Power Electronix

NoteBook

Dr. Mohammad Z Khader

By: Mustafa Zahlan & Imtyaz Omar

POWER UNIT

ELECTRICAL ENGINEERING

Subject Power electronics Date 18/2/2014 lec. No. #1

• the devices in the Power electronics need solid state physics

• the

• Mercury arc rectifier act as a diode that use Mercury as conductor
note that it can hold large current "The beginning of power electronics"

• after Mercury arc rectifier the metal tank rectifier appear.

• Grid controlled vacum tube use bulbs & has multiple terminal
note that old radio use five bulbs.

• transistor is semiconductor device can act as triode which has
three terminal (bulbs).

• Igintron, Phanatron, Thyrator can hold large current but relativly
it was small current.

* all above pre history of power electronics. (- 1957)

• first phase:

~~...~~ Application of fast-switching fully controlled semiconductor device
which can make fast switching for large frequency.

• In thyrestor can hold thousands of Amperes the large terminal is
a diode a small one is gate act as a controllet that allow ~~...~~
specific amount of current to pass.

Subject Date No.

* Applications:-

[1] Motor drives:

from some Kilo watts up to hundreds or thousands of Kilowatts it use to change the speed of the motors

[2] Electroplating: عمليات الطلاء ك.ك.ع لتيار عالي

[3] Induction heating: عمليات التسخين

[4] Magnetic leviation: عمليات الرفع الكهربائية

[5] High voltage dc transmission:

→ when DC power transmission its more economical because the resistance of the DC is less than the AC because of skin effect in which AC current transmitt on the outer surface of the conductor while DC current transmitted on all the cross-section area.

→ in large distance countries the conversion of AC voltage to DC & then transmitt it through transmission lines & then convert it to AC is better than the transmission of AC directly because of the losses.

- we mean by good power quality is the pure sinusoidal wave voltage without harmonics & discontinuity & with constant peak to peak value & frequency.
- the process of electric power generation from Solar energy use power electronics.
-

■ Advantages:-

① Easy & flexible.

② Faster because it take millisecond, while the mechanical switch take long time.

③ noise is less in power electronics:

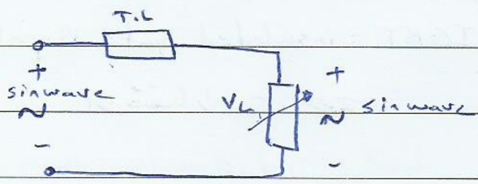
as example: old telephony system use relays so when we move numbernine for example nine relays will change it state so alarge noise also it need maintmenace because of sparks.

④ high effecency

■ Disadvantages:

① it generates harmonics. because of the process of on/off switching

② Harmonics are injected ~~to~~ into power system lines the performance of other load affected ⟶ illustration.



$v = V_m \sin \omega t$

$i = \frac{V_m}{2} \sin(\omega t + \theta) +$

$V_2 \sin(3\omega t)$

* the power factor is prefered to be near than 1 to make the generated powr maximum

■ Major issues in power electronics

- reliable: موثوقة ويعمل لفترة طويلة بدون تقطع أو تلف
- less volume & wight for planes & spaceships & spacestations
- less cost for large amount produced devices.

■ Power devices:

IGBT : insulated gate Bipolar transistor

الاقتصارات جهد.

■ Slide 23 :

thyrestor will be studgied in detailed in this course.

■ Slide 24 :

- normal thyristor is used in low freq 50-60 Hz for rectification application also TRIAC can be used
- normal thyristor can be used for ~~high frequency~~ low frequency & high power.
- GTO : also thyrestor & has property of stop of operation & can be used for larger frequencies & high power can be used in cases & UPS : ~~[illegible]~~ un inturrpted power supply.
- MOS BIOP : works for larger frequency but with low power.
- when the frequency increase the power become less

- UPS = Uninterrupted power supply take the power from the (رطاس) & if the connector disconnect then it take the power from the battery.

lecture no.2 :

- Slide 1 :
- Slide 4 :

- AC : 230 V & 60 Hz

full wave rectifier using thyrestor : we use switching on & off to control the average value.

- using triac we can control the amount of power absorbs by the load.
- Choppers used to convert the DC at one level to another level.

Choppers used to convert the DC level ~~[illegible]~~ by using transistor to cutt the DC at specific intervales to change the average value.

- invertor change ~~D~~C to AC.

- our concentration is in the power convertor. but we use the filters to make the signal more smooth. also we use the feedback control switching

Subject Power electronics Date 23/2/2014 lecture No. 3

Slide 7:-

switched mode is the subject of power electronics.

Slide 8:-

we avoid the use of magnetics in power electronics.

Slide 9:-

we avoid the use of resistor because it generate loss in power.

why to avoid linear mode?

because of the DC component which represent a loss.

Slide 10:-

ideal switch consumes zero power since in ~~eith~~ both cases either the voltage or current is zero.

Slide 12:-

the effeciency is 50% since we lost 500 watt at the transmission line.

Slide 13:-

we can use the amplifiers

Slide 14:-

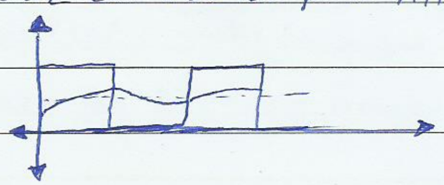
the use of switch to broke the input signal such that

Slide 15:-

$D \equiv$ Duty cycle $\Rightarrow D = \frac{\text{Time on}}{\text{total period}}$

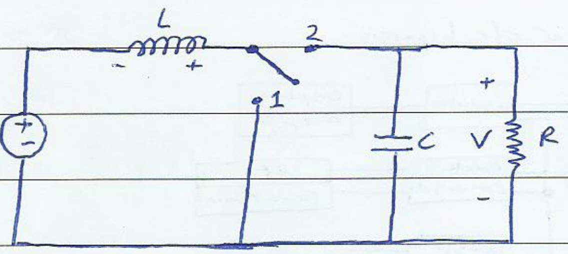
Slide 16:

since ~~the~~ we have some time on & some time off so this not disirable so we can use low pass filter.



Slide 18:-

the boost convertor is used to store energy the to release it to obtain large voltage from low one example in car the available voltage is 12V & to start the engine we need 11,000 V so we use the boost converter to make this.



$$V_{dc} = L\frac{di}{dt}$$

$$di = \frac{V_{dc}}{L} \cdot dt$$

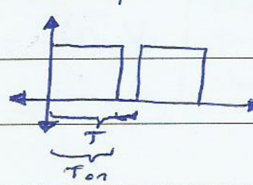
$$i = \frac{V_{dc} t}{L} + k$$

note that if the switching is instantaneously then the obtained voltage is infinite.

• when the switch is moved to (2) then the voltage will be negative across the inductor since the change in current is negative so the out put voltage will be the voltage across the inductor plus the Vg.

the new voltage depend on the period of switching that is $\frac{1}{1-D}$

where D = Duty cycle

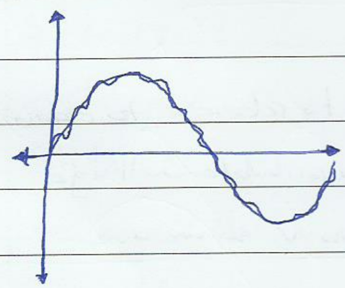


in this case voltage will be high since $D \simeq 1$

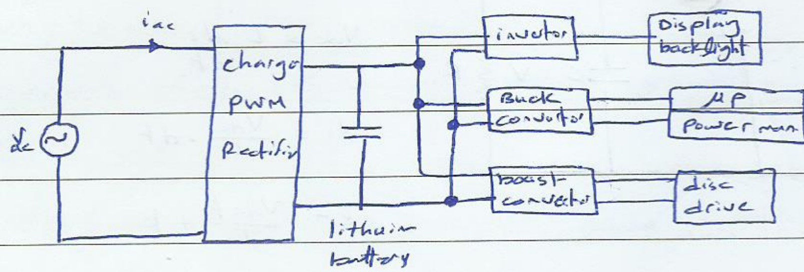
Slide 19:

* single phase inverter.

• the object of the capacitor & the inductor to make smoothing.



• Slide 21: Example of power electronics.



• why inverter because screen need high freequency

• why battery to isolate the source Vac from the rest items of the computer.

• why to use boost convertor for Disk drive because its run on higher voltage.

• Buck convertor is a type of convertor that converts DC to DC.

Subject Power electronics Date 25/2/2014 lecture No. 4

* Power computation:-

$p(t) = v(t) \cdot i(t)$ → the product of current & voltage.

$P = VI$

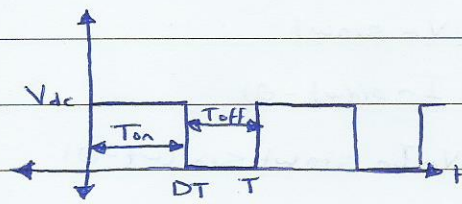
• note that for a resistive load:

$p(t) = R i^2(t)$

$P = RI^2$

$RI_{eff}^2 = \frac{R}{T}\int_0^T i^2(t) \cdot dt$ where $I_{eff} = \sqrt{\frac{1}{T}\int_0^T i^2(t) \cdot dt}$

• if $D = \frac{T_{on}}{T_{on} + T_{off}}$



* where Ton, Toff shown on the figure

* note that $T_{on} + T_{off} = T$ ≡ the period of the one cycle.

* $T_{off} = (1-D)T$

* $\boxed{V_{av} = \frac{D\cancel{T} V_{dc}}{\cancel{T}} = DV_{dc}}$

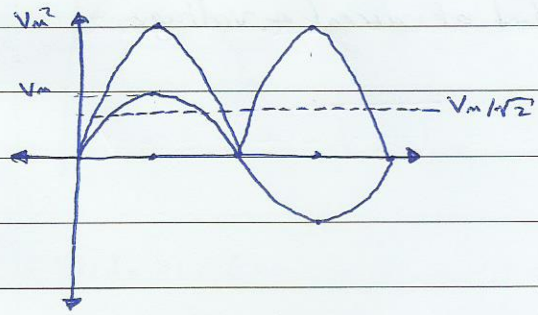
* $\boxed{V_{rms} = \sqrt{\frac{D\cancel{T} V_{dc}^2}{\cancel{T}}} = \sqrt{D}\, V_{dc}}$ the equivalent dc value that give the same energy of the shown AC voltage.

* now let $v(t) = V_m \sin \omega t$

$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_m^2 \sin^2 \omega t \, d\omega t} = \sqrt{\frac{\omega}{2\pi}\int_0^{\frac{2\pi}{\omega}} V_m^2 \sin^2 \omega t \cdot dt}$

Subject Date No.

$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\int_0^{2\pi}\frac{1}{2}(1-\cos 2\omega t)\,d\omega t} = \sqrt{\frac{V_m^2}{2}} = \frac{V_m}{\sqrt{2}} = V_m/\sqrt{2}$$



- now for the power :-

let i lag v by certain angle θ

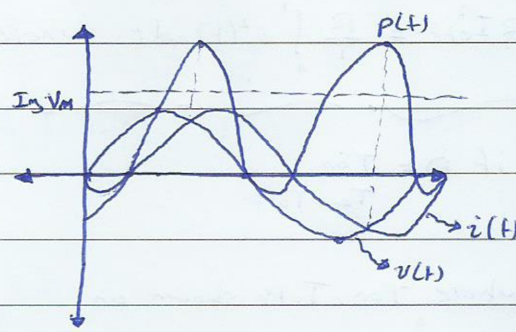
$v(t) = V_m \sin\omega t$

$i(t) = I_m \sin(\omega t - \theta)$

$p(t) = V_m I_m \sin\omega t \sin(\omega t - \theta)$

$P_{avg} = \frac{V_m I_m}{2}\cos(\theta)$

$p(t) = \frac{V_m I_m}{2}\cos(\theta) + \frac{V_m I_m}{2}\cos(2\omega t - \theta)$.

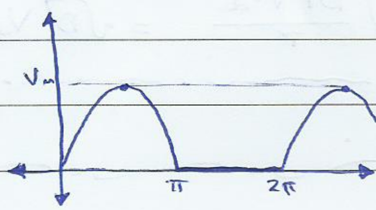


* for half-wave rectified :-

$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\int_0^{\pi}\sin^2\omega t \cdot d\omega t}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\cdot\frac{\pi}{2}}$$

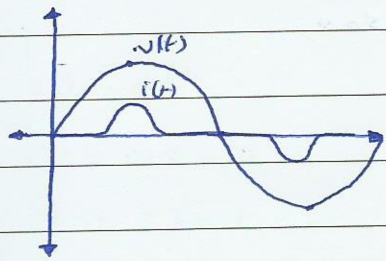
$$\boxed{V_{rms} = V_m/2}$$

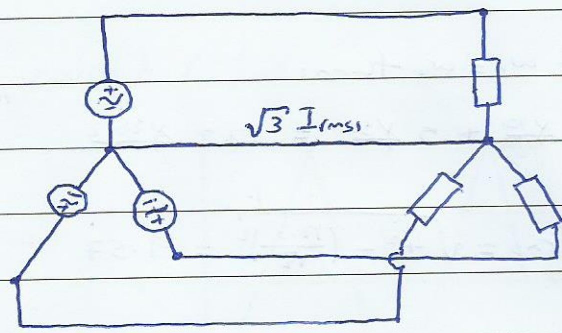


Subject Date No.

32

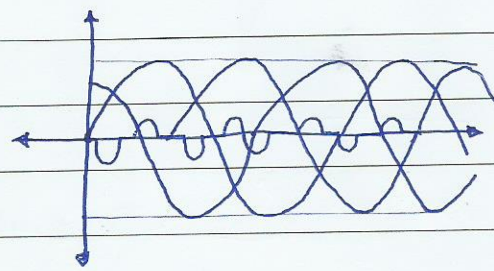
. For single phase :-





$* \; i_n = i_1(t) + i_2(t) + i_3(t)$

$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i^2(t)\cdot dt}$



$I_{rms} = \sqrt{3}\, I_{rms1}$

* now multiple frequencies :-

$v(t) = V_1 \sin w_1 t + V_2 \sin w_2 t$

$v^2(t) = V_1^2 \sin^2 w_1 t + V_2^2 \sin^2 w_2 t + V_1 V_2 \sin w_1 t \sin w_2 t$

$v^2(t) = V_1^2 \sin^2 w_1 t + V_2^2 \sin^2 w_2 t + \frac{V_1 V_2}{2}\left[\cos(w_1 - w_2)t + \cos(w_1 + w_2)t\right]$

$V_{rms} = \sqrt{V_{rms1}^2 + V_{rms2}^2}$

Example :- let $v(t) = 4 + 8\sin(w_1 t + 10^\circ) + 5\sin(w_2 t + 50^\circ)$

find the rms value if ① $w_1 = w_2$ ② $w_1 = 2w_2$?

Answer :-

[1] if $w_1 = 2w_2$ then $w_1 \neq w_2$ so

$V_{rms} = \sqrt{4^2 + \frac{8^2}{2} + \frac{5^2}{2}} = \sqrt{60.5} = 7.778$

NOTEBOOK

Subject Date No.

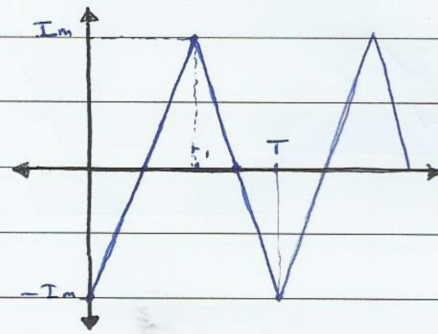
$\overline{12)}$ if $\omega_1 = \omega_2$ then:

$$8\angle 10 + 5\angle 50 = 12.3\angle 25.2$$

" $8\cos 10 + j8\sin 10 + 5\cos 50 + j\sin 50$ "

$$V_{rms} = \sqrt{4^2 + \left(\frac{12.3}{\sqrt{2}}\right)^2} = 9.57$$

* Consider the following current find the rms value?



• $0 \longrightarrow t_1$

• $y = mx + b$

$$i_1 = \underbrace{\frac{2I_m}{t_1}}_{m} t \underbrace{- I_m}_{b}$$

$$m = \frac{2I_m}{t_1} \qquad b = -I_m$$

• $I_m = mt_1 + b$ & $-I_m = mT + b$ solve them to take the values of m & b.

• $m(T - t_1)$

- Sinusoidal Source with non-linear load.

$v(t) = V_1 \sin(\omega t + \theta) \longrightarrow V_{rms} = V_1/\sqrt{2}$

$i(t) = I_o + \sum I_n \sin(n\omega t + \phi_n) \longrightarrow I_{rms} = \sqrt{I_o^2 + (I_1/\sqrt{2})^2 + \dots}$

$P = \frac{V_1}{\sqrt{2}} \cdot \frac{I_1}{\sqrt{2}} \cos(\theta_1 - \phi_1)$ $\quad Q = (V_1/\sqrt{2})(I_1/\sqrt{2}) \sin(\theta_1 - \phi_1)$

$|S| = I_{rms} \cdot V_{rms}.$

$$\boxed{P.F = P/|S|}$$

$$P.F = \frac{V_{rms} \cdot I_{1rms} \cos(\theta_1 - \phi_1)}{V_{rms} \cdot I_{rms}} = \frac{I_{1rms}}{I_{rms}} \cos(\theta_1 - \phi_1)$$

$$\boxed{P.F = \text{Distortion factor} \times \text{displacement factor.}}$$

- note that:

Displacement Factor $\equiv \cos(\theta_1 - \phi_1)$

Displacement angle $\equiv \theta_1 - \phi_1$

Distortion factor $\equiv (I_{1rms} / I_{rms})$

- Total harmonic distortion $= \sqrt{\sum \frac{\sum_{n\neq 1}^{\infty} I_{n\,rms}^2}{I_{1rms}^2}}$ → review it

Total harmonic distortion $= \sqrt{\frac{I_{rms}^2 - I_{1rms}^2}{I_{1rms}^2}}$

Total harmonic distortion $= \sqrt{\frac{1}{(DF)^2} - 1} = THD$

Subject Date No.

$$S'^2 = P^2 + Q^2 + D^2$$

$$D = \sqrt{S'^2 - P^2 - Q^2} = V_{rms}\sqrt{\sum_{n\neq 1}^{\infty} I_n^2}$$

$$D.F = 1/\sqrt{1 + THD^2}$$

■ Example:- $v(t) = 100\cos(377t)$

$i(t) = 8 + 15\cos(377t + 30) + 6\cos(2*377t + 45)$

$+ 2\cos(3\times377t + 60)$

- $P = \frac{100}{\sqrt{2}} \times \frac{15}{\sqrt{2}} \times \cos(-30) = 650$ watt

- $Q = \frac{100}{\sqrt{2}} \times \frac{15}{\sqrt{2}} \sin(-30) = -375$ VAR "capacitive"

- $I_{rms} = \sqrt{(8)^2 + (15/\sqrt{2})^2 + (6/\sqrt{2})^2 + (2/\sqrt{2})^2} = 14$ A

- $|S'| = (100/\sqrt{2})(14) = 990$ VA

- $D = \sqrt{(990)^2 - (650)^2 + (-375)^2} = 648$ VAD.

- $P.F = \frac{650}{990} = 0.66$

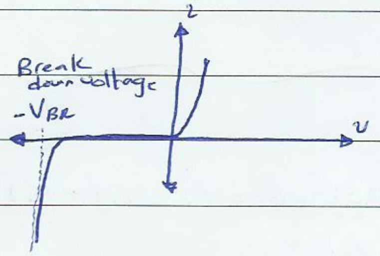
- $D.F = \frac{15/\sqrt{2}}{14} = 0.76$

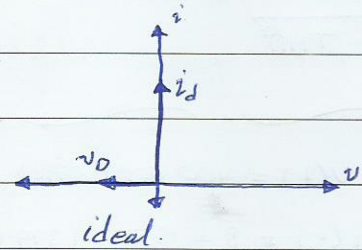
$$\boxed{\begin{array}{l} P.F = DF \times \text{displacement} \\ P.F = 0.76 \times 0.866 \\ P.F = 0.66 \end{array}}$$

- $THD = \sqrt{\left(\frac{1}{0.76}\right)^2 - 1} = 0.86$

* note that the (علاقة التثبيت) is very important because if we don't fix it this would generate sparks + vibrations that increase the resistance of the diode.

