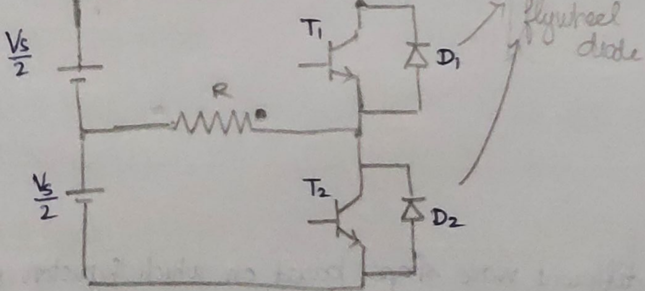
(b) Current source inverter (CSI)

Types (Phase)

(a) Single phase → Half bridge / Full bridge

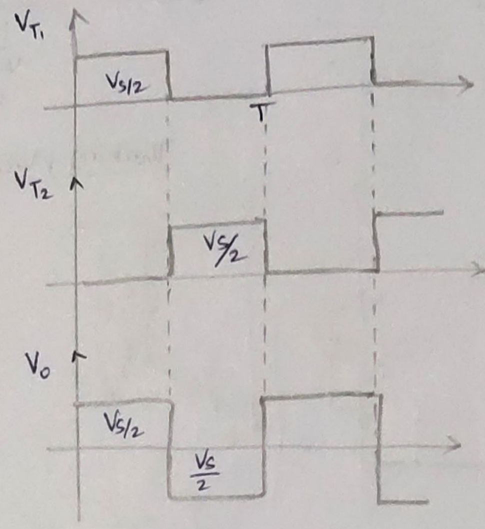
(b) Three phase → 180° conduction mode / 120° conduction mode

Single phase half bridge rectifier

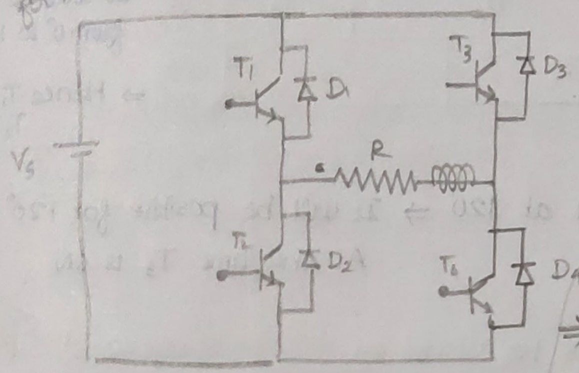


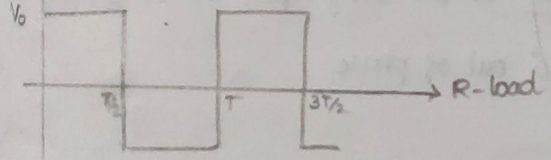
If I want SQH square wave

turn on T_1 for 10 ms and T_2 for 10 ms



1ϕ Full Bridge inverter (R-load)





R load

Positive half cycle ⇒ T_1 and T_2 on

Negative half cycle ⇒ T_3 and T_4 on

RL load

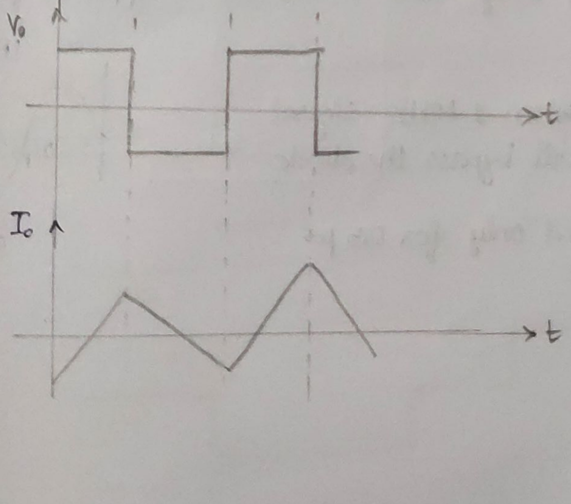
⇒ Initially T_1 & T_4 are on
Inductor charges + −