*



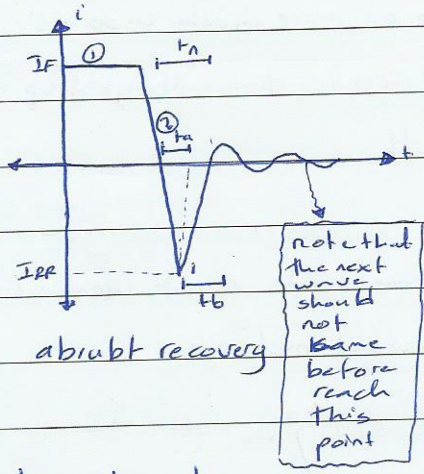


- Reverse break down voltage its the maximum voltage we can apply to the diode with remain it to do its work. & we avoid it.
- t_{rr} ≡ reverse recovery time.
- 6000 volt → peak value not rms.
- the forward portion of the characteristics can be approximatly describe by $I_D = I_s\,(e^{V_D/nV_T} - 1)$
- if the temperature is high then the current is low.
- note that usually $e^{V_D/nV_T} \gg 1$ then $\boxed{I_D = I_s\, e^{V_D/nV_T}}$
- I_D always much greater than I_s → reverse current.
- now if V_D is negative then the current become

$$I_D = I_s\,(\underbrace{e^{V_D/nV_T}}_{\text{less than } 1} - 1)$$

$$\boxed{I_D = -I_s}$$

• note that the reverse saturation current I_s is in range of nano or micro Amperes see example?



abrubt recovery

① when the current passes through the Diode

② at the instant of turn the curent off

• note that the reverse recovery current can be greater than I_F

• t_b assumed to be 25% because at this time we will not enter the nonlinear region yet.

• we should not apply new current before the total recovery time apply.

• $t_{rr} = t_a + t_b$
total recovery time

• we should not apply high frequency to diode because high frequency means ~~high~~ low time between two waves so that t_{rr} not yet passed

• t_{rr} = the time need to remove the charge on the diode in the reverse direction.

• Soft recovery factor (SF) = t_b / t_a.

• $I_{RR} = t_a \, di/dt$

$Q_{RR} \cong \frac{1}{2} I_{RR} t_a + \frac{1}{2} I_{RR} t_b$
charge of the reverse recovery

• $t_{rr} \; t_a = \frac{2Q_{RR}}{di/dt}$ — t_b is negligible compared with t_a then because the moving up direction is faster than moving down.

$t_a = \sqrt{\frac{2Q_{RR}}{di/dt}} = \sqrt{2Q_{RR}\frac{di}{dt}}$

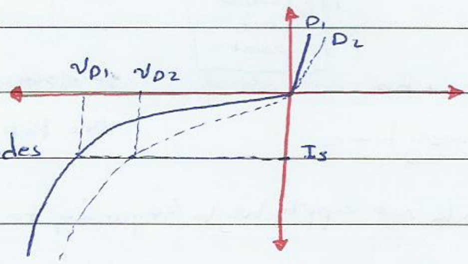
Subject *Power electronics* Date 6/3/2014 lecture No. 8

- **why to use diode in series:**

if we have a certain requirement of voltage 4 one diode can't held this voltage we can connect two or more diode in series this will ~~not~~ effect the voltage since it will increase the voltage drop. but same current will pass through both.

- note that if the characteristics of the two diode is not identical then the voltage will be divided in non-equivalent method.

why this make problem:



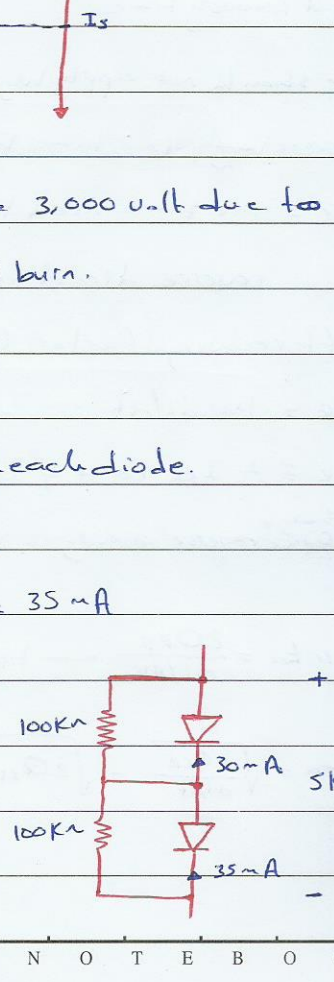
because if we connect two diodes each one can hold 6000 Volt inseries with 10,000 volt source one may take 7000 volt and another take 3,000 volt due too the non-identical characteristics so the first will burn.

- **How we can solve this?**

by connecting ~~parallel~~ resistor in parallel with each diode.

- **Examples:-** $V_D = 5KV$, $I_{s1} = 30mA$, $I_{s2} = 35mA$

$$\frac{V_{D1}}{100K} + 30mA = 35mA + \frac{V_{D2}}{100K\Omega}$$



$$V_{D1} + V_{D2} = 50KV$$

$$V_{D1} = 50KV - V_{D2}$$

$$\frac{5K}{100K} + 30mA - \frac{v_{D2}}{100K} = \frac{v_{D2}}{100K} + 35mA$$

$$50mA - 5mA = \frac{v_{D2}}{50K}$$

$$\boxed{v_{D2} = 45 * 50 = 2,25\,KV} \quad \& \quad \boxed{v_{D1} = 2.75\,KV}$$

- now we need v_{D1} & v_{D2} to be equal:

$$\frac{2.5K}{R_1} + 30mA = \frac{2.5K}{R_2} + 35mA$$

now let $\boxed{R_1 = 100K}$ → we assume it such that it near the Is value

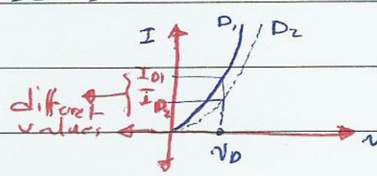
$$25mA + 30mA = \frac{2.5K}{R_2} + 35mA \longrightarrow R_2 = \frac{2.5K}{20mA}$$

$$\boxed{R_2 = 50 * 2.5K = 125K\Omega}$$

- note that we put resistances in parallel to solve steady state problem "same voltage for both"
- & we put RC circuit in parall with diode to solve the transient problem "have same transient voltage characteristics"

■ Parallel connection:

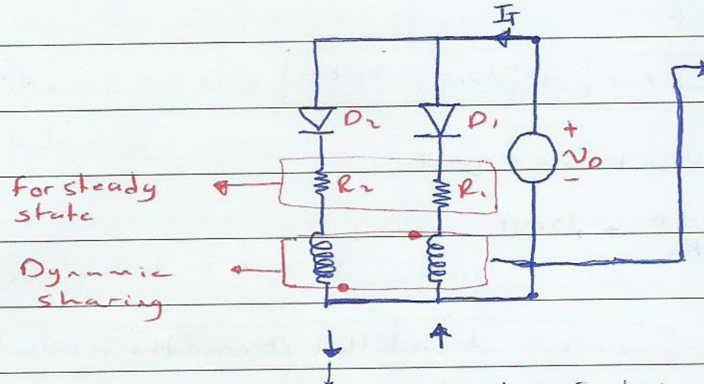
- note that in this case the diode is forward biased & its used to limit the current but this make Problem since we not gurantee with the same current to pass through the two diodes so we add resistances in series but in this case they have very small value ($m\Omega$) range.



Subject Date No.

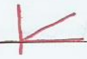
■ But how to solve the Dynamic problem?

by using coils with negative dot convention.



if at certain instant the current increase in diode D_1 so to maintain I_T constant we need the current in the second diode to be reduced & this done by using the coils.

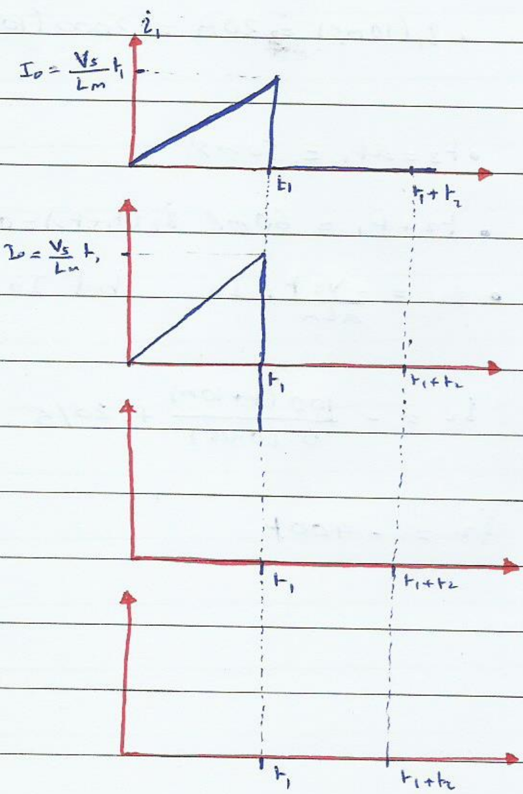
■ Recovery of trapped Energy with diode:

- note that when the switch closed then the voltage across the coil will increase since that $i(t) = \frac{1}{L}\int v.dt$  since the source is dc.
- when the switch open if the recovery of trapped energy not available then a spark will exist

~~while~~ when the recovery of trapped energy is supported then when the voltage is built & switch open the energy will transfer through the transformer in inverse polarity & diode is on so the energy will go to the battery.

Subject Power electronics Date 9/3/2014 lecture No. 9

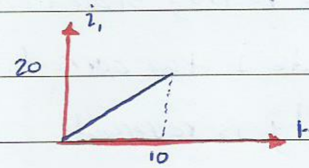
- note that L_m is the inductance seen by the source current & the battery stored energy in it
- in mode 1 the current through the diode is zero since the polarity is reversed.
- in mode 2 the current i_1 is zero due to openning the switch.



Subject Date No.

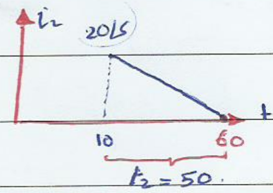
■ Example:- $V_s = 100$, $L_m = 50mH$, $a = 5$, find all current & voltages?

• Solution:-



• $i_1 = \frac{100}{0.05} t = 2000t$

• $i_1(10ms) = 20A = 2000(10ms) = 20A$



• $t_2 = a t_1 = 50ms$

• $t_2 + t_1 = 60ms$ $i_2(t_1 + t_2) = 0$

• $i_2 = \frac{-V_s t}{a L_m} + I_o$ but $I_o = i(t_1)/a = 20/5$

$i_2 = -\frac{100(t+10m)}{5(0.05)} + 20/5$

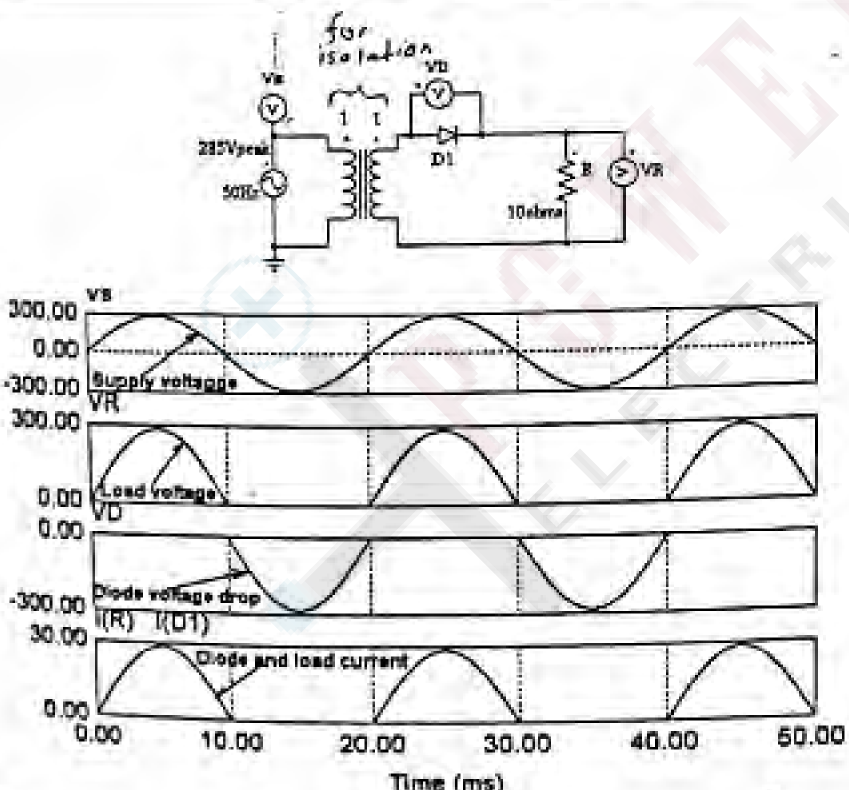
$i_2 = -400t$

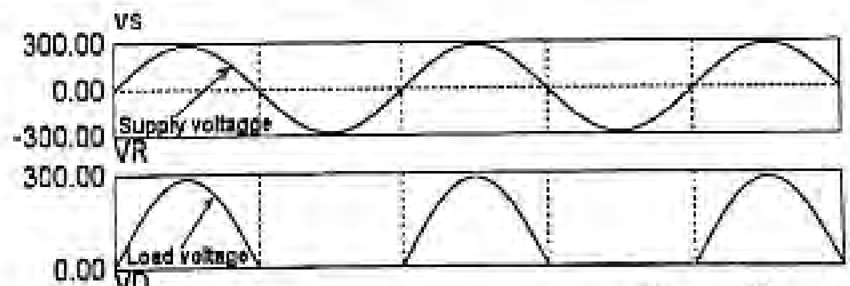
Power Electronics
Lecture (5)

Prof. Mohammed Zeki Khedher
Electrical Engineering Department of
University of Jordan

Diode Circuits or Uncontrolled Rectifier

Rectification: The process of converting the alternating voltages and currents to direct currents





$$V_{dc} = \frac{1}{2\pi}\int_0^{\pi} V_m \sin\omega t \; d\omega t = \frac{V_m}{\pi}$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{V_m}{\pi R}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} V_m^2 \sin^2 \omega t \; d\omega t} = \frac{V_m}{2}$$

$$I_{rms} = \frac{V_{rms}}{R} = \frac{V_m}{2R}$$

the load and diode currents
supplied current

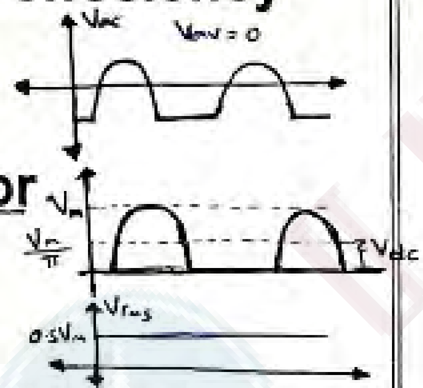
$$I_S = I_D = \frac{V_m}{2R}$$

$P_{dc} = I_{dc}^2 R$ $\quad V_{rms}^2 = V_{ac}^2 + V_{dc}^2$

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

Performance Parameters

$\eta = P_{dc} / P_{ac}$ **rectification effeciency**



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

$FF = \underline{V_{rms}} / \underline{V_{dc}}$ **form factor**

wave form

مقياس لمقدار التموجات ال ← **ripple factor**

$$RF = \frac{V_{ac}}{V_{dc}} = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}} = \sqrt{\frac{V_{rms}^2}{V_{dc}^2} - 1} = \sqrt{FF^2 - 1}$$

voltage we supply is fundamental but harmonics appear in current doesn't add to power.

$$THD_i = \sqrt{\frac{I_S^2 - I_{S1}^2}{I_{S1}^2}} = \sqrt{\frac{I_S^2}{I_{S1}^2} - 1}$$

$$THD_v = \sqrt{\frac{V_S^2 - V_{S1}^2}{V_{S1}^2}} = \sqrt{\frac{V_S^2}{V_{S1}^2} - 1}$$ → load ... not ...

$$PF = \frac{P_{ac}}{V_S I_S} = \frac{\overset{rms}{V_S} \overset{rms}{I_{S1}} \cos \phi_1}{V_S I_S} = \overset{distortion}{\frac{I_{S1}}{I_S}} \cos \phi_1$$

$= Distortion\ Factor * Displacement$

Transformer Utilization Factor

- $TUF = P_{dc}/V_s I_s$

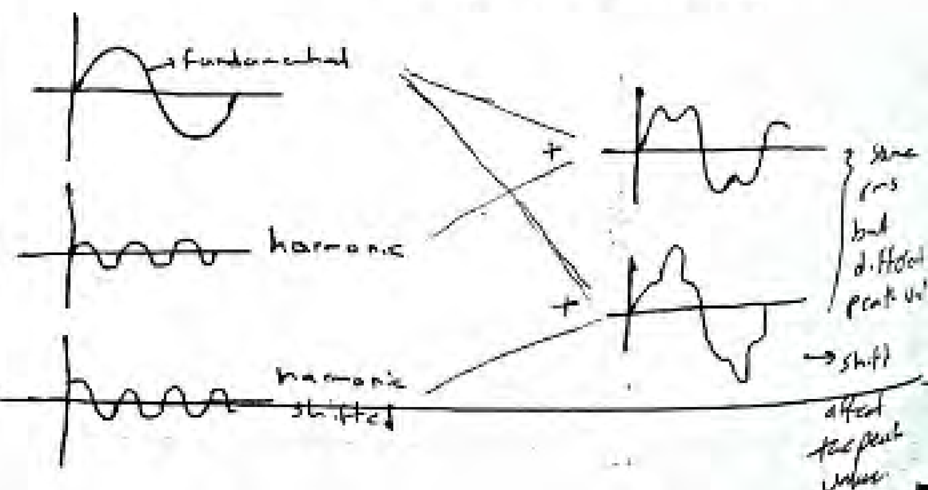
the devision of the utilization factor to the power factor give

$$\frac{PF}{TUF} = \frac{\frac{P_{ac}}{V_s I_s}}{\frac{P_{dc}}{V_s I_s}} = P_{ac}/P_{dc} \longrightarrow \text{rectification factor effeciency.}$$

Crest Factor

$CF = I_{s\text{-peak}} / I_{s_{rms}}$

↓ peak caused by the harmonics.



Example 1: The rectifier shown in Figure has a pure resistive load of *R* Determine (a) The efficiency, (b) Form factor (c) Ripple factor (d) Peak inverse voltage (PIV) of diode D1.

$$V_{dc}=\frac{1}{2\pi}\int_0^{\pi}V_m\sin(\omega t)\,d\omega t=\frac{V_m}{2\pi}(-\cos\pi-\cos(0))=\frac{V_m}{\pi}\qquad I_{dc}=\frac{V_{dc}}{R}=\frac{V_m}{\pi R}$$

$$V_{rms}=\sqrt{\frac{1}{2\pi}\int_0^{\pi}(V_m\sin\omega t)^2}=\frac{V_m}{2}\qquad I_{rms}=\frac{V_m}{2R}$$

$$\eta=\frac{P_{dc}}{P_{ac}}=\frac{V_{dc}*I_{dc}}{V_{rms}*I_{rms}}=\frac{\frac{V_m}{\pi}*\frac{V_m}{\pi R}}{\frac{V_m}{2}*\frac{V_m}{2R}}=\underline{40.53\%}$$

$$FF=\frac{V_{rms}}{V_{dc}}=\frac{\frac{V_m}{2}}{\frac{V_m}{\pi}}=\frac{\pi}{2}=\underline{1.57}$$

$$RF=\frac{V_{ac}}{V_{dc}}=\sqrt{FF^2-1}=\sqrt{1.57^2-1}=\underline{1.211}$$

It is clear from the Figure that the PIV is $\underline{V_m}$

negative voltage

- VA = V_sI_s = 0.707 V_m x 0.5 V_m /R
- TUF = P_{dc}/V_sI_s = $(0.318)^2$ / (0.707 x 0.5) = 0.286
- CF = $I_{s\text{-peak}}/I_s$ = 1/0.5 =2
- PF = P_{ac}/VA = 0.5^2 / (0.707X0.5) = 0.707

The main disadvantages of half wave rectifier are:

- High ripple factor,
- Low rectification efficiency,
- Low transformer utilization factor, and,
- DC saturation of transformer secondary winding.

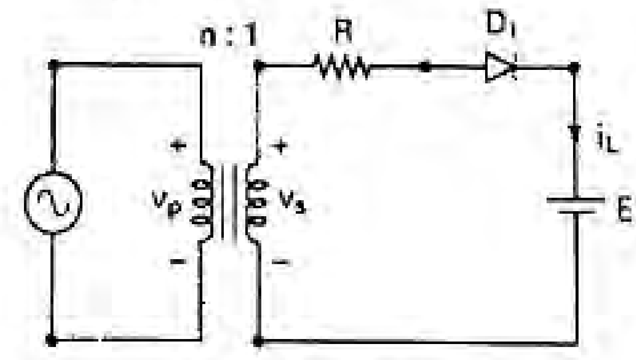
the current signal in secondary shift the voltage wave form to saturation

dipp will be here.

since the transformer doesn't reflect dc current

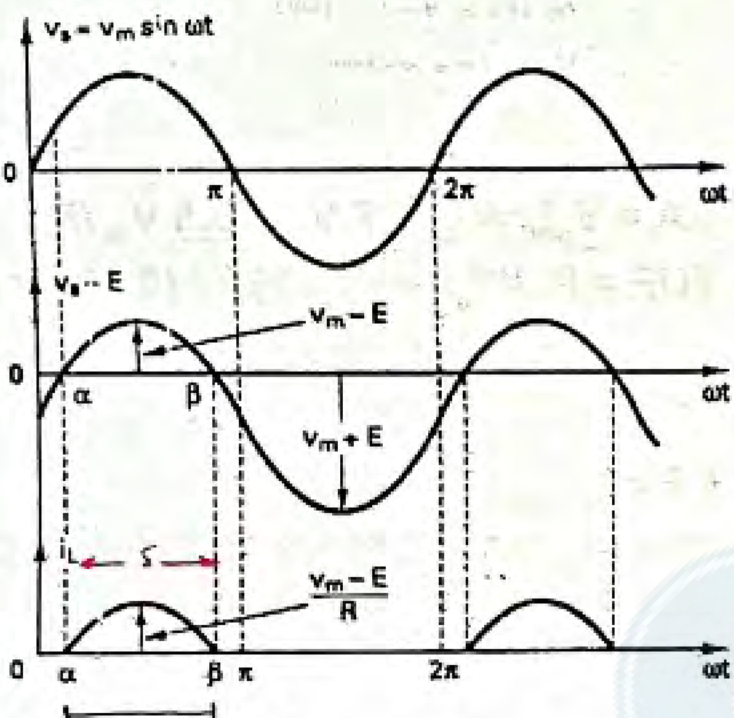
Half wave Rectifier with a Battery

To charge a battery.



(a) Circuit

when V_i > E then the E will charge to reach V_i



the period in which the battery is charged.

$$V_m \sin\alpha = E$$

which gives

when the angle is > α the we charge the battery

$$\alpha = \sin^{-1}\frac{E}{V_m}$$

Diode D_1 will be turned off when $v_s < E$ at

$$\beta = \pi - \alpha$$

the period to charge the battery is

$\alpha < \omega t < \pi - \alpha$

$\alpha < \omega t < \beta$

$$I_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\beta} \frac{V_m \sin\omega t - E}{R}\, dt$$

$$I_{dc} = \frac{1}{2\pi R}\left[2V_m \cos\alpha + 2E\alpha - \pi E\right]$$

↳ α in radians

① what is the power rated for the resistor.

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi-\alpha}\left(\frac{V_m \sin\omega t - E}{R}\right)^2 d\omega t}$$

$$I_{rms} = \sqrt{\frac{1}{2\pi R^2}\left[\left[\frac{V_m^2}{2} + E^2\right](\pi - 2\alpha) + \frac{V_m^2}{2}\sin 2\alpha - 4V_m E\cos\alpha\right]}$$

$P_R = (I_{rms})^2 R$

$P_R = 8.2^2 \times 4.26$

$\boxed{P_R = 286.4\,W}$

④ Power in battery

$P_E = (I_{dc}) * V_{dc}$

why since harmonic not generate power

$\boxed{P_E = 12 * 5 = 60W}$

→ period to charge

$\frac{100}{60} = 1.66\ Hz$

⑤ efficiency:

$\eta = \frac{60}{60 + 286.4} = 17.32\%$

Example: A battery with $E = 12V$ & 100WH

$I_{dc} = 5A$, $V_{rms} = 120V$, 60Hz, $a = \frac{2}{1}$

what is the charge period δ?

① $V_m \sin\alpha = E$

$\sin\alpha = \frac{E}{V_m} \rightarrow \alpha = \sin^{-1}\left(\frac{12}{60\sqrt{2}}\right)$

$\boxed{\alpha = 8.13^\circ = 0.1419\,rad}$

$V_m = \sqrt{2} * 60$

$V_m = 84.85$

$\delta = \pi - 2\alpha$

$\boxed{\delta = 180 - 2 * 8.13 = 163.74^\circ}$

② what is the value of R?

$5 = \frac{1}{2\pi R}\left[2 * 60\sqrt{2} * \cos(8.13) + 2 \times 12 * 0.1419 - \pi \times 12\right]$

$\boxed{R = 4.26\Omega}$

$PIV = V_m + E = 60\sqrt{2} + 12$

$= 96.85V$

Power Electronics
Lecture (6)

Prof. Mohammed Zeki Khedher
Electrical Engineering Department of University of Jordan

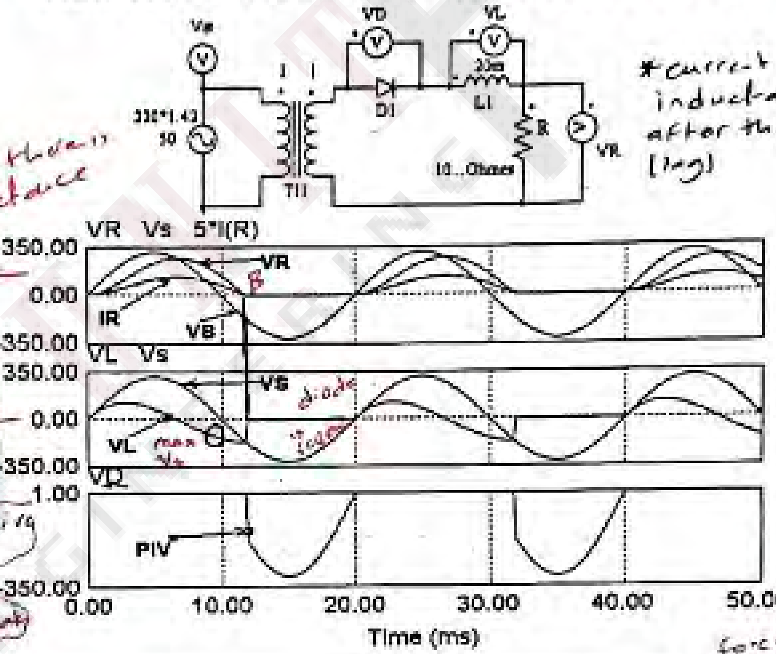
note that at $\omega t = 0$ $i(\omega t) = 0$ then: $A = \frac{V_m}{Z}\sin\theta$

$$Z = \sqrt{R^2 + (\omega L)^2} \quad \& \quad \tan\theta = \frac{\omega L}{R}$$

$$i(t) = \frac{V_m \sin(\omega t - \theta)}{Z} + A e^{-\frac{t}{L/R}}$$

note that at β point the voltage across the inductance equal to the voltage of the source so that $i(\omega t) = 0$, $i(\beta) = 0$ | β distinguish angle.

Half Wave Diode Rectifier With R-L Load



since there is inductance

IR lag the Vs voltage

VL is the slope of the current

it goes negative since the slope is negative after the peak

*current in the inductance ~ zero after the voltage (lag)

* Diode off when current through it is zero.

* $V_i = L\frac{di}{dt} + Ri$

$V_m \sin\omega t = Ri + L\frac{di}{dt}$

$i(t) = i_f(t) + i_n(t)$

force response — natural response

$$i(\omega t) = \frac{V_m}{Z}\left(\underbrace{\sin(\omega t - \phi)}_{\text{force response}} + \underbrace{\sin(\phi)e^{-\frac{\omega t}{\tan\phi}}}_{\text{natural response}}\right)$$

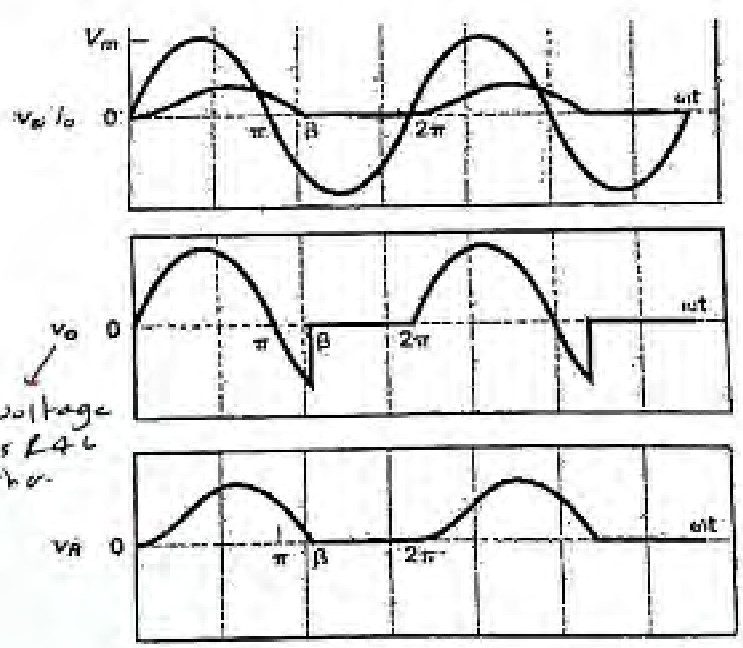
$$i(\beta) = \frac{V_m}{Z}\left(\sin(\beta - \phi) + \sin(\phi)e^{-\frac{\beta}{\tan\phi}}\right) = 0$$

↳ solve it using trial & error method

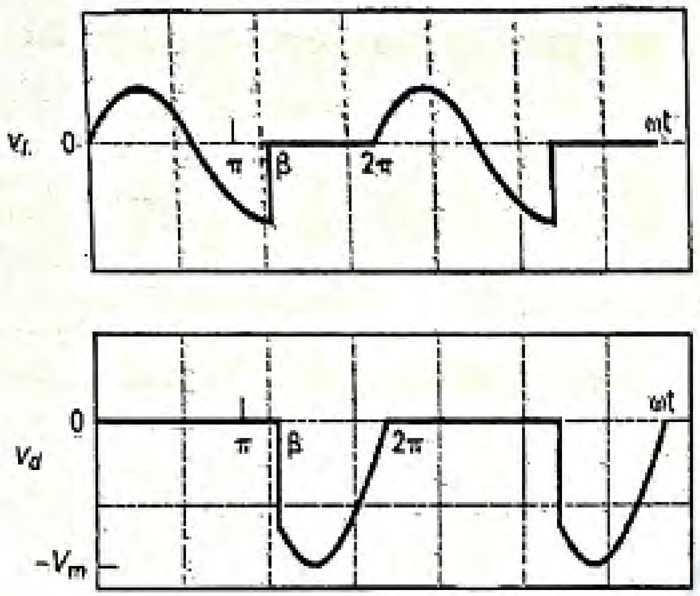
$$V_{dc} = \frac{V_m}{2\pi} * \int_0^{\beta} \sin\,\omega t\; d\omega t = \frac{V_m}{2\pi} * (1 - \cos\,\beta)$$

$$V_{rms} = \sqrt{\frac{1}{2\pi} * \int_0^{\beta} (V_m \sin\,\omega t)^2\, dwt} = \frac{Vm}{2\sqrt{\pi}} * \sqrt{\beta + 0.5(\;-\sin(2\beta)}$$

$$I_{dc} = \frac{1}{2\pi}\int_0^{\beta} i(t)\,dt = \frac{1}{2\pi}\int^{\beta} \frac{V_m}{Z}\left(\sin(\omega t - \phi) + \sin(\phi)e^{-\frac{\omega t}{\tan\phi}}\right) d\omega t$$



the voltage across R & L together



(b)

note that v_D is the complement of the output voltage since through in reverse period

$$i(t) = i_f(t) + i_n(t).$$

$$i_f(t) = \left(\frac{V_m}{Z}\right)\sin(\omega t - \theta)$$

where $Z = \sqrt{R^2 + (\omega L)^2}$ and $\theta = \tan^{-1}\left(\frac{\omega L}{R}\right)$

$$Ri(t) + L\frac{di(t)}{dt} = 0.$$

For this first-order circuit, the natural response has the fo

$$i_n(t) = Ae^{-t/\tau}$$

$$i(t) = i_f(t) + i_n(t) = \frac{V_m}{Z}\sin(\omega t - \theta) + Ae^{-t/\tau}$$

$$i(0) = \frac{V_m}{Z}\sin(0 - \theta) + Ae^{0} = 0$$

$$A = -\frac{V_m}{Z}\sin(-\theta) = \frac{V_m}{Z}\sin(\theta)$$

Substituting for A in Eq. 3-9,

$$i(t) = \frac{V_m}{Z}\sin(\omega t - \theta) + \frac{V_m}{Z}\sin(\theta)e^{-t/\tau}$$

$$= \frac{V_m}{Z}\left[\sin(\omega t - \theta) + \sin(\theta)e^{-t/\tau}\right].$$

$$i(\omega t) = \frac{V_m}{Z}\sin(\omega t - \theta) + \frac{V_m}{Z}\sin(\theta)e^{-\omega t/\omega\tau}$$

$$= \frac{V_m}{Z}\left[\sin(\omega t - \theta) + \sin(\theta)e^{-\omega t/\omega\tau}\right].$$

$$i(\beta) = \frac{V_m}{Z}[\sin(\beta - \theta)] + \frac{V_m}{Z}\sin(\theta)e^{-\beta/\omega\tau} = 0$$

$$\boxed{\sin(\beta - \theta) + \sin(\theta)e^{-\beta/\omega\tau} = 0.}$$

→ solve it use upper curve in the lower slide

$$i(\omega t) = \begin{cases} \frac{V_m}{Z}\sin(\omega t - \theta) + \frac{V_m}{Z}(\sin\theta)e^{-\omega t/\omega\tau} & \text{for } 0 \le \omega t \le \beta \\ 0 & \text{for } \beta \le \omega t \le 2\pi \end{cases}$$

→ diode is on

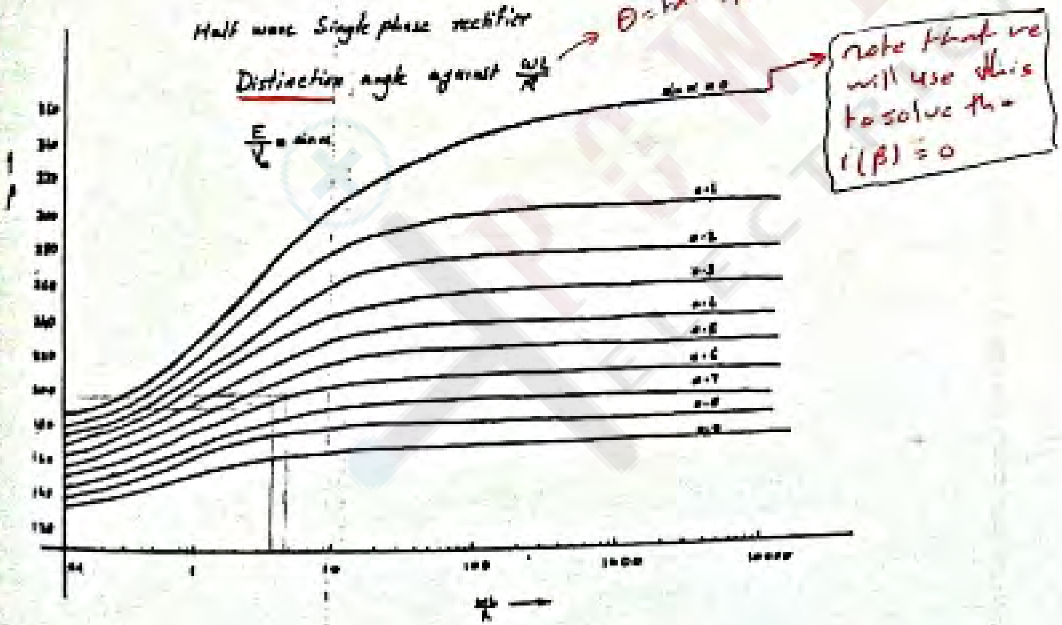
→ diode is reverse current is zero

where $Z = \sqrt{R^2 + (\omega L)^2}$, $\theta = \tan^{-1}\left(\frac{\omega L}{R}\right)$, and $\tau = \frac{L}{R}$.

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i^2(\omega t)\,d(\omega t)} = \sqrt{\frac{1}{2\pi}\int_0^{\beta} i^2(\omega t)\,d(\omega t)}.$$

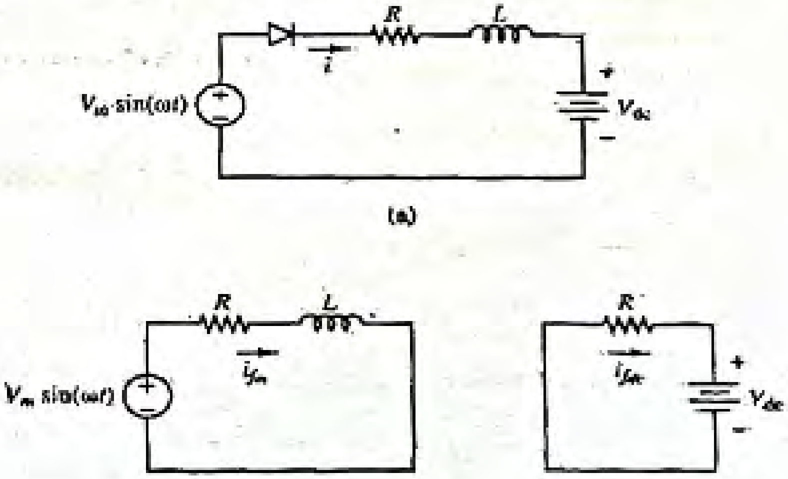
↓ more complex expression than that for voltage

$$I_{av} = \frac{1}{2\pi}\int_0^{\beta} i(\omega t)\,d(\omega t).$$



Supplying Power to a dc Source from an ac Source

↳ charging battery using RL rectifying circuit



(a) (b) (c)

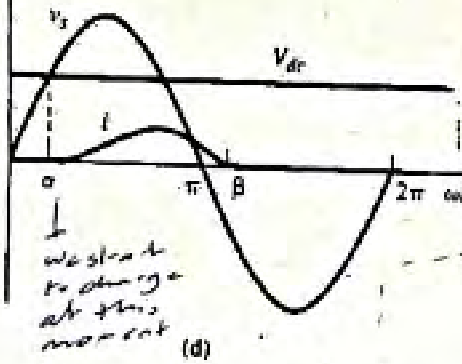
$i = 0$ at $\omega t = \alpha$

$V_m \sin\alpha = V_{dc}$

$0 = \frac{V_m}{Z}\sin(\alpha - \theta) - \frac{V_{dc}}{R} + A e^{\frac{-\alpha}{\omega L/R}}$

$$\boxed{\alpha = \sin^{-1}\left(\frac{V_{dc}}{V_m}\right)}$$

$A = \left[\frac{V_m}{Z}\sin(\alpha-\theta) - \frac{V_{dc}}{R}\right] e^{\frac{\alpha}{\omega L/R}}$



(d)

Example: $R = 2\Omega$, $L = 20mH$, $V_{dc} = 100V$, $V_s = 120V_{rms}$, $f = 60Hz$.

- $\sin\alpha = \frac{V_{dc}}{V_m} = \frac{100}{120\sqrt{2}} = \frac{100}{169.7} = 0.589$
- $\alpha = 36.1° = 0.63$ rad/sec.

$\frac{\omega L}{R} = \frac{2\pi * 60 * 20m}{2} = 3.77$

$\longrightarrow$ From graph: $\beta = 193°$

$\longrightarrow i(\omega t) = 21.8\sin(\omega t - 1.31) - 50 + 75.3\, e^{-\frac{\omega t}{3.77}}$

$\longrightarrow I_{dc} = \frac{1}{2\pi}\int_{0.63}^{3.77} i(\omega t)\cdot d\omega t$

$I_{dc} = 2.25A$

$\longrightarrow I_{rms} = \frac{1}{2\pi}\int_{\alpha}^{\beta} i^2(\omega t)\cdot d\omega t = 3.98A$

$V_m \sin(\omega t) = Ri(t) + L\frac{di(t)}{dt} + V_{dc}$

$i(t) = i_f(t) + i_n(t)$.

$i_f(t) = \frac{V_m}{Z}\sin(\omega t - \theta) - \frac{V_{dc}}{R}$.

$i_n(t) = Ae^{-t/\tau}$.

$$i(\omega t) = \begin{cases} \frac{V_m}{Z}\sin(\omega t - \theta) - \frac{V_{dc}}{R} + Ae^{-\omega t/\omega\tau} & \text{for } \alpha \le \omega t \le \beta \\ 0 \quad \text{otherwise.} \end{cases}$$

- $P_E = (100)(2.25) = 225$ watt
- $P_R = (3.98)^2 * 2 = 31.2$ watt
- $P_L = 0 \longrightarrow$ ideal inductance $= 0$ / we charge it then take the voltage.

$$A = \left(-\frac{V_m}{Z}\sin(\alpha - \theta) + \frac{V_{dc}}{R}\right)e^{\alpha/\omega\tau}.$$

- $\eta = \frac{225}{225 + 31.2} = ---$
- $P.F = \frac{256.2}{(3.98)(120)} = 0.54$

$TUF = \frac{225}{(3.98)(120)}$

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta} i^2(\omega t)d(\omega t)}.$$

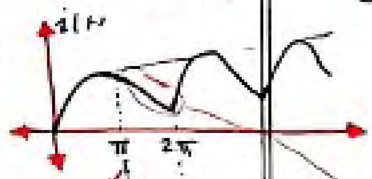
$$P_{dc} = IV_{dc}.$$

where I is the average current, that is,

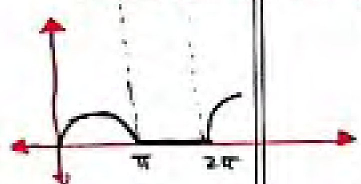
$$I = \frac{1}{2\pi}\int_{\alpha}^{\beta} i(\omega t)d(\omega t).$$

without free wheeling diode then the previous sketches are considered.