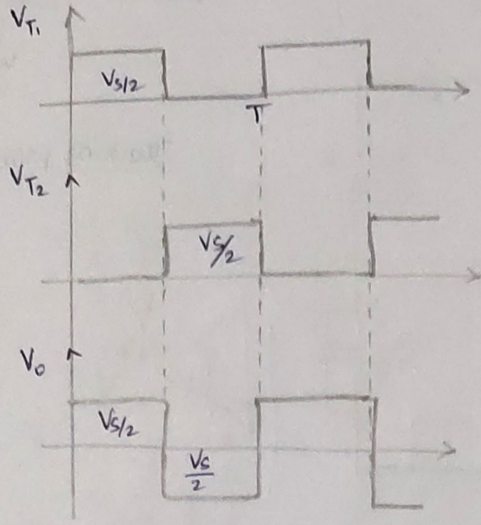
⇒ T_1 & T_4 are off

⇒ Inductor polarity reverses − +
and starts discharging.

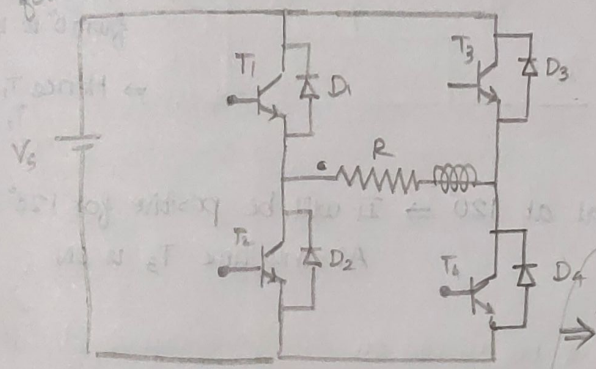
⇒ Due to inductor, T_3 and T_2 turn on

For RL load





1ϕ Full Bridge inverter (R-load)



R load

Positive half cycle ⇒ T_1 and T_2 on

Negative half cycle ⇒ T_3 and T_4 on

RL load

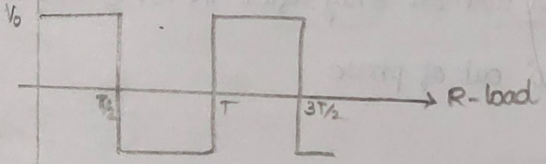
⇒ Initially T_1 & T_4 are on
Inductor charges

⇒ T_1 & T_4 are off

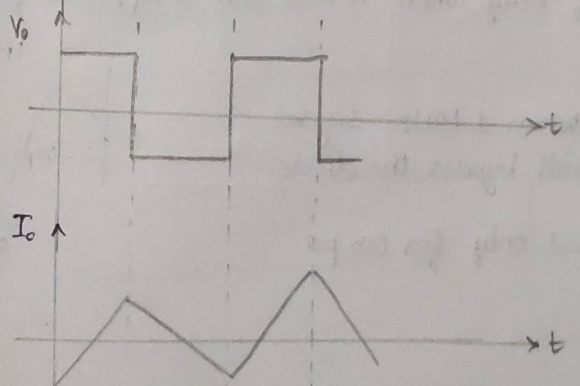
⇒ Inductor polarity reverses

and starts discharging.