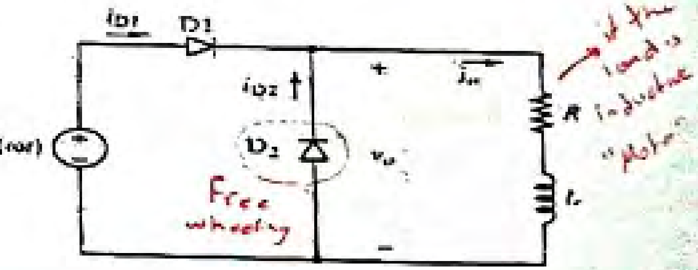
- with freewheeling diode:



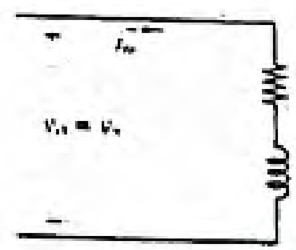
V_s negative + diode 2 is on now so the current is exponential

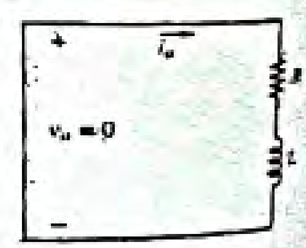


FREEWHEELING DIODE



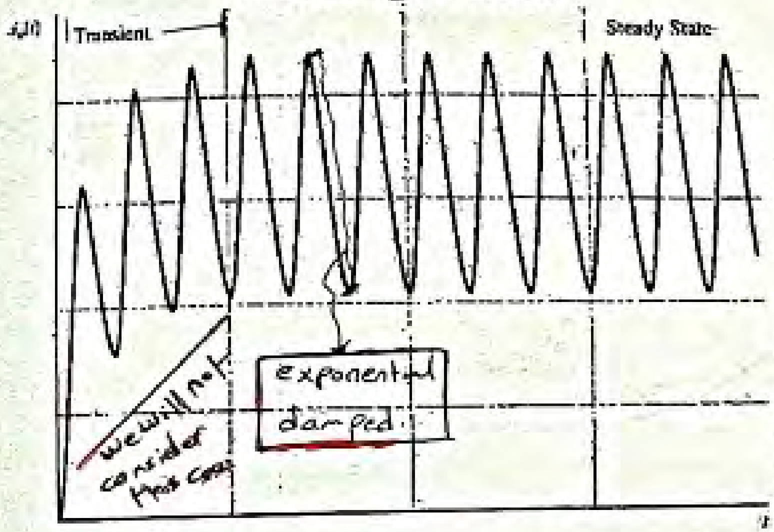
(a)

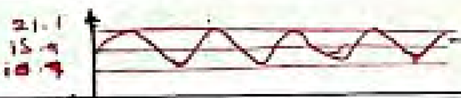




note that the main component in the total current is the fundamental or the harmonic is reduced due to two reason → ① because we divided into X_n which depend on the frequency which doubled with harmonics

Load Current transient to steady state





we want to reduce the fluctuation by increasing L

Result

$$i(t) = \frac{V_m}{\pi} + \frac{V_m}{2}\sin(\omega_0 t) - \sum_{n=2,4,6\ldots}^{\infty} \frac{2V_m}{(n^2-1)\pi}\cos(n\omega_0 t)$$

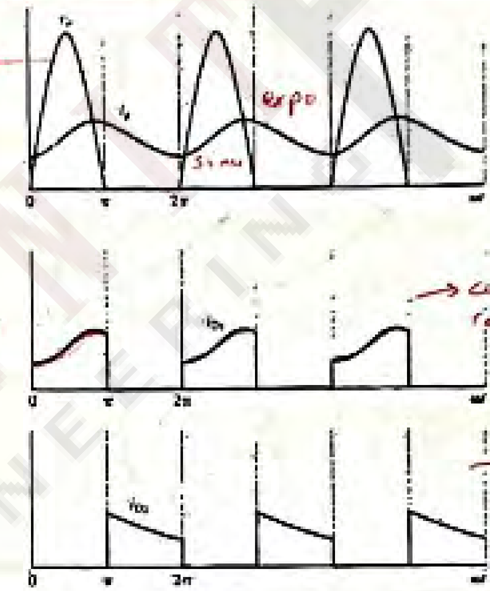
find Fourier Series

$$a_0 = \frac{1}{2\pi}\int_0^{\pi} V_m \sin(\omega t)\, d\omega t$$

$$a_0 = \frac{V_m}{\pi}$$

$$a_n = \frac{1}{\pi}\int_0^{\pi} V_m \sin(\omega t)\cos(\omega t)\, d\omega t$$

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



Reducing Load Current Harmonics

$$i_o(t) \approx I_0 = \frac{V_0}{R} = \frac{V_m}{\pi R} \quad \left(\frac{L}{R} \to \infty\right)$$

$$\Delta I_o = 2I_1$$

Example :-

$R = 2\Omega$, $L = 25\,mH$, $V_m = 100$

$f = 60\,Hz$ find

$$V_{dc} = \frac{V_m}{\pi} = \frac{100}{\pi} = 31.8\,V$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{31.8}{2} = 15.9\,A$$

F	V_n	X_n	Z_n	I_n
0	31.8	0	2	15.9
60	50	$2\pi(0.025)(60)$	9.63	5.19
120	21.2	$2\pi(0.025)(120)$	18.96	1.12
240	4.24	$2\pi(0.025)(240)$	37.73	0.11

$$\rightarrow i(t) = 15.9 + 5.19\sin(\omega t + \theta_1) + 1.12\sin(\omega t + \theta_2) + 0.11\sin(\omega t + \theta_3)$$

$$I_{rms} = \sqrt{(15.9)^2 + \left(\frac{5.19}{\sqrt{2}}\right)^2 + \left(\frac{1.12}{\sqrt{2}}\right)^2 + \left(\frac{0.11}{\sqrt{2}}\right)^2}$$

$$I_{rms} = 16.34\,A$$

$$P = R I^2$$

$$P = 16.34^2\,(2)$$

$$P = 534\ \text{watt}$$

$$I_{dcFW} = \frac{15.9}{2}$$

$$I_{dcFW} = 7.95\,A$$

$$I_{D1} = I_{D2} = \frac{16.34}{\sqrt{2}} = 11.55\,A$$

rms

Example Half wave with freewheeling diode

source is 240 V rms at 60 Hz and $R = 8\,\Omega$. (a) Assume L is infinite for practical purposes. Determine the power absorbed by the load and the power factor as seen by the source. Sketch v_o, i_{D1}, and i_{D2}. (b) Determine the average current in each diode. (c) Determine L such that the peak-to-peak current is no more than 10% of the average current.

$$i_o(\omega t) \approx I_0 = \frac{V_0}{R} = \frac{V_m/\pi}{R} = \frac{(240\sqrt{2})/\pi}{8} = 13.5\,A = I_{rms}$$

Power in the resistor is

$$P = (I_{rms})^2 R = (13.5)^2 8 = 1459\,W.$$

Source rms current is computed from

$$I_{s,rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} (13.5)^2\, d(\omega t)} = 9.55\,A.$$

The power factor is

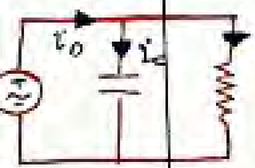
$$pf = \frac{P}{V_{s,rms} I_{s,rms}} = \frac{1459}{(240)(9.55)} = 0.637.$$

Each diode conducts for one-half of the time. Average current for each diode is $I_o/2$ 13.5/2 = 6.75 A.

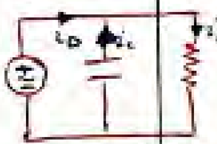
$$\frac{\frac{240\sqrt{2}}{2}}{2\pi(60)L} \rightarrow L = 0.5\ldots$$

Half wave rectifier with capacitor filter

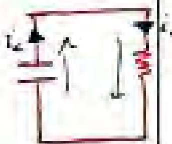
① $\alpha \to \pi/2$

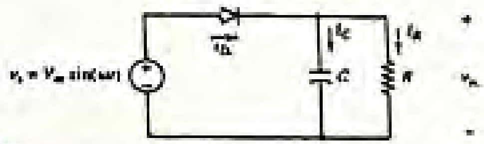


② $\frac{\pi}{2} \to \theta$

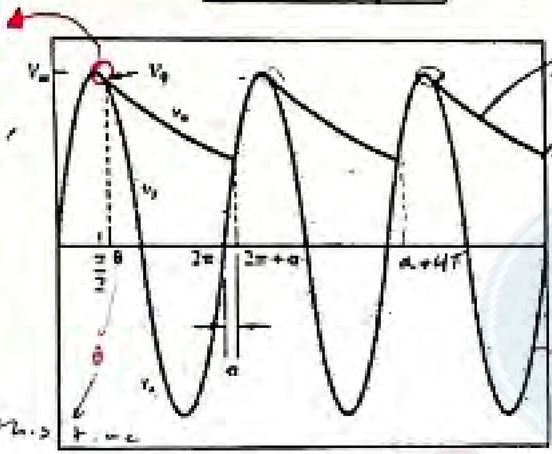


③ $\theta \to \alpha + 2\pi$





at this region the current in the capacitor is -ve so the $i_R = i_C + i_D$ in this region. at the peak $i_c = 0$



when $V_o > V_s$ so the diode is off & hence the voltage in the capacitor is dropped in the resistor & then recharge when $V_s > V_o$

supplied voltage

at this time the current in diode so

$$v_o(\omega t) = \begin{cases} V_m \sin \omega t & \text{diode on} \\ V_\theta e^{-(\omega t - \theta)/\omega RC} & \text{diode off} \end{cases}$$

$$\frac{d}{d(\omega t)}(V_m \sin \omega t) = V_m \cos \omega t$$

and

$$\frac{d}{d(\omega t)}\left(V_m \sin \theta e^{-(\omega t - \theta)/\omega RC}\right) = V_m \sin \theta \left(-\frac{1}{\omega RC}\right) e^{-(\omega t - \theta)/\omega RC}$$

At $\omega t = \theta$, the slopes of the voltage functions are equal:

$$V_m \cos \theta = \frac{V_m \sin \theta}{-\omega RC} e^{-(\theta - \theta)/\omega RC} = \frac{V_m \sin \theta}{-\omega RC}$$

$$\frac{V_m \cos \theta}{V_m \sin \theta} = \frac{1}{-\omega RC}$$

$$\frac{1}{\tan \theta} = \frac{1}{-\omega RC}$$

Solving for θ and expressing θ so it is in the proper quadrant.

$$\boxed{\theta = \tan^{-1}(-\omega RC) = -\tan^{-1}(\omega RC) + \pi.}$$

In practical circuits where the time constant is large,

$$\boxed{\theta \approx \frac{\pi}{2} \quad \text{and} \quad V_m \sin \theta \approx V_m}$$

$$V_m \sin(2\pi + \alpha) = (V_m \sin \theta) e^{-(2\pi + \alpha - \theta)/\omega RC}$$

$$\boxed{\sin(\alpha) - (\sin \theta) e^{-(2\pi + \alpha - \theta)/\omega RC} = 0.}$$

solved by graph

$$i_C(\omega t) = \omega C \frac{dv_o(\omega t)}{d(\omega t)}.$$

$$i_C(\omega t) = \begin{cases} -\frac{V_m \sin \theta}{R} e^{-(\omega t - \theta)/\omega RC} & \text{for } \theta \le \omega t \le 2\pi + \alpha \text{ (diode off)} \\ \omega C V_m \cos(\omega t) & \text{for } 2\pi + \alpha \le \omega t \le 2\pi \text{ (diode on)} \end{cases}$$

$$i_s = i_D = i_R + i_C$$

$$I_{C,\text{peak}} = \omega C V_m \cos(2\pi + \alpha) = \omega C V_m \cos\alpha.$$

Resistor current at $\omega t = 2\pi + \alpha$ is obtained from Eq. 3-37:

$$i_R(2\omega t + \alpha) = \frac{V_m \sin(2\omega t + \alpha)}{R} = \frac{V_m \sin\alpha}{R}.$$

Peak diode current is

$$\boxed{I_{D,\text{peak}} = \omega C V_m \cos\alpha + \frac{V_m \sin\alpha}{R} = V_m\left(\omega C \cos\alpha + \frac{\sin\alpha}{R}\right).}$$

$$\boxed{\Delta V_o = V_m - V_m \sin\alpha = V_m(1 - \sin\alpha).}$$

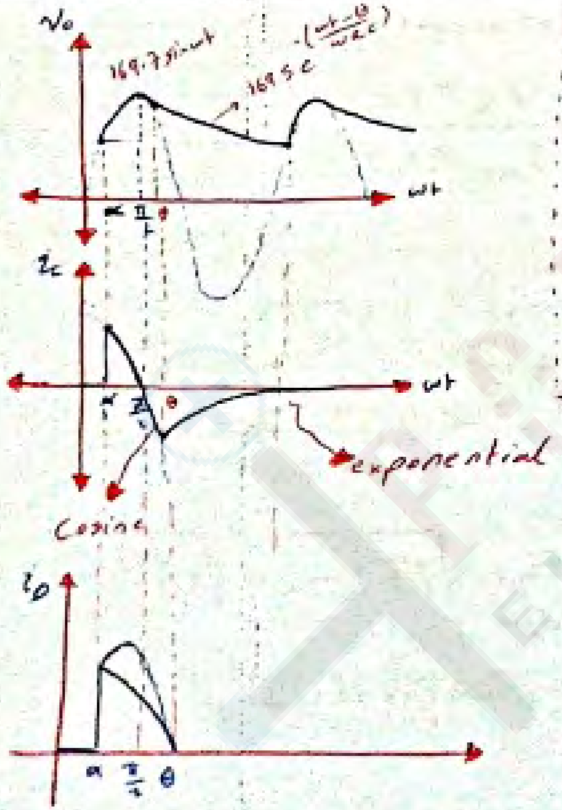
If $V_0 \approx V_m$

$\theta \approx \pi/2$, then at $\alpha = \pi/2$ is

$$v_o(2\pi + \alpha) \approx V_m e^{-(2\pi + \pi/2 - \pi/2)/\omega RC} = V_m e^{-2\pi/\omega RC}.$$

The ripple voltage can then be approximated as

$$\Delta V_o \approx V_m - V_m e^{-2\pi/\omega RC} = V_m\left(1 - e^{-2\pi/\omega RC}\right).$$



- **Example:**
- 120 Vrms, $R = 500\,\Omega$, $f = 60$ Hz, $C = 100\,\mu F$
- $V_m = 120 * \sqrt{2} = 169.7$ V
- $\theta = \tan^{-1}(-\omega RC) = \tan^{-1}(2\pi(60)(100\mu)(500))$

  $\theta = 93°$
- from graph: $\alpha = 48°$
- $V_m \sin(\theta) = 169.7 \sin(93) = 169.5$
- $\Delta V = V_m (1 - \sin\alpha)$

  $\Delta V = 43$ V
- $i_{D_{peak}} = 169.7 \left(2\pi * 60 * 100\mu * \cos 48 + \frac{\sin 48}{500}\right)$

  $= 24.5$ A
- want ripple < 10% V_m then find C

  $\alpha \approx \sin^{-1}\left(1 - \frac{1}{fRC}\right) \longrightarrow C = 3333\,\mu F$

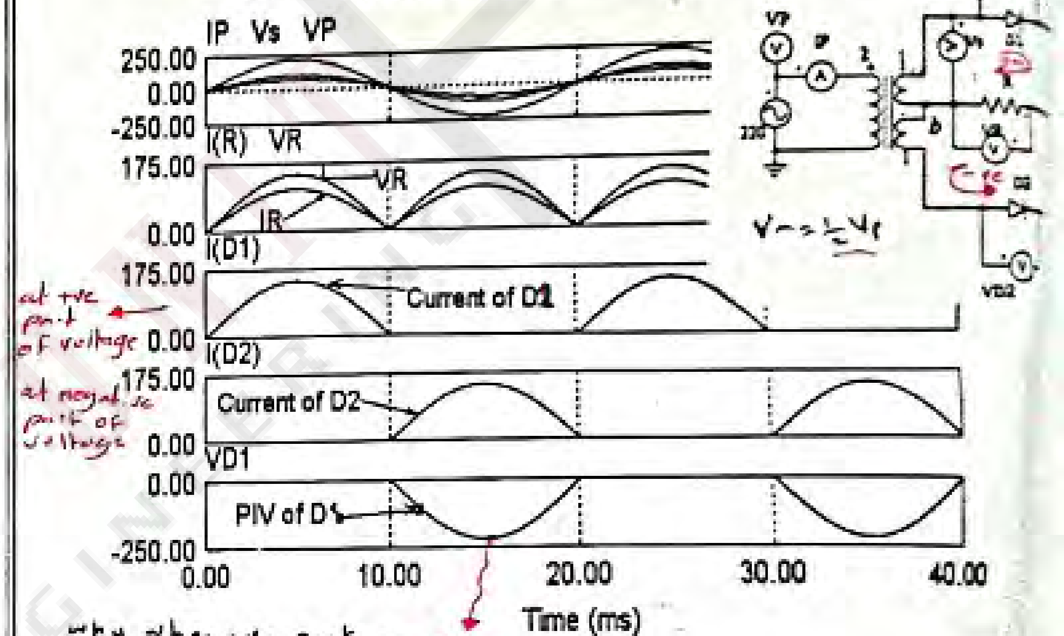
  $\hookrightarrow \frac{\Delta V}{V_m} \approx \frac{1}{fRC}$ will 8% error

Power Electronics
Lecture (7)

Prof. Mohammed Zeki Khedher
Electrical Engineering Department of
University of Jordan

Single-Phase Full-Wave Diode Rectifier

Center-Tap Diode Rectifier two half wave



why when +ve peak is applied to upper diode then the voltage at the right most node is +Vm & at the left node to second diode is -ve Vm

Vm + Vm = 2Vm

$$V_{dc} = \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t \; d\omega t = \frac{2V_m}{\pi} \qquad I_{dc} = \frac{2V_m}{\pi R}$$

$$V_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi}(V_m \sin\omega t)^2 \; d\omega t} = \frac{V_m}{\sqrt{2}} \qquad I_{rms} = \frac{V_m}{\sqrt{2}\, R}$$

since the square of it as the square of the sine.

PIV of each diode = $2V_m$

$$I_S = I_D = \frac{V_m}{2\, R}$$

Example 3. The rectifier in Fig.2.8 has a purely resistive load of R Determine (a) The efficiency, (b) Form factor (c) Ripple factor (d) TUF (e) Peak inverse voltage (PIV) of diode D1 and(f) Crest factor of transformer secondary current.