⇒ Due to inductor, T_3 and T_2 turn on



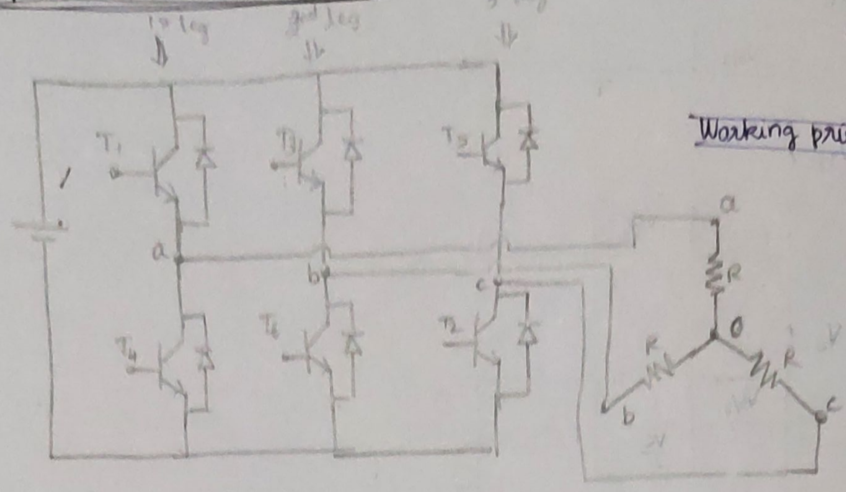
For RL load

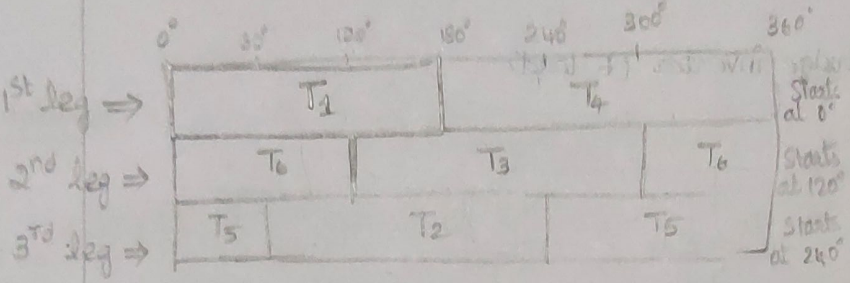


3 ϕ Inverter 180° Conduction

Inverter Vs UPS
↓
very fast connection load.

Working principle same





a phase will start at 0°

It will be positive from 0° to 180°

⇒ Hence T_1 conducts
T_2 is off

b phase will start at 120° ⇒ It will be positive for 120° to 300°

At this time T_3 is ON

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T_1 and T_4 should not be turned on simultaneously ⇒ short ckt

T_3 and T_6

T_5 and T_2

⇒ T_4, T_6, T_2 should turn on only after T_1, T_3, T_5 are turned off

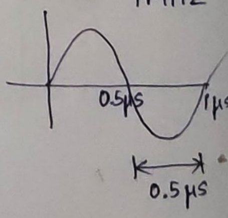
⇒ T_4 & T_1 are 180° out of phase
T_3 & T_6
T_5 & T_2

10^{-6}

1MHz

A diode will turn off only when reverse bias is applied for more than its t_{rr}

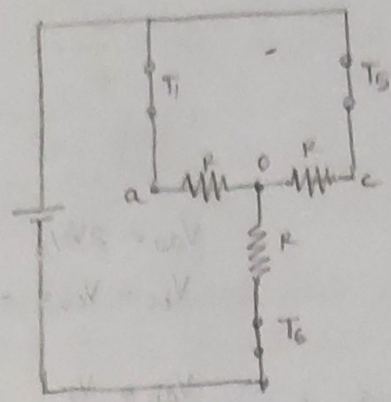
1MHz

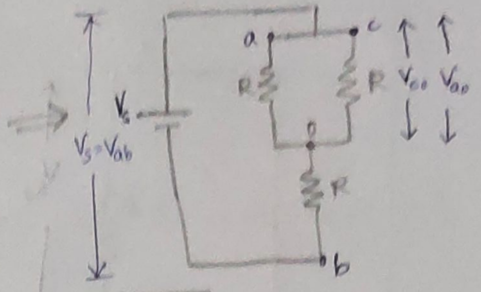


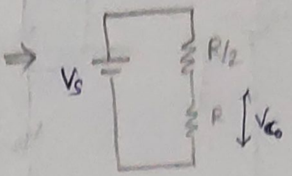
If $t_{rr} = 1\mu s$ ⇒ When 1 MHz signal will bypass the diode

⇒ Rev. bias is applied only for 0.5 μs

For 0° to 60°, T_1, T







$V_{co} = \frac{V_s\left(\frac{R}{2}\right)}{R+\frac{R}{2}}$

$= \frac{V_s R}{2\left(\frac{2R+R}{2}\right)}$

$V_{ao} = V_{co} = \frac{V_s}{3}$

$V_{bo} = -\frac{2V_s}{3}$

(Polarity is negative)