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{V_{dc} * I_{dc}}{V_{rms} * I_{rms}} = \frac{\frac{2\,V_m}{\pi} * \frac{2\,V_m}{\pi R}}{\frac{V_m}{\sqrt{2}} * \frac{V_m}{\sqrt{2}\,R}} = 81.0$$

increased with respect to half wave

$$FF = \frac{V_{rms}}{V_{dc}} = \frac{\frac{V_m}{\sqrt{2}}}{\frac{2\,V_m}{\pi}} = \frac{\pi}{2\sqrt{2}} = 1.11$$

$$RF = \frac{V_{ac}}{V_{dc}} = \sqrt{FF^2 - 1} = \sqrt{1.11^2 - 1} = 0.48$$

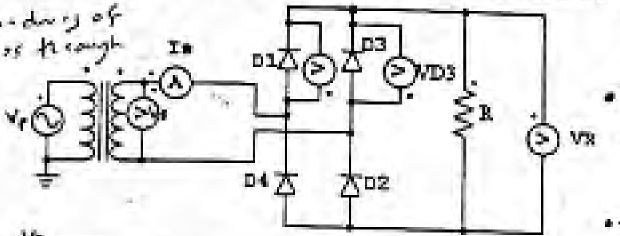
The PIV is $2V_m$

Example: $V_r = 100V$, $60HZ$, $R = 10\Omega$, $L = 10mH$, Bridge

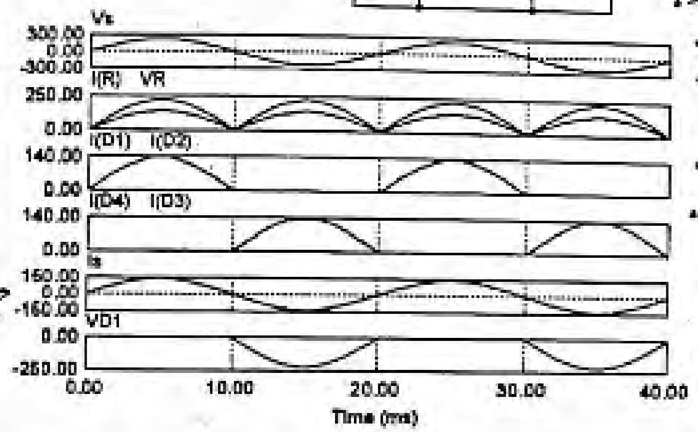
with L & R without battery

Single-Phase Full Bridge Diode Rectifier With Resistive Load

in this the secondary of transformer will pass through it the two ac current



• V_m here equal to V_p



current to transformer

• the voltage applied to one diode is V_m & for two diode is $2V_m$

• voltage for this case is same for primary & secondary while not for the previous

$V_{dc} = \frac{2 \cdot 100}{\pi} = 63.7V$ $\quad I_{dc} = \frac{63.7}{10} = 6.37$

n	V_n	X_n	Z_n	I_n
2	42.4	$2 \cdot 2\pi \cdot 60 \cdot 10m$	15	2.24
4	8.49	$4 \cdot 2\pi \cdot 60 \cdot 10m$	18.1	0.47

$$v_L(t) = V_{dc} + \sum_{n=2,4,\ldots} (a_n \cos n\omega t + b_n \sin n\omega t)$$

$I_{rms} = \sqrt{(6.37)^2 + \left(\frac{2.24}{\sqrt{2}}\right)^2 + \left(\frac{0.47}{\sqrt{2}}\right)^2}$

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

P.F. = 0.96 = $\frac{P_{ac}}{VI_{rms}}$

$$a_n = \frac{1}{\pi}\int_0^{2\pi} v_L \cos n\omega t\, d(\omega t) = \frac{2}{\pi}\int_0^{\pi} V_m \sin \omega t \cos n\omega t\, d(\omega t) = \frac{2V_m}{\pi}\left[\frac{1}{n-1} + \frac{1}{n+1}\right]$$

• $I_{D_{dc}} = \frac{6.37}{2}$

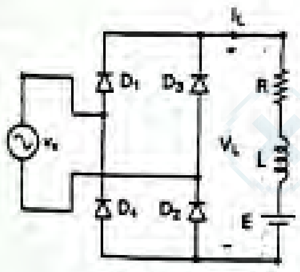
$$\boxed{a_n = \frac{4V_m}{\pi} \sum_{n=2,4,\ldots}^{\infty} \frac{-1}{(n-1)(n+1)}}$$

• $I_{D_{rms}} = \frac{I_{rms}}{\sqrt{2}}$

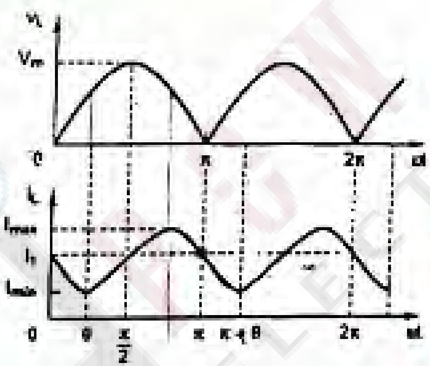
$$\boxed{b_n} = \frac{1}{\pi}\int_0^{2\pi} v_L \sin n\omega t\, d(\omega t) = \frac{2}{\pi}\int_0^{\pi} V_m \sin \omega t \sin n\omega t\, d(\omega t) = \boxed{0}$$

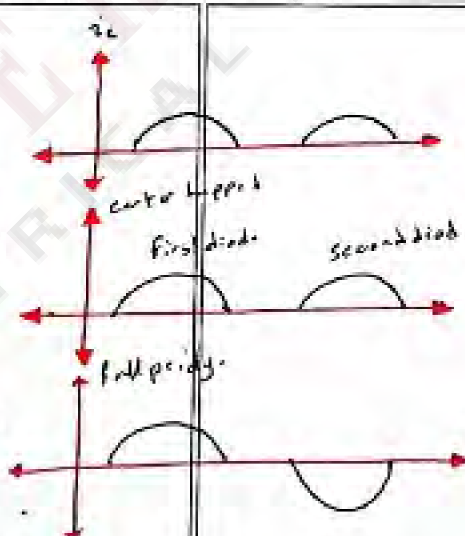
Substituting the values of a_n and b_n, the expression for the output voltage is

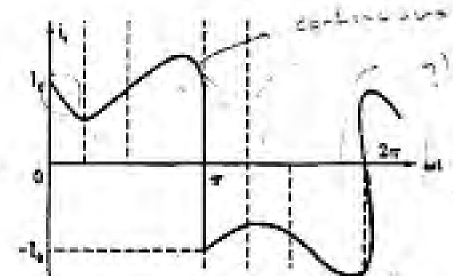
$$v_L(t) = \frac{2V_m}{\pi} - \frac{4V_m}{3\pi}\cos 2\omega t - \frac{4V_m}{15\pi}\cos 4\omega t - \frac{4V_m}{35\pi}\cos 6\omega t - \cdots$$



(a) Circuit

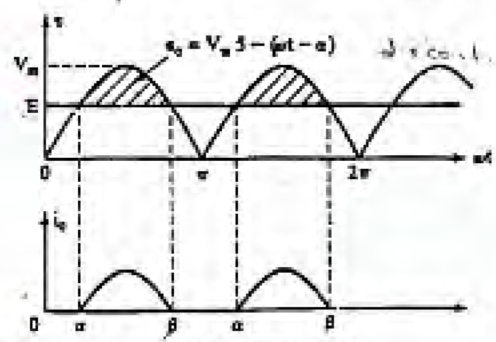






Continuous if there is a battery & $\beta > \alpha + \pi$

discontinuous if $\beta < \alpha + \pi$



(d) Discontinuous current

$$i_D = \frac{\sqrt{2}\, V_s}{Z}\sin(\omega t - \theta) + A_1 e^{-(R/L)t} - \frac{E}{R}$$

• note that if we have an inductor & resistor without battery then the current is continuous

* Example:

$V_{rms} = 120\,V$

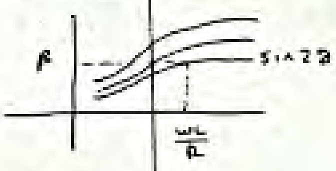
$R = 2\,\Omega$

$L = 10\,mH$

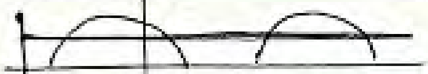
$V_{dc} = 80\,V$

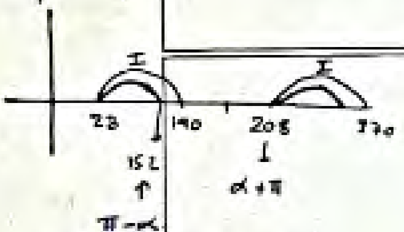
$\alpha = \sin^{-1}\left(\frac{80}{\sqrt{2}\,120}\right)$

$\alpha = 28°$



→ $\beta = 190°$





→ discontinuous.

→ note that we can solve the continuous by fourier series for the never voltage

Case 1: continuous load current.

for center tapped the power factor is $1/\sqrt{2}$

at $\omega t = \pi$, $i_L = I_1$.

$$A_1 = \left(I_0 + \frac{E}{R} - \frac{\sqrt{2}\,V_s}{Z}\sin\theta\right) e^{(R/L)(\pi/\omega)}$$

$$\frac{\left(\frac{V_m}{\sqrt{2}}\right)^2 / R}{2\,\frac{V_m}{\sqrt{2}}\,\frac{V_m}{2R}}$$

$$i_0 = \frac{\sqrt{2}\,V_s}{Z}\sin(\omega t - \theta) + \left(I_0 + \frac{E}{R} - \frac{\sqrt{2}\,V_s}{Z}\sin\theta\right) e^{(R/L)(\pi/\omega - t)} - \frac{E}{R}$$

$i_0(\omega t = 0) = i_0(\omega t = \pi)$. That is, $i_0(\omega t = 0) = I_0$

$$I_0 = \frac{\sqrt{2}\,V_s}{Z}\sin\theta\,\frac{1 + e^{-(R/L)(\pi/\omega)}}{1 - e^{-(R/L)(\pi/\omega)}} - \frac{E}{R} \quad \text{for } I_0 \geq 0$$

$$i_0 = \frac{\sqrt{2}\,V_s}{Z}\left[\sin(\omega t - \theta) + \frac{2}{1 - e^{-(R/L)(\pi/\omega)}}\sin\theta\, e^{-(R/L)t}\right] - \frac{E}{R}$$

for $0 \leq \omega t \leq \pi$ and $i_L \geq 0$

$$I_r = \left[\frac{1}{2\pi}\int_0^{\pi} i_0^2\, d(\omega t)\right]^{1/2}$$

$$I_{rms} = (I_r^2 + I_r^2)^{1/2} = \sqrt{2}\,I_r$$

$$I_d = \frac{1}{2\pi}\int_0^{\pi} i_D\, d(\omega t)$$

Case 2: discontinuous load current.

$$\alpha = \sin^{-1}\frac{E}{V_m}$$

At $\omega t = \alpha$, $i_L(\omega t) = 0$ and Eq. (3-65) gives

$$A_1 = \left[\frac{E}{R} - \frac{\sqrt{2}\,V_s}{Z}\sin(\alpha - \theta)\right] e^{(R/L)(\alpha/\omega)}$$

which, after substituting in Eq. (3-65), yields the load current

$$i_0 = \frac{\sqrt{2}\,V_s}{Z}\sin(\omega t - \theta) + \left[\frac{E}{R} - \frac{\sqrt{2}\,V_s}{Z}\sin(\alpha - \theta)\right] e^{(R/L)(\alpha/\omega - t)}$$

At $\omega t = \beta$, the current falls to zero, and $i_0(\omega t = \beta) = 0$. That is,

$$\frac{\sqrt{2}\,V_s}{Z}\sin(\beta - \theta) + \left[\frac{E}{R} - \frac{\sqrt{2}\,V_s}{Z}\sin(\alpha - \theta)\right] e^{(R/L)(\alpha - \beta)/\omega} = 0 \;\; - E/R$$

<u>Example 4</u> single-phase diode bridge rectfier has a purely re load of R=15 ohms and, VS=300 sin 314 t and unity trans ratio. Determine (a) The efficiency, (b) Form factor, (c) Ripple (d) The peak inverse voltage, (PIV) of each diode, , and, (e power factor.

$$V_{dc} = \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t\; d\omega t = \frac{2V_m}{\pi} = 190.956\ V \qquad I_{dc} = \frac{2V_m}{\pi R} = 12.73$$

$$V_{rms} = \left[\frac{1}{\pi}\int_0^{\pi}(V_m \sin\omega t)^2\, d\omega t\right]^{1/2} = \frac{V_m}{\sqrt{2}} = 212.132\ V$$

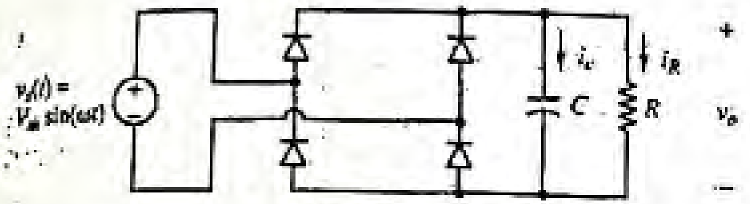
$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{V_{dc}\, I_{dc}}{V_{rms}\, I_{rms}} = 81.06\ \% \qquad FF = \frac{V_{rms}}{V_{dc}} = 1.11$$

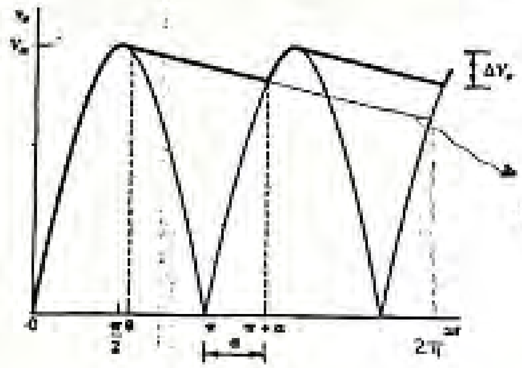
$$RF = \frac{V_{ac}}{V_{dc}} = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}} = \sqrt{\frac{V_{rms}^2}{V_{dc}^2} - 1} = \sqrt{FF^2 - 1} = 0.482$$

The PIV= 300V

$$\text{Input power factor} = \frac{Real\ Power}{Apperant\ Power} = \frac{V_S\, I_S \cos}{V_S\, I_S}$$

السؤال Diode sacally





* same equations for half wave but with replace 2π by π.

in half wave rectifier

Example:

$R = 500\Omega$, $C = 100\mu F$
$V = 120$ rms, $f = 60Hz$

$$v_o(\omega t) = \begin{cases} |V_m \sin \omega t| & \text{one diode pair on} \\ (V_m \sin \theta) e^{-(\omega t - \theta)/\omega RC} & \text{diodes off} \end{cases}$$

$$\theta = \tan^{-1}(-\omega RC) = -\tan^{-1}(\omega RC) + \pi.$$

- $\omega RC = 2\pi(60)(500)(100\mu)$
  $\omega RC = 18.85$

$$(V_m \sin\theta) e^{-(\pi+\alpha-\theta)/\omega RC} = -V_m \sin(\pi + \alpha)$$

$$\boxed{(\sin\theta) e^{-(\pi+\alpha-\theta)/\omega RC} - \sin(\alpha) = 0.}$$

- $\alpha = 60.6°$ from graph
- $\theta = \pi - \tan^{-1}(\omega RC)$
  $\theta = 93°$
- $\Delta V_o = V_m(1 - \sin\alpha)$
  $\Delta V_o = 169.7(1 - \sin(60.6))$
  $\Delta V_o = 22V$

$$\boxed{\Delta V_o = V_m - |V_m \sin(\pi + \alpha)| = V_m(1 - \sin\alpha).}$$

the capacitor needed to make $\Delta V_o = 0.1 V_m$

$\rightarrow \frac{\Delta V_o}{V_m} = 0.1 = \frac{1}{2fRC} \rightarrow C = 1670\ \mu F$

half the value of half wave.

where $\omega RC \gg \pi$,

$$\theta \approx \pi/2$$

$$\alpha \approx \pi/2.$$

$$v_o(\pi + \alpha) = V_m e^{-(\pi+\pi/2-\pi/2)/\omega RC} = V_m e^{-\pi/\omega RC}.$$

$$\Delta V_o \approx V_m\left(1 - e^{-\pi/\omega RC}\right).$$

$$e^{-\pi/\omega RC} \approx 1 - \frac{\pi}{\omega RC}.$$

$$\boxed{\Delta V_o \approx \frac{V_m \pi}{\omega RC} = \frac{V_m}{2fRC}.}$$

ripple voltage.

center tapped I_{rms} $\frac{V_m}{2R}$

bridge $\frac{V_m}{\sqrt{2}R}$

Comparision between Single Phase Rectifiers

maximum voltage can apply in reverse case of diode without breakdown

	Half wave (Fullwave)	Full wave: center-tap	Full wave: bridge
Peak repetitive reverse voltage VRRM 1.57 Vdc	3.14Vdc		3.14 Vdc
Rms input voltage per transformer leg Vs 1.11 Vdc		2.22 Vdc	1.11 Vdc
Diode average current IF.AV.	1.00 Idc	0.50 Idc	0.50 Idc
Diode rms current IF.RMS. Idc	1.57 Idc	0.785 Idc	0.785
Form factor of diode current IF.RMS.	1.57	1.57	1.57
Rectification ratio	0.405	0.81	0.81
Form factor	1.57	1.11	1.11
Ripple factor	1.21	0.482	0.482
Transformer rating primary VA Pdc	2.69 Pdc	1.23 Pdc	1.23
Transformer rating secondary VA Pdc	3.49 Pdc	1.76 Pdc	1.23
Output ripple frequency fr	1 fi	2 fi	2 fi

half wave $V_{dc} = \frac{V_m}{\pi}$

full wave $V_{dc} = \frac{2V_m}{\pi}$

in full wave is half the value

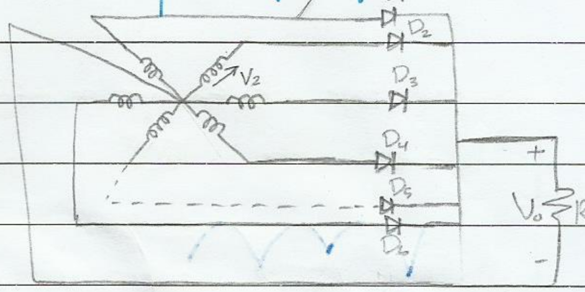
increase with full wave

I_{rms} is differ for both so the rating differ

Tuesday 25th / Mar / 2014

lecture 16

- Multi-phase Rectifier :



لو فرضنا إنو عدد 1 phase = q

$\therefore$ period $= 2\pi/q$

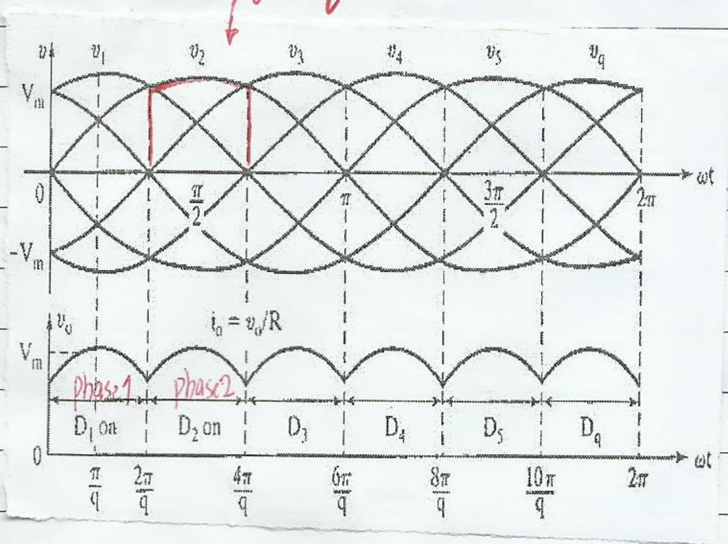
$$V_{dc} = \frac{2}{2\pi/q}\int_0^{\pi/q} V_m \cos \omega t \, d\omega t = V_m \frac{q}{\pi} \sin\frac{\pi}{q}$$

لو عملنا التكامل (sin بدل cos) لازم نكامل من

$$\frac{2\pi}{q} \rightarrow \frac{4\pi}{q}$$

← في كل فترة واحد من diode شغال والباقي off . " سلايد "

$\frac{2\pi}{q} \rightarrow \frac{4\pi}{q}$



$$V_{rms} = \sqrt{\frac{2}{2\pi/q}\int_0^{\pi/q} V_m^2 \cos^2(\omega t)\, d\omega t} = V_m\left[\frac{q}{2\pi}\left(\frac{\pi}{q} + \frac{1}{2}\sin\frac{2\pi}{q}\right)\right]^{1/2}$$

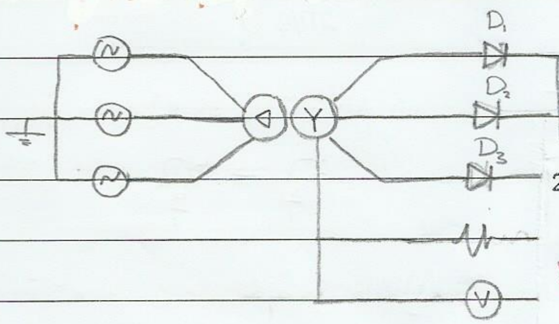
if fullwave $\Rightarrow q = 2$

$\Rightarrow \therefore V_{rms} = \frac{V_m}{\sqrt{2}}$

$$I_{rms} \text{ "For single diode" } = \sqrt{\frac{2}{2\pi}\int_0^{\pi/q} I_m^2 \cos^2 \omega t \, d\omega t} = \frac{V_{rms}}{R\sqrt{q}} \rightarrow \text{if } q = 2 \Rightarrow I_{rms} = \frac{V_m}{\sqrt{2}R}$$