$V_{bo} = -\frac{V_s(R)}{R+\frac{R}{2}}$

$= -\frac{V_s(2)}{(3)}$

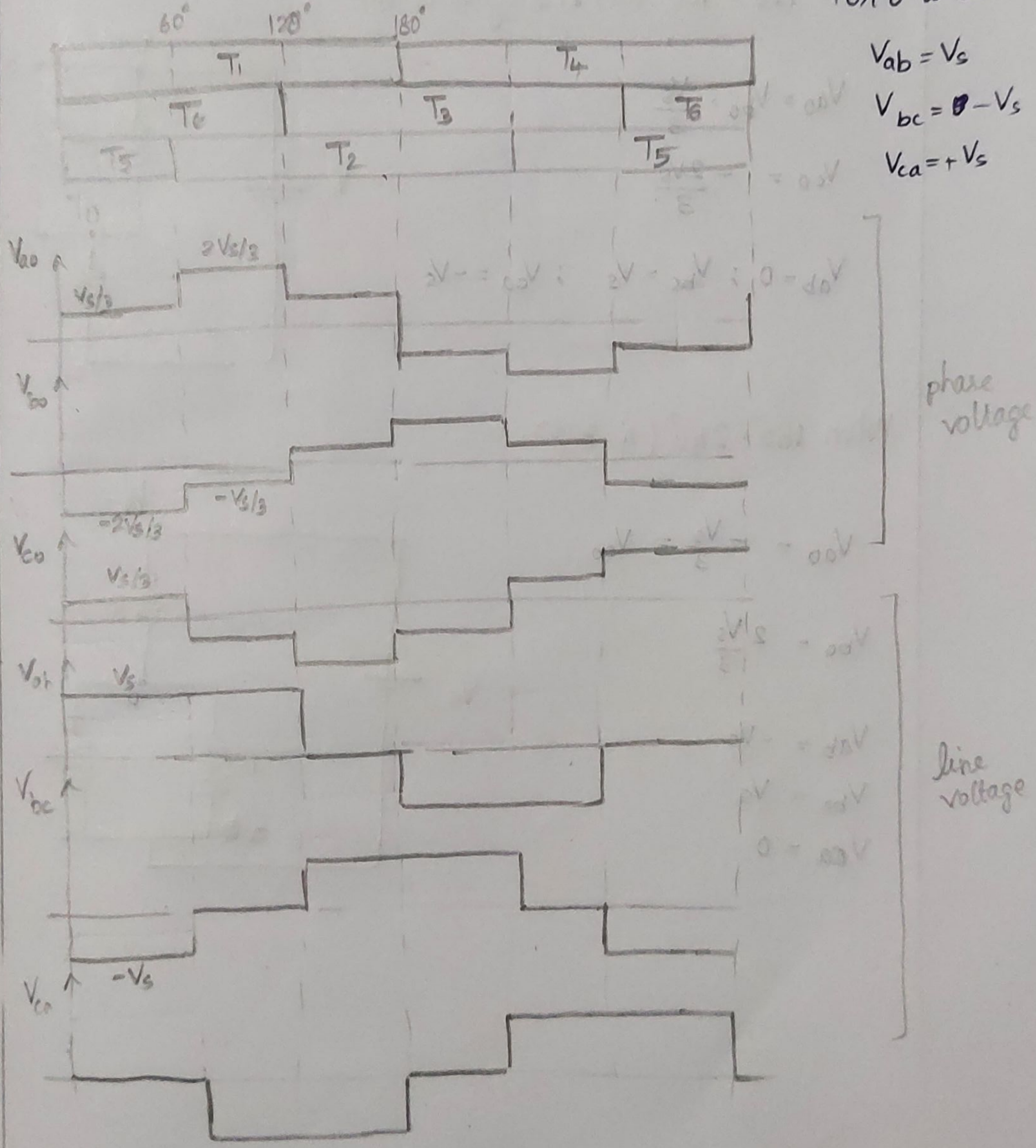
$V_{co} = \frac{V_s}{3}$

For 0° to 60°

$V_{ab} = V_s$

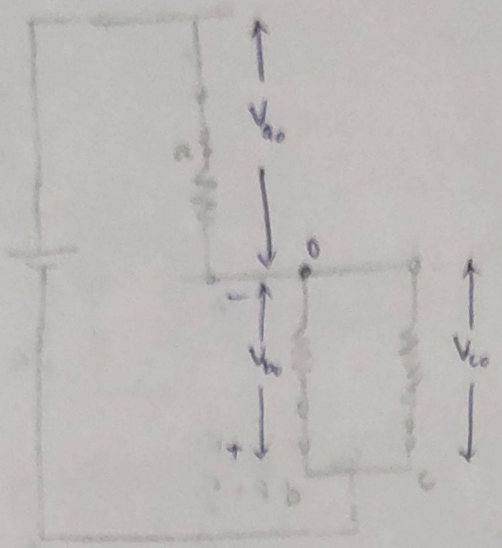
$V_{bc} = -V_s$

$V_{ca} = +V_s$



When 60° to 120°

T_1, T_2, T_6



$V_{ao} = 2V_s/3$

$V_{bo} = V_{co} = -V_s/3$

$V_{ab} = V_s$

$V_{bc} = 0$

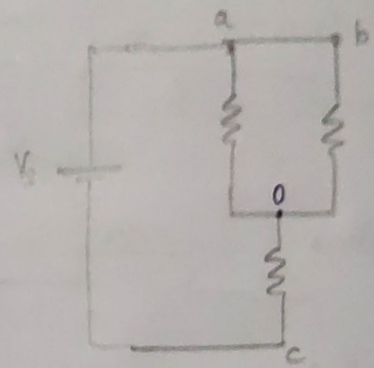
$V_{ca} = -V_s$

When 120° – 180° (3, 2, 3 Thyristors on)

$V_{ao} = V_{bo} = \frac{V_s}{3}$

$V_{co} = -\frac{2V_s}{3}$

$V_{ab} = 0$; $V_{bc} = V_s$; $V_{ca} = -V_s$



When 180°-240° (4, 3, 2)

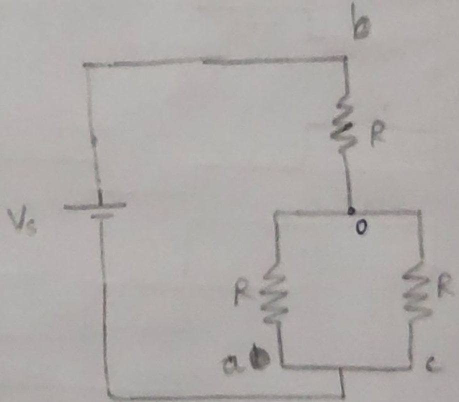
$V_{ao} = -\frac{V_s}{3} = V_{co}$

$V_{bo} = 2\frac{V_s}{3}$

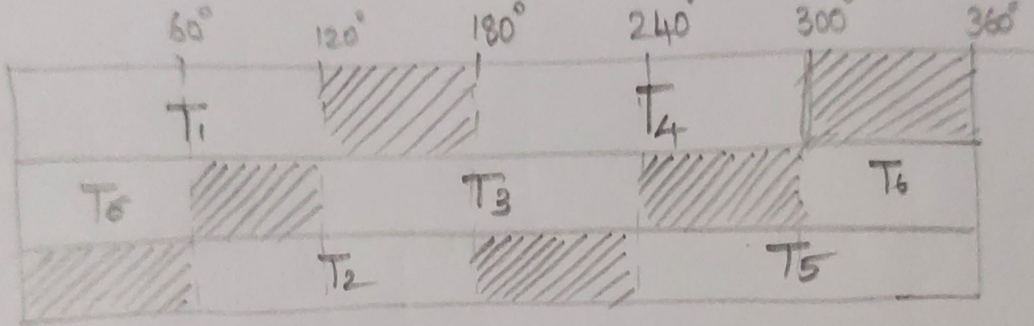
$V_{ab} = -V_s$

$V_{bc} = V_s$

$V_{ca} = 0$



120° conduction mode



Same as 180 conduction mode but here first 120° degree it conducts, next 60° it will be off (shaded region)