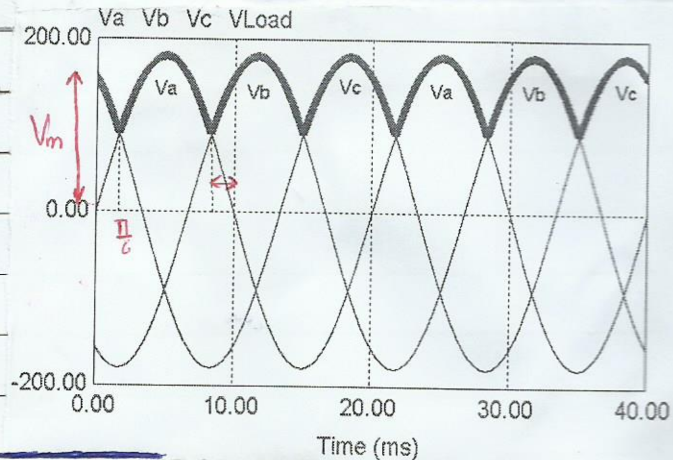
يلي كنا ناخده قبل

• Three phase Half-wave Rectifier



each phase is half-wave rectifier

⇒ each wave is 120°



$$\rightarrow V_{dc} = \frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} V_m \sin \omega t \, d\omega t = \frac{3\sqrt{3}\, V_m}{2\pi}$$

$$I_{dc} = \frac{3\sqrt{3}\, V_m}{2 * 2\pi R}$$

$$\rightarrow V_{rms} = \sqrt{\frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} (V_m \sin \omega t)^2 \, d\omega t} = \sqrt{\frac{1}{2} + \frac{3\sqrt{3}}{8\pi}}\; V_m = 0.8407\, V_m$$

$$I_{rms} = \frac{0.8407\, V_m}{R}$$

$$\cdot\ \underbrace{I_r = I_s}_{\text{current in single diode.}} = \frac{0.8407\, V_m}{\sqrt{3}\, R}$$

$$PIV \Rightarrow \sqrt{2}\, V_{LL} = \sqrt{3}\, V_m$$

• Example: 3phase star rectifier is operated from 460V, 50Hz supply at the 2^{ed} ary side and the load $R = 20\Omega$, Determine:

→ Rectifier efficiency, Form Factor, Ripple Factor, Peak inverse voltage,

$$V_s = \frac{460}{\sqrt{3}} = 265.58 \qquad \underset{peak}{V_m} = 265.58 * \sqrt{2} = 375.59$$

← حولها إلى phase

$$\Rightarrow V_{dc} = \frac{3\sqrt{3}\, V_m}{2\pi} = \qquad I_{dc} = \frac{V_{dc}}{R}$$

$$V_{rms} = 0.8407\, V_m \qquad I_{rms} = \frac{V_{rms}}{R}$$

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{V_{dc}\, I_{dc}}{V_{rms}\, I_{rms}} = 96.767\,\%$$

$$FF = \frac{V_{rms}}{V_{dc}} = 101.657\,\%$$

$RF = \sqrt{1 - FF^2} = 18.28\%$

$PIV = \sqrt{3}\, V_m = 650.54$

$$\Rightarrow PF = \frac{(0.8407\, V_m)^2 / R}{3 * \frac{V_m}{\sqrt{2}} * \underbrace{\frac{0.8407\, V_m}{\sqrt{3} R}}_{I_s}} = 0.6844$$

$$TUF = \frac{\overbrace{(0.827\, V_m)^2 / R}^{P_{dc}}}{3 * \frac{V_m}{\sqrt{2}} * \frac{0.8407\, V_m}{\sqrt{3} R}} = 0.6643$$

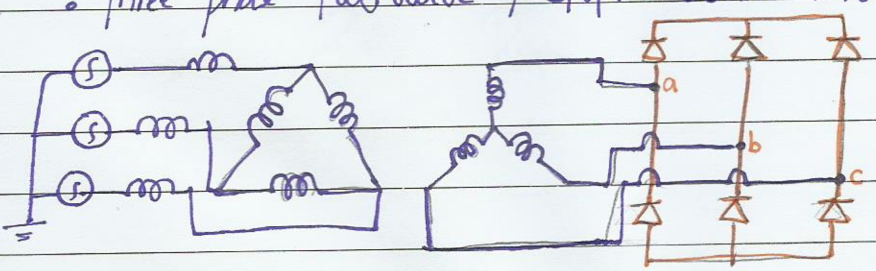
9

$\sqrt{3} R \rightarrow$ rms phase current $= \frac{\text{rms total}}{\sqrt{3}}$

$\sqrt{2} \rightarrow$ rms phase voltage $= \frac{\text{peak voltage}}{\sqrt{2}}$

$$\eta = \frac{TUF}{PF} = 97.7\%$$

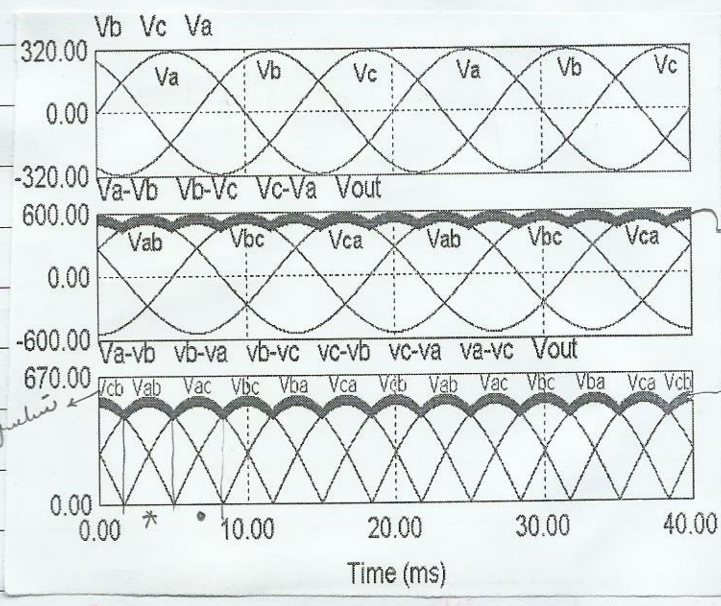
• Three phase Fullwave Rectifier with RLoad:



- voltage that is given to the load is line to line.
- in each moment [2phase → ON, the 3ed → OFF

⇐ يعني كل °120 بشتغل واحد من ال phases

ويعني °60 ، يعني °120 الثاني بالعكس ، OFF 60 ، وهكذا :



→ peak cosine line to line

١. أول °60 ⇐ أعلى شي Va

٣ * ⇐ أقل شي Vb ⇐ الناتج Vab

٣. ⇐ أقل شي Vc ⇐ الناتج Vac

٢. أول freq هي السادسة وهي fundamental

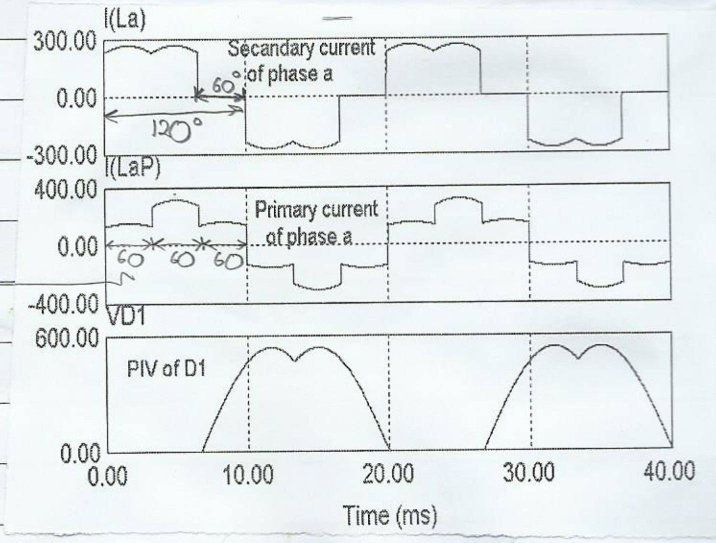
٣. 360 (يعني period) مقسمة الى 6 أقسام

⇐ كل °60 قمة عند الأعلى .

... 360° is divided into 6 section

Thursday 27th/Mar/2014

lecture 17



through it the voltage is doubled

2ed ary:

120 +ve → 60 OFF → 120 -ve

$$\rightarrow V_{rms} = \left[\frac{2}{2\pi/6} \int_0^{\pi/6} 3 V_m^2 \cos^2 \omega t \, d\omega t \right]^{1/2} = \left(\frac{2}{3} + \frac{9\sqrt{3}}{4\pi} \right)^{1/2} V_m = 1.6554 \, V_m$$

line voltage

$$I_r = \left[\frac{4}{2\pi} \int_0^{\pi/6} I_m^2 \cos^2 \omega t \, d\omega t \right]^{1/2} = 0.5518 \, I_m$$ "For one diode"

$\frac{2}{2\pi/4}$

$\boxed{\sqrt{2} * I_{one\ diode}}$

$$\Rightarrow \text{the transformer } 2^{ed}\text{ary current} = \frac{8}{2\pi} \int_0^{\pi/6} I_m^2 \cos^2 \omega t \, d\omega t = 0.7804 \, I_m$$

• For a three phase rectifier ⇒ q = 6 :

$$V_o(t) = 0.9549 \, V_m \left(1 + \frac{2}{35} \cos(6\omega t) - \frac{2}{143} \cos(12\omega t) + \cdots \right)$$

Note:

#. Slide D performance comparsion between Single & 3phase Rectifier.

• **Example:** the 3phase bridge rectifier is operated from 460V, 50Hz supply and the load resistance is $R = 20\,\Omega$. Determine: η, FF, RF, PIV, PF,

(L-L)

$\frac{\sqrt{3}}{\pi/6}\int_0^{\pi/6} V_m \cos \omega t \, d\omega t$

$V_{dc} = \frac{3\sqrt{3}V_m}{\pi} = 1.654\, V_m = 621.226.$ $\qquad I_{dc} = \frac{V_{dc}}{R} = 31.0613\,A.$

$V_{rms} = \sqrt{\frac{3}{2} + \frac{9\sqrt{3}}{4\pi}}\, V_m = 621.752.$ $\qquad I_{rms} = \frac{V_{rms}}{R} = 31.0876.$

الفرق بينهم تقريبًا 0.5 V عشان Ripple ضعيفة قليلة.

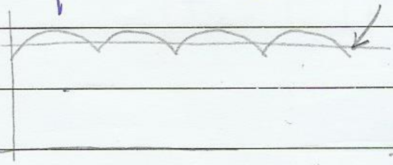
$\eta = \frac{P_{dc}}{P_{ac}} = 99.83\%$

$FF = \frac{V_{rms}}{V_{dc}} = 100.08\%$

$RF = \sqrt{1 - FF^2} = 4\%$ " كيف طلعت قيمتها عن أول شي "
⇐ كانت أكثر من 100%

$PIV = \sqrt{3}\,V_m = 650.54\,V$

• 3-phase Bridge Rectifier with RL load:



تأثير E وهي عالية جدا
تصبح Ripple قليل تقريبًا DC
وهذه الحالة في شحن البطاريات

"if E very close to the peak" ⇐ تكون في هذه الحالة " Discont

$v_{ab}(t) = \sqrt{2}\, V_{ab} \sin(\omega t)$ $\qquad \frac{\pi}{3} \leq \omega t \leq \frac{2\pi}{3}$

$V_{ab} \rightarrow V_{rms}$

$i_o(t) = \frac{\sqrt{2}\, V_{ab}}{Z} \sin(\omega t - \theta) - \frac{E}{R} + A_1 e^{-\frac{R}{L}t}$

$Z = \sqrt{R^2 + \omega^2 L^2}$

$\theta = \tan^{-1} \omega L / R$

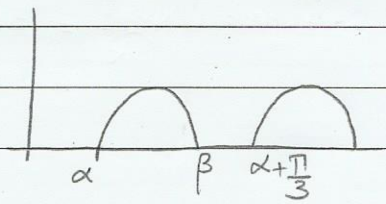
⇒ under a steady state: $i_o(\omega t = \pi/3) = i_o(\omega t = 2\pi/3) = I_o$

$\therefore I_o = \frac{\sqrt{2}\, V_{ab}}{Z} \cdot \frac{\sin(2\pi/3 - \theta) - \sin(\pi/3 - \theta)\, e^{-(R/L)(\pi/3\omega)}}{1 - e^{-(R/L)(\pi/3\omega)}} - \frac{E}{R}$

I_o → initial value

↳ Conditions for Continuos load Current :

$$\left(\frac{E}{\sqrt{2}\,V_{ab}}\right)_{critical} = \left[\frac{\sin\left(\frac{2\pi}{3}-\theta\right) - \sin\left(\frac{\pi}{3}-\theta\right) e^{-\pi/3\tan\theta}}{1-e^{-\pi/3\tan\theta}}\right] \cos\theta$$



two case

→ $\beta > (\alpha + \pi/3) \Rightarrow$ Continuous

→ $\beta < (\alpha + \pi/3) \Rightarrow$ Dis. cont.

Tuesday 1st/Apr/2014.

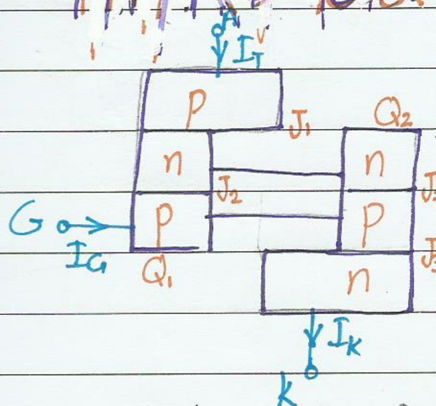
lecture 18

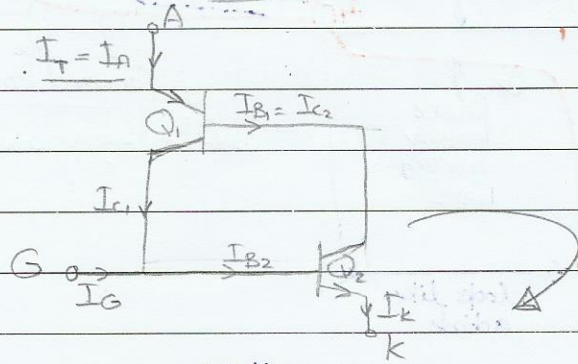
ملاحظة: يلي بعد المحاضرة (18) كان كله مش موجود بالسلايدات (ومش اشي زيادة بالمحاضرة على الموقع)

THYRISTOR

the purpose of a thyristor ⇒ is to be able to Control diode.

Slide 1,2,3,4,5.





3 junction ⇒ looks like 2 transistor: npn, pnp

- if there's no gate current, it won't work ⇒ (*) بعد ما نوصل I_G بحتاج فترة لـ يوصل للـ Operation mode اللي بدنا إياها وبعد بشيل I_G عادي بالنسبة للـ I_{C_1} & I_{B_2} لحالهم بكفي إنه تشغله

$\Rightarrow I_C = \beta I_B + (1+\beta) I_{CBO}$ ⇒ dc value of the collecter to base current.

$I_C = \alpha I_E + I_{CBO}$

$I_E = I_C + I_B$

$\Rightarrow \boxed{I_B = I_E(1-\alpha) - I_{CBO}}$

transistor: npn, pnp

npn:

$I_C = I_{C_2}$, $I_B = I_{B_2}$, $I_{E_2} = I_K$

$I_{C_2} = \alpha_2 I_K + I_{CBO_2}$

$\boxed{I_{C_2} = \alpha_2 (I_A + I_G) + I_{CBO_2}}$

pnp:

$I_{E_1} = I_A$, $I_C = I_{C_1}$, $\alpha = \alpha_1$

$I_{CBO} = I_{CBO_1}$, $I_B = I_{B_1}$

$\boxed{I_{B_1} = I_A(1-\alpha_1) - I_{CBO_1}}$

from the equivalent ckt, we see that:

$I_{C_2} = I_{B_1}$

$$\Rightarrow I_A = \frac{\alpha_2 I_g + I_{CBO_1} + I_{CBO_2}}{1-(\alpha_1+\alpha_2)}$$

case 1:

$I_g = 0$

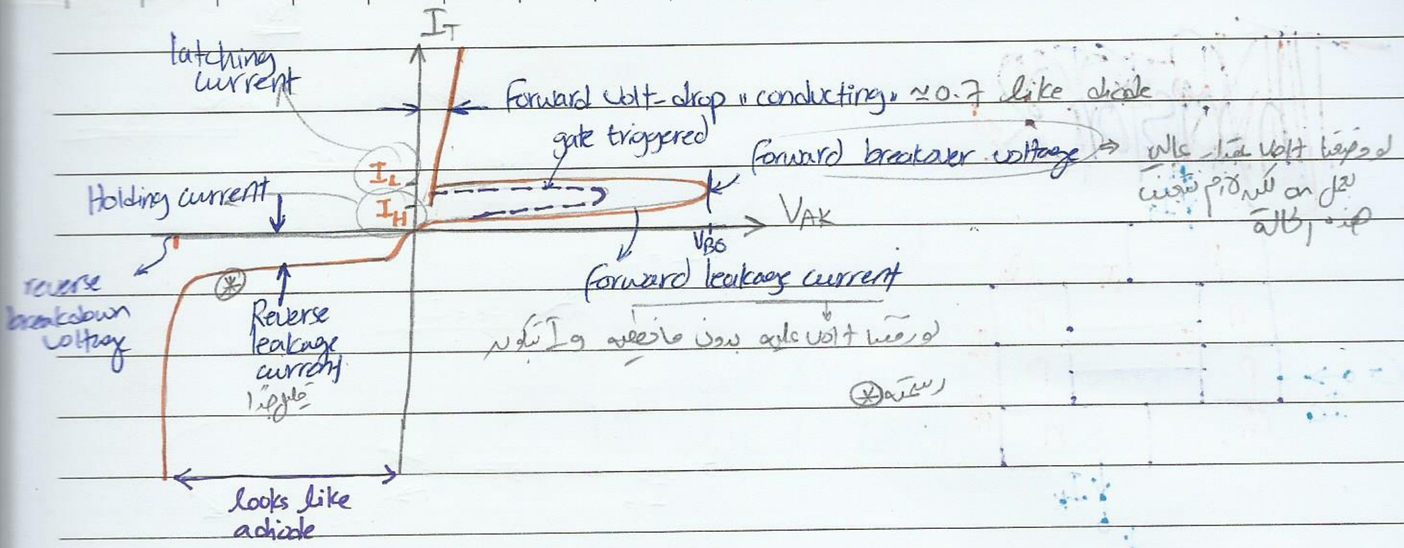
$$I_A = \frac{I_{CBO_1} + I_{CBO_2}}{1-(\alpha_1+\alpha_2)}$$

case 2:

$I_G \neq 0$

$$I_A = \frac{\alpha_2 I_g + I_{CBO_1} + I_{CBO_2}}{1-(\alpha_1+\alpha_2)}$$

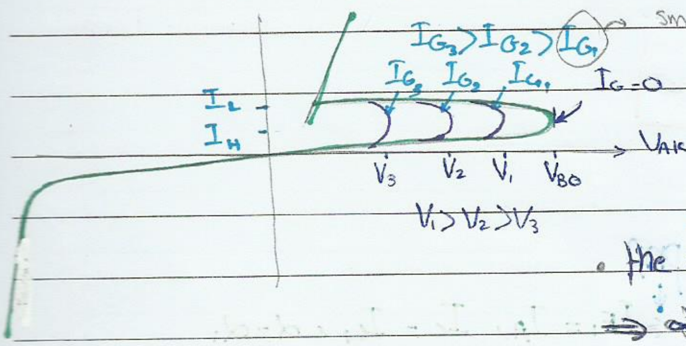
firing ⊛ = عملية إعطاء إشارة لل gate
the same as triggering



→ latching current: min current at starting [after switching ON]
⟹ at transion [OFF → ON].

→ Holding current: min current below which the thyristor will stop [before switching OFF] ⟹ at transion [ON → OFF]
⟹ & usually $I_H < I_L$

↳ effects of gate Current:

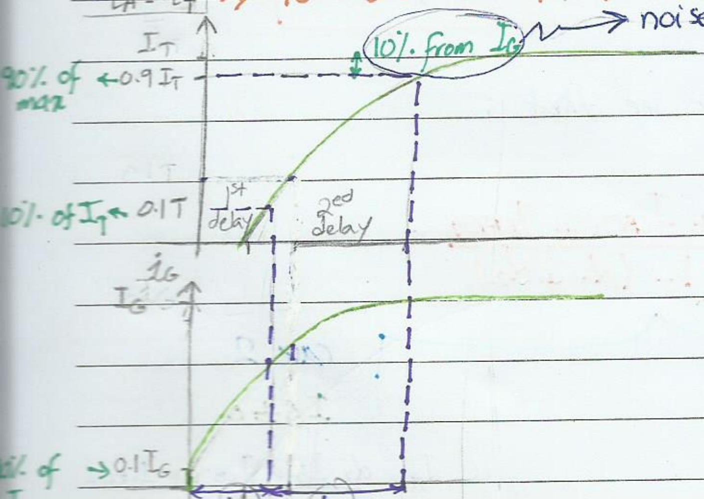


→ small amount of current needed at high voltage.
→ to be able to work as a switch.

• the current at forward break down voltage = 0
⟹ يعني ما نعطيه تيار، لكنه يعمل switching

↳ Turn ON Characteristic:

$i_A = i_T$



10% from I_G → noise السبب هو الحالية وجود

• turn on charcateristic is important to ensure that thyrstor is ON, if stopped before that the thyristor might stop.

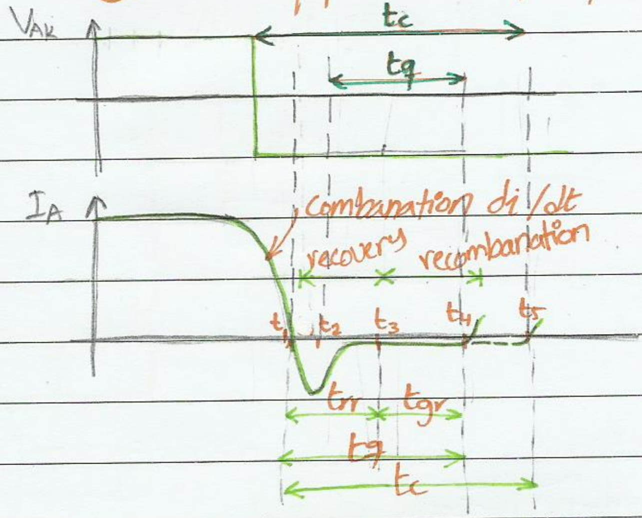
$$t_{ON} = t_d + t_r$$

t_d: $0.1 I_G \rightarrow 0.1 I_T$

t_r: $0.1 I_T \rightarrow 0.9 I_T$

t_{ON} is the minimum time to ensure that thyr is working

↳ Switch OFF Characteristic : the same as switch off for diode ⇒ when $I_A = 0$.

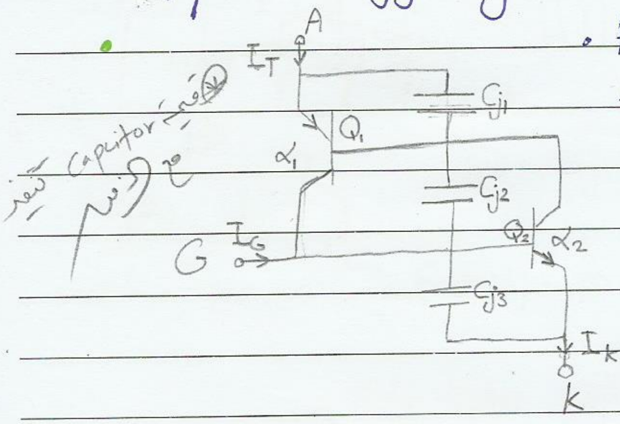


(تعتمد على ckt, الدارة)

t_c: circuit OFF time

t_q: device OFF time

- **dV/dt triggring** : concern about rate of change of voltage.



- the three junctions have a charges between them ⇒ the charges [between p & n] will work as acapitor.
  ⇒ between junctions

⇒ because of the capitors [ton] increases exponentially, if there's no capitor it'll be sharp increasing.

$$i_{j2} = \frac{dq_2}{dt} = \frac{d}{dt}\left(C_{j2} V_{j2}\right)$$

$$\boxed{i_{j2} = \frac{C_{j2}\, dV_{j2}}{dt} + V_{j2}\frac{dC_{j2}}{dt}}$$

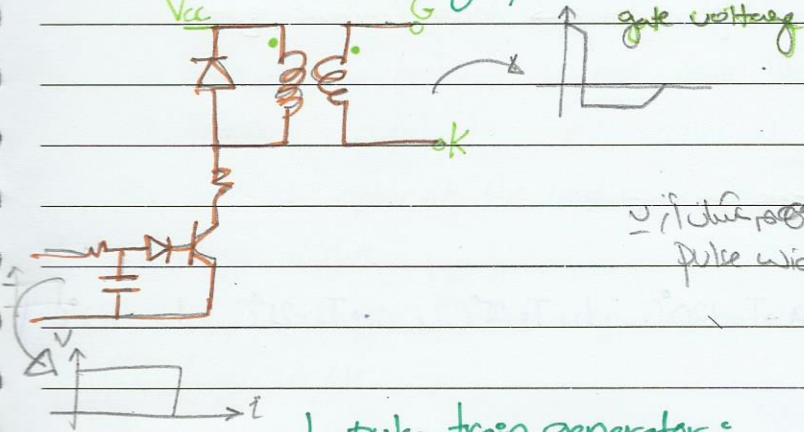
↳ Method of Thyristor Turn on :

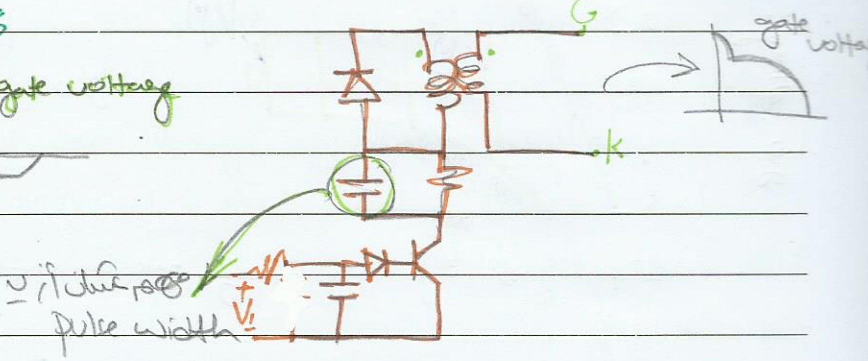
1. thermal turn on ⇒ مسألة الوقت يلي بحول فيه (switch-ON) مهمة مقارنة أنه خاوع على درجة حرارة الـ thyristor لأنه سيعمل switching في غير الوقت المقصود.
2. Light
3. High Voltage
4. Gate Current
5. dV/dt ⇒ a low amount of voltage but there's spark [انفجار، شرارة] this will cause switching due to capitor where dV/dt will produce current.

Thursday 10th / Apr / 2014

lecture 22

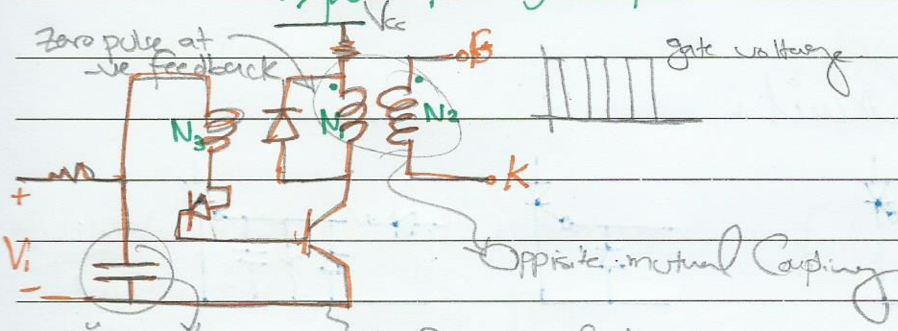
. Short & long pulse :





لما يكبر pulse width

↳ pulse train generator :



راح يصير شحن للتوقف

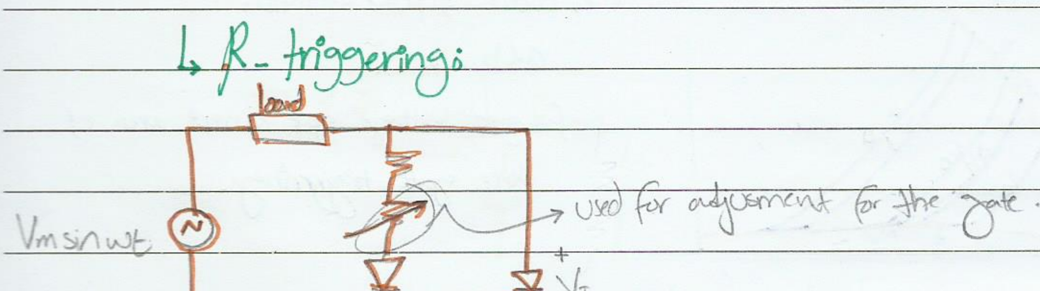
From the feedback loop, we get the pulse train.

→ pulse train with timer and AND gate :

For Comparsion between AC & DC

شرحه شغلة في السلايدات

↳ R - triggering :



and there's RC triggering ; check out the Slides

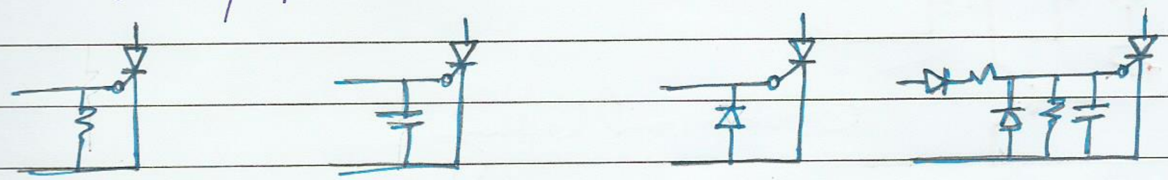
• Gate Triggering Characteristic:

higher temp → lower Current gate.

that's the range operating in. if T=120° we can't supply it with Current or voltage higher than *

a → T = 120°C , b → T = 25°C , c → T = -25°C , d = -50°C

↳ Gate Protection Circuit:



Resistor

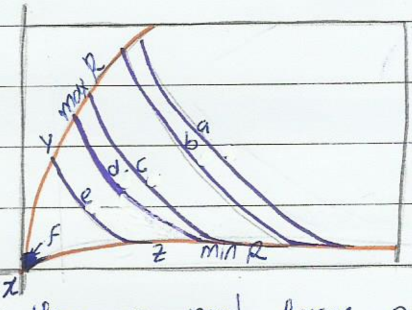
Capacitor in case of transient

free wheeling diode

كلهم مع بعض

to protect the gate ←

• Gate Input Characteristic:



لما كان (عرض pulse) كبير بس تيار قليل . العكس صح ⇐ عشان يصير triggering

a, b, c, d, e ⇒ pulse duration

a < b, ... < e

f ⇒ gate voltage gate current area of sure gate triggering.

if V & I are low then we need large pulse width.

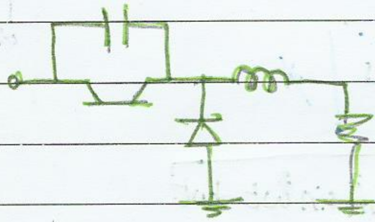
if V & I are high then a small pulse is enough.

• High Temperature due to :
↳ this cause a low power quality

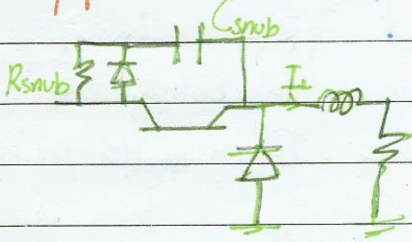
← هاي الامور يلي لازم نخفضها و نتجنب استمرارها
since thyristor works at a proper temp, it's different [due to] these reasons :

1. sustained overload : current passes through higher than rated current
2. transient overload : O.L occurs at a short period of time.
3. short ckt either at the load or in one of the device. اذا كان عنا شي راح تزيد الحرارة.
4. large di/dt
5. surge voltage بسبب short circuit أو switching أو spark غير متوقع
6. large dV/dt
7. excessive gate power in case of SCRs اذا اعطيت ال gate current لفترات طويلة.
8. insufficient gate drive in case of SCRs اذا اعطيت كمية voltage غير كافية لل firing راح تسبب ارتفاع بدرجة الحرارة.

دارة 2 مهمة • Snubber : to protect any device [protecting thyristor or transistor]
بس مهم نعرف رسمتها.



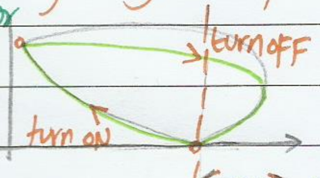
• Turn OFF Snubber circuit : works as the snubber ^^



Using Snubber

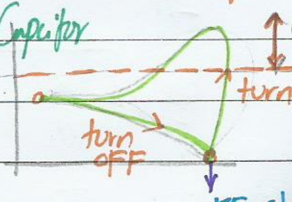
• Trajectory Comparsion With & Without Capitor :

No capitor



over voltage when turning off

Significant Capitor



capacitor لل
تيار إضافي بروح عابياً على الاجهزة

OFF stage there's no over voltage

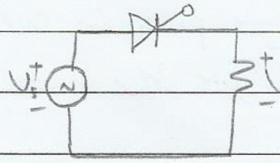
• Controlled Rectifier: "الدكتور قال كله يلي أخذناه قبل كان مقدمات !!"

Normail Rectifier are considered as uncontrolled rectifier
away to control the output is to use SCR instead of diode, two Condition must be met before SCR can conduct:

1. ~~SCR~~ must be forward ~~bias~~
2. current must be applied to the gate of SCR

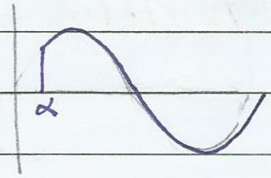
→ Controlled HalfWave RLoad:

$V_o = V_{avg} = V_{DC} = \int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t$



$$\boxed{V_o = \frac{V_m}{2\pi}(1 + \cos \alpha)} \ *$$

avg. DC output voltage. — Firing angle



$$\boxed{P = I_{rms}^2 R = \frac{V_{rms}^2}{R}} \ *$$

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

$$\boxed{V_{rms} = \frac{V_m}{2} \sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}}} \ *$$

if $\alpha = 0 \Rightarrow V_{rms} = V_m/2$

(لازم نحولها ل Rad)

• Example: Design a circuit to produce an average voltage of 40V across 100Ω From 120Vrms, 60Hz ac source, Determine the power absorbed by R & pF?

$V_o = \frac{V_m}{2\pi}(1 + \cos \alpha)$

$40 = \frac{120\sqrt{2}}{2\pi}(1 + \cos \alpha) \Rightarrow \alpha = 61.2° = 1.07 \text{ rad.}$

$V_{rms} = \frac{V_m}{2} \sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}} = 75.6 \text{ V}$

$P = \frac{V_{rms}^2}{R} = 57.1 \text{ W}$ $\quad pF = \frac{\overset{P_{ac}}{57.1}}{(120)(75.6)} = 0.63$

Sunday 13th/Apr/2014

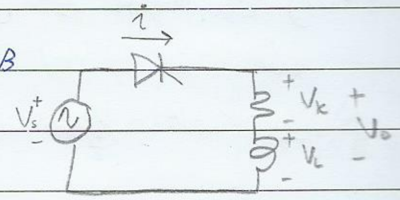
lecture 23

• Note: if an uncontrolled diode is used $(\alpha=0) \Rightarrow V_o = \frac{V_m}{\pi} = \frac{120\sqrt{2}}{\pi} = 54V$

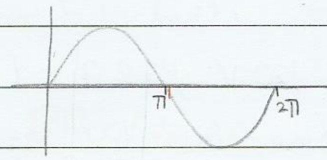
• R in series ال الوصل تخفيض الـ voltage بإضافة

→ Controlled Half wave RL load:

$$i(\omega t) = \begin{cases} \frac{V_m}{Z}\left[\sin(\omega t - \theta) - \sin(\alpha-\theta)e^{(\alpha-\omega t)/\omega\tau}\right] & \alpha < \omega t < \beta \\ 0 & \text{otherwise} \end{cases}$$

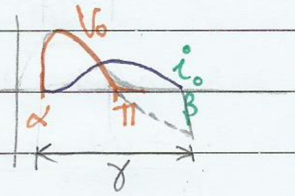


$$\boxed{I_{rms} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta} i^2(\omega t)\, d\omega t}} \quad *$$



$$I_{oavg} = \frac{1}{2\pi}\int_{\alpha}^{\beta} i(\omega t)\, d\omega t \quad *$$

$$\boxed{V_{oavg} = \frac{V_m}{2\pi}(\cos\alpha - \cos\beta)} \quad * \text{ (-ve since } \beta > \pi)$$



$\beta > \pi$

$$\boxed{P = I_{rms}^2 R} \quad *$$

$\gamma \equiv$ conduction angle $= \beta - \alpha$
distinction firing

اشتقاقها موجود في السلايدات (مهم) ← $\tan(\alpha-\theta) = \frac{\sin\gamma}{e^{-\gamma/\omega L/R} - \cos\gamma}$ → to find $\alpha \Rightarrow$ β & γ have to be known. we can find them from the graph.

$\theta = \tan^{-1}\frac{\omega L}{R}$

• Examples: if $V = 120V$, $R = 20\Omega$, $L = 0.04H$, $\alpha = 45$, $f = 60Hz$

$V_m = 120\sqrt{2} = 169.7\,V$

$Z = \sqrt{20^2 + 0.04 \times 2\pi \times 60} = 25\Omega$

$\theta = \tan^{-1}\omega L/R = 0.646$. $\qquad \omega L/R = 0.754$.

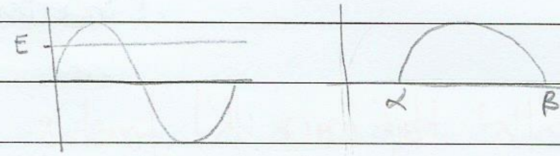
from the graph $\Rightarrow \alpha = 45°$

$i(\omega t) = \frac{V_m}{Z}\left[\sin(\omega t - \theta) - e^{\omega t/0.754}\right] \qquad \alpha \le \omega t \le \beta \rightarrow 172+45 = 217$

$I_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\beta} i(\omega t)\, d\omega t = 2.19V$

$I_{rms} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta} i^2(\omega t)\, d\omega t} = 3.26A \qquad PF = \frac{213}{120 \times 0.26} = 0.54$

→ if there's a source [controlled half wave RL load with source]



$\sin \alpha = \dfrac{E}{V_m}$

هي أقل زاوية على أعمل فيها Firing

$\alpha = \sin^{-1}(E/V_m)$

$i_w(t) = \dfrac{V_m}{Z}\sin(\omega t - \theta) - \dfrac{E}{R} + A e^{-\omega t/(\omega L/R)}$

$A = \left[\dfrac{-V_m}{Z}\sin(\alpha - \theta) + \dfrac{E}{R}\right] e^{\alpha/(\omega L/R)}$

- Example: 120 V, $R = 2\,\Omega$, $L = 20\,mH$, $E = 100\,V$, $f = 60\,Hz$; $\alpha = 45$;

$\alpha_{min} = \sin^{-1}\dfrac{100}{120\sqrt{2}} = 36°$

$i(\omega t) = 21.8\sin(\omega t - 1.312) - 50 + 75 e^{-\omega t/3.77}$

في هذه الحالة لازم نستخدم graph الموجود في السلايدات لكي graph تابع ... ← $\beta = 3.37$ rad

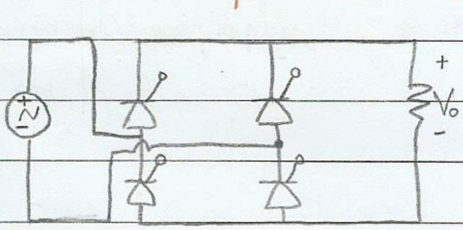
$I_{rms} = \sqrt{\dfrac{1}{2\pi}\displaystyle\int_{\alpha=45}^{\beta=3.37} i^2(\omega t)\, d\omega t} =$

$I_{dc} = \dfrac{1}{2\pi}\displaystyle\int_{\alpha}^{\beta} i(\omega t)\, d\omega t = 2.19\,A$

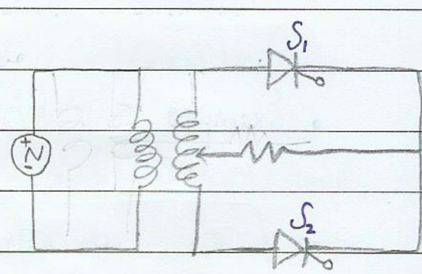
$P_E = 2.19 \times 100 = 219\,W$

$P_R = I_{RMS}^2 \times R = 3.9^2 \times 2$

→ Controlled Full-wave Rectifier:



bridge Rectifier



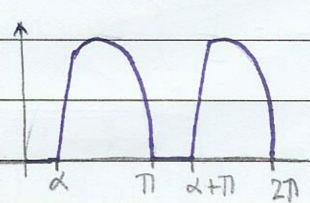
centre tapped

⇒ current is half-wave

I_{rms} in R is what we calculate

I_{rms} in S_1 & S_2 → $\dfrac{I_{cal}}{\sqrt{2}}$

output for Resistive load →



Tuesday 15th/Apr/2014

lecture 24

⇒ For resistive load:
$$V_o = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin(\omega t)\, d\omega t = \frac{V_m}{\pi}(1+\cos\alpha)$$

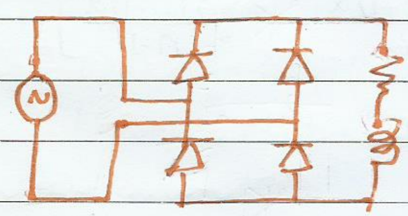
$$I_o = V_o/R$$

$$I_{rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}\left(\frac{V_m}{R}\sin\omega t\right)^2 d\omega t}$$

$$I_{rms} = \frac{V_m}{R}\sqrt{\frac{1}{2} - \frac{\alpha}{2\pi} + \frac{\sin 2\alpha}{2\pi}}$$ ⇒ if $\alpha = 0$, $I_{rms} = \frac{V_m}{\sqrt{2}R}$ → as full wave Rectifier

$P = I_{rms}^2 R$ (p delivered to the load).

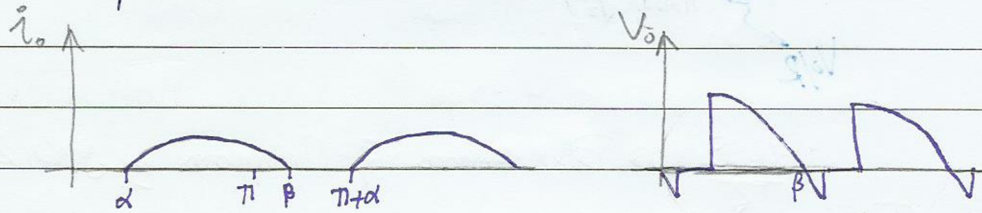
⇒ Full-wave Controlled Rectifier with RL load:



in this case current always +ve while voltage [+ve OR -ve] depends on α

→ Discontinuous Mode: it's like half-wave Rectifier except that period for the output is π.

$\beta < \alpha + \pi$

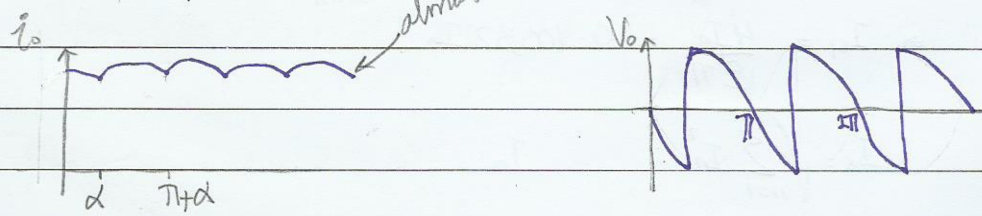


$$i_o(\omega t) = \frac{V_m}{Z}\left[\sin(\omega t - \theta) - \sin(\alpha - \theta)e^{-(\omega t - \alpha)/\omega\tau}\right]$$

$Z = \sqrt{R^2 + (\omega L)^2}$, $\theta = \tan^{-1}(\omega L/R)$, $\tau \to L/R$

→ Continuous Mode:

$\beta > \pi + \alpha$



largest Harmonic at $\alpha = 90^\circ$

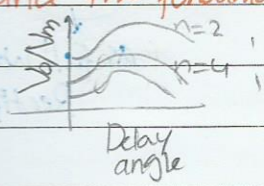
$\rightarrow \omega t = \pi + \alpha$

- Fourier Series : $v_o(\omega t) = V_o + \sum_{n=1}^{\infty} V_n \cos(n\omega t + \theta_n)$

$\sqrt{a_n^2 + b_n^2}$

harmonics from the graph ;

$\Rightarrow$ there's no odd harmonic since the fundamental = 2



$$V_o = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin \omega t \, d\omega t = \frac{2V_m}{\pi}\cos\alpha$$

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

$$b_n = \frac{2V_m}{\pi}\left[\frac{\sin(n+1)\alpha}{n+1} - \frac{\sin(n-1)\alpha}{n-1}\right]$$

$\Rightarrow$ depends on α values

$$\theta = \tan^{-1}(-b_n/a_n)$$

$$I_n = \frac{V_n}{Z}$$

$$I_{rms} = \sqrt{I_o^2 + \sum_{n=2,4}^{\infty}\left(\frac{I_n}{\sqrt{2}}\right)^2}$$

V_o/R

الحد الفاصل بين Discontinuous & Continuous ع $\alpha = \theta$

$\frac{\omega L}{R}$ مقدار delay بيسبب firing بيساوي مقدار delay بيسبب

- High inductor ; Fourier series for i_s :

$I_{dc} = 0$

$$a_n = \frac{1}{\pi}\int_{\alpha}^{\alpha+\pi} I_a \cos(n\omega t)\, d\omega t - \int_{\alpha+\pi}^{\alpha+2\pi} I_a \cos(n\omega t)\, d\omega t$$

$$\Rightarrow I_{s1} = \frac{4 I_a}{\sqrt{2}\pi} = 0.90032 I_a$$

$$I_s = \sqrt{\sum_{n=1}^{\infty} I_n^2} = I_a$$

$$HF = \sqrt{\left(\frac{I_s}{I_{s1}}\right)^2 - 1} = 0.483$$

$\alpha = 60^\circ = \pi/3$

• Example: $V_s = 120\,v$, $R = 10\Omega$, $f = 60Hz$, $\alpha = 60^\circ$, $L = 20mH$?!

$$\theta = \tan^{-1}\frac{\omega L}{R} = \tan^{-1}\left(\frac{2\pi \times 60 \times 0.02}{10}\right) = 0.646\,rad \approx 37^\circ$$

$$\alpha = 60^\circ = 1.047\,rad.$$

$$\Rightarrow \alpha > \theta \quad \therefore \text{discontinous}$$

From the graph, $\gamma = 156$.

$$\beta = \gamma + \alpha = 216$$

$$\Rightarrow I_o = \frac{1}{\pi}\int_{\alpha}^{\beta} i(\omega t)\,d\omega t = 7.05A.$$

• Example: single phase, fullwave controlled rectifier with RL load where $V_s = 120\,v$, $f = 60Hz$ $\alpha = 60^\circ$, $R = 10\Omega$, $L = 100mH$?!

$$\theta = \tan^{-1}\left(\frac{2\pi \times 60 \times 0.1}{20}\right) = 75^\circ.$$

$$\alpha < \theta \Rightarrow \text{Continuous}.$$

$$V_o = \frac{2V_m}{\pi}\cos\alpha = \frac{2 \times 120\sqrt{2}}{\pi}\cos 60 = 54\,V.$$

From graph 4-12: $\frac{V_2}{V_m} = 0.76$

F	V_o/V_m	V_o	Z	I_o
60	0.76	54	10	5.4
2x60	0.76	129.8	76	1.71
4x60	0.3	50.4	151	0.33
6x60	0.18	32.2	226	0.14

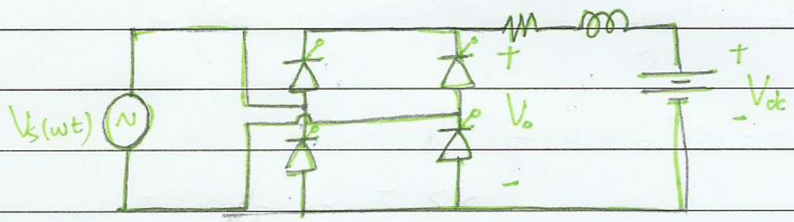
$$I_{rms} = \sqrt{(5.4)^2 + \left(\frac{1.71}{\sqrt{2}}\right)^2 + \left(\frac{0.33}{\sqrt{2}}\right)^2 + \left(\frac{0.14}{\sqrt{2}}\right)^2} = 5.54A.$$

$$P = 5.54^2 \times 10 = 307\,W$$

Thursday 17th/Apr/2014

lecture 25

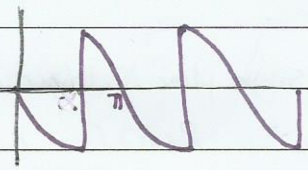
→ RL Source Load:



if $\alpha < 90°$ ⇒ +ve output

if $\alpha > 90°$ ⇒ -ve output, we can't connect it to a positive battery, we have to flip it [works as inverter DC → AC return power to the source].

⇒ $\alpha \geq \sin^{-1}(V_{dc}/V_m)$



Operating as inverter.

For Continuous Current:

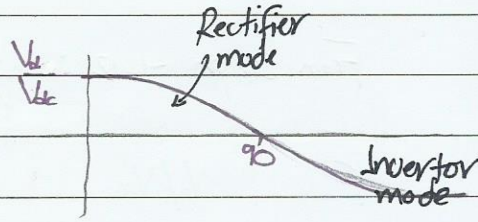
$$V_o = \frac{2V_m}{\pi}\cos\alpha \qquad I_o = \frac{V_o - V_{dc}}{R}$$

$$P_{dc} = I_o V_{dc}$$

$$P = I^2_{RMS} R = I_o^2 R \quad \text{if } L \text{ is high.}$$

→ Average DC Output Voltage:

$$V_{dc} = \frac{2\sqrt{2}\, V_s \cos\alpha}{\pi}$$



assuming AC side inductance is zero

Note that Output can go -ve for $\alpha > 90$ [this mean -ve power flow ⇒ inversion].

• Example: $V = 120\ v,\ E = -110\ v,\ R = 0.5\Omega,\ L$ is large, $f = 60\ Hz,\ P_{\alpha} = 1000\ w$?!

$$I = \frac{1000}{110} = 9.09A$$

R تجاهلنا

$$V = 9.09 \times 0.5 - 110 = -105.5\ v$$

$$-105.5 = \frac{2V_m \cos\alpha}{\pi} \Rightarrow \alpha = 165.5.$$

$$P_s = 1000 - 9.09^2 (0.5) = 959\ w$$

$$P_R = 9.09^2 \times 0.5 = 41\ w$$

if thyristor not ideal $\Rightarrow V_{th} = 1v \therefore V_{th} = 2V$ since each time 2 thyr are Operating

$$V_s = -105.5 - 2 = -107.5$$

$$I_E = I_R = \frac{110 - 107.5}{0.5} = 5A.$$

we can change it value by changing α.

$$P_E = 5 \times 110 = 550\ w$$

$$P_{TH} = 5 \times 1 = 5\ w$$

$$P_{TH(total)} = 2.5 \times 5 = 10\ w$$

$$\therefore P_s = 550 - 10 - 5^2 \times 0.5 = 557.5\ w.$$

- Example: 240 Vrms, 60 Hz, $V_{dc} = 100$ V, $R = 5\,\Omega$, L is very large, Continuous

  $P_{dc} = 1000$ W, $\alpha = ?!$

  α is less than 90° because it's working as rectifier

  $\Rightarrow$ if $\alpha > 90^\circ$ it's inverter

$$I_o = \frac{1000}{100} = 10A$$

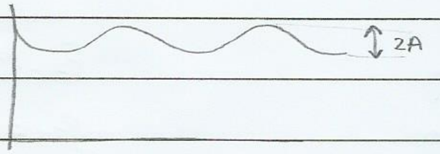
$$V_o = 10 \times 5 + 100 = 150$$

$$= \frac{2V_m}{\pi} \cos\alpha$$

$$150 = \frac{2 \times 240\sqrt{2}}{\pi} \cos\alpha \Rightarrow \alpha = 46^\circ$$

Find L that will limit peak to peak load current to 2A?

L is large but not very lage [not dc but there's a small ripple].



$$I_{2rms} = \frac{2}{2\sqrt{2}} = 0.707$$

harmonic

" fundamental

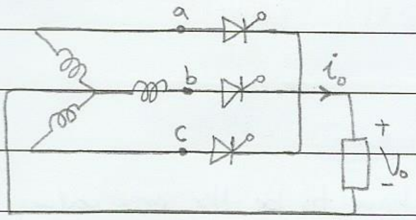
neglict the rest.

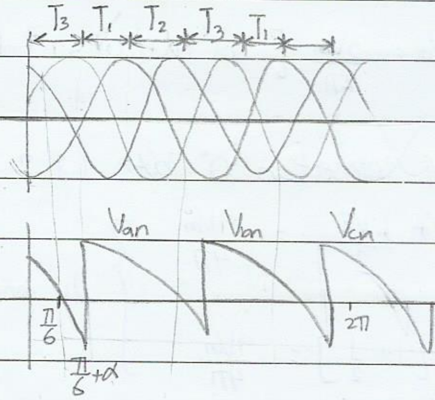
$\Rightarrow$ From the graph (4-12) $\Rightarrow \frac{V_2}{V_{rms}} = 0.68 = \frac{V_2}{240\sqrt{2}} \Rightarrow V_{2\,peak} = 230$ V

$$\Rightarrow \frac{230}{I_{peak}} = 230 = 2\pi \times 60 \times 2 \times L$$

$$\Rightarrow L = 0.31\ H.$$

Three Phase Controlled Rectifier :





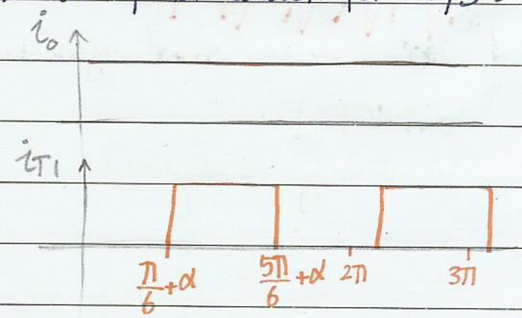
α مابناخدها من الصفر بناخدها من 30° من أول نقطة تقاطع.

كل فترة واحد راح يشتغل والباقين كله متوقف.

all of them are shifted by α

يعني بناخر Firing تبعهم بمقدار α

⇒ each thyristor conducts for $2\pi/3 = 120°$ ⇒ Constant load Current.



• Note :

$V_{RN} = v_{an} = V_m \sin(\omega t)$

$V_{YN} = v_{bn} = V_m \sin(\omega t - 120°)$

$V_{BN} = v_{cn} = V_m \sin(\omega t - 240)$.

T_1 triggered at $\omega t = \frac{\pi}{6} + \alpha = 30 + \alpha$

T_2 " " $\omega t = 150 + \alpha$

T_3 " " $\omega t = 270 + \alpha$

if the refrence voltage is $V_{RN} = v_{an} = V_m \sin(\omega t)$:

اشتقاقها موجود في السلايد ⇒ $V_{dc} = \frac{3}{2\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_m \sin \omega t \, d\omega t = \frac{3\sqrt{3}}{2\pi} V_m \cos\alpha = \frac{3 V_{Lm}}{2\pi} \cos\alpha$

max dc output voltage at $\alpha = 0$ ⇒ $V_{dc\,max} = \frac{3\sqrt{3}\, V_m}{2\pi}$

$$V_{rms} = \left(\frac{3}{2\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_m^2 \sin^2 \omega t \, d\omega t \right)^{1/2}$$

$$= \sqrt{3}\, V_m \left(\frac{1}{6} + \frac{\sqrt{3}}{8\pi} \cos 2\alpha \right)^{1/2}$$

3phase Half-wave Controlled Rectifier For RL load :

For $\alpha < 30 \Rightarrow V_{dc} = \frac{3\sqrt{3}\,V_m}{2\pi} \cos\alpha$ ... 1

For $\alpha > 30 \Rightarrow V_{dc} = \frac{3V_m}{2\pi}\left[\cos(\alpha + 30) + 1\right]$ ... 2

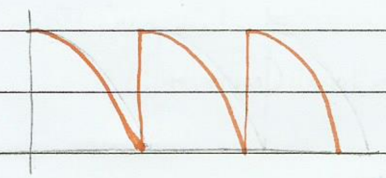
at point of intersection 30° both 1 & 2 must have to be the same value.

1 ... $\frac{3\sqrt{3}\,V_m}{2\pi} * \frac{\sqrt{3}}{2} = \frac{9V_m}{4\pi}$

2 ... $\frac{3V_m}{2\pi}\left[1 + \frac{1}{2}\right] = \frac{9V_m}{4\pi}$

the same value at $\alpha = 30^\circ$.

$\alpha = 30$

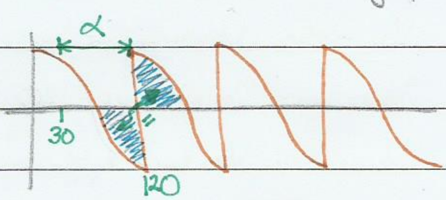


$\alpha = 60$

+ve avg. voltage

$\alpha = 90$

+ve avg. voltage



zero avg voltage

$\alpha > 90^\circ$

-ve avg. voltage

- *Example :* 3phase, 208V, 60Hz, $R = 10\Omega$ a. 90% of max V_{dc}, b = 50%

a. $V_m = \frac{208}{\sqrt{3}}\sqrt{2} = 169.83$

$\cos\alpha = 0.9 \Rightarrow \alpha = 25.84^\circ$.

since $\alpha < 30$, then $V_{dc} = \frac{3\sqrt{3}\,V_m}{2\pi}\cos = 126.4\,V$

$I_{dc} = 126.4/10 = 12.64A$.

$I_{rms} = \frac{\sqrt{3}\,V_m}{R}\left[1/6 + \frac{\sqrt{3}}{8}\cos 2\alpha\right]^{1/2} = 13.6A$.

$\eta = \frac{12.64^2 \times 10}{13.6 \times 10} = 88.1\,\%$, $TUF = \frac{12.64^2 \times 10}{3 \times \frac{208}{\sqrt{3}} \times 13.6} = 0.564$

b. $V_{dc} = \frac{3V_m}{2\pi}(1+\cos(\alpha+30)) = \frac{3\sqrt{3}\,V_m}{2\pi}\cos\alpha$

$\frac{3\times 169.83}{2\pi}(1+\cos(\alpha+30)) = \frac{3\sqrt{3}}{2\pi}\times 169.83\times 0.5$

$\Rightarrow \alpha = 67.7$

$\Rightarrow V_{rms} = \sqrt{3}\,V_m\left[\frac{5}{24} - \frac{\alpha}{4\pi} + \frac{1}{8\pi}\sin\left(\frac{\pi}{3}+2\alpha\right)\right]^{1/2} = 94.74\text{V}.$

$V_{dc} = \frac{3\times 169.83}{2\pi}(1+\cos(\alpha+30)) = 70.23$

$I_{dc} = \frac{70.23}{10} = 7.023$

$I_{dc\,TH} = \frac{7.023}{3} = 2.34$

$I_{rms} = 94.74/10 = 9.474.$

$I_{rms\,TH} = 9.474/\sqrt{3} = 5.47$

$\eta = \frac{7.023^2\times 10}{9.474^2\times 10} = 54.95\%$

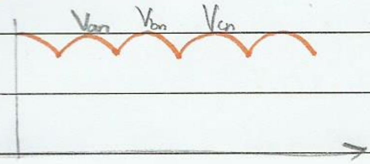
$TUF = \frac{7.023^2\times 10}{3\times\frac{208}{\sqrt{3}}\times 5.47} = 25\%$

$PF = \frac{9.494^2\times 10}{3\times\frac{208}{\sqrt{3}}\times 5.47} = 0.455.$

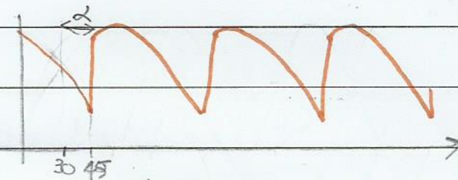
22th/Apr/2014 Tuesday

lecture 26

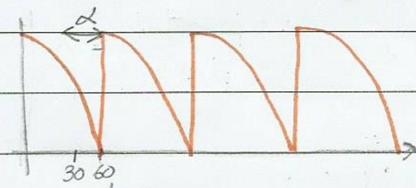
→ 3 phase Half-wave Controlled with R-L & FWD: no -ve parts.



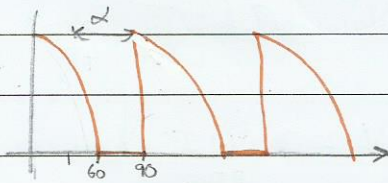
$\alpha = 0$



$\alpha = 15$



$\alpha = 30$



$\alpha = 60$

↳ more than 30° there's no -ve parts "it's zero" because it's resistive & after 30° there's no current " no current from the other thyristor until 90°..

⇒ BUT, at Free wheeling it won't be like this because after the 1st thyristor stop working "after 30°" the free wheeling diode will work.

T_1 conducts from $(30+\alpha)$ to 180 ⇒ $V_o = V_m \sin(\omega t) = V_{an}$

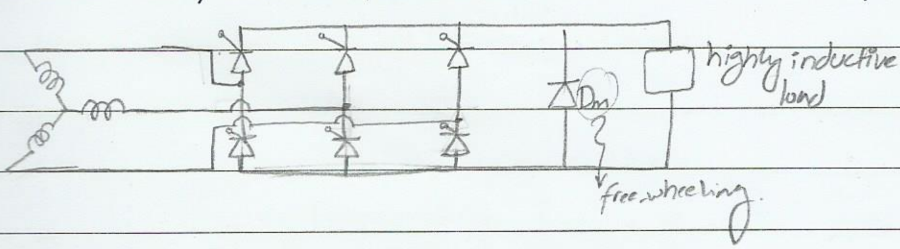
T_2 " " $(150+\alpha)$ to 300 ⇒ $V_o = V_m \sin(\omega t - 120) = V_{bn}$

T_3 " " $(270+\alpha)$ to 420 ⇒ $V_o = V_m \sin(\omega t - 240) = V_{cn}$

$$\Rightarrow V_{dc} = \frac{3}{2\pi}\int_{30+\alpha}^{180} V_o \, d\omega t = \frac{3V_m}{2\pi}\left[1 + \cos(\alpha + 30)\right]$$

→ Three phase Semi-Converter: ≡ half Controlled bridge converter.

each period one of the diode is on ⇒ which will prevent the -ve.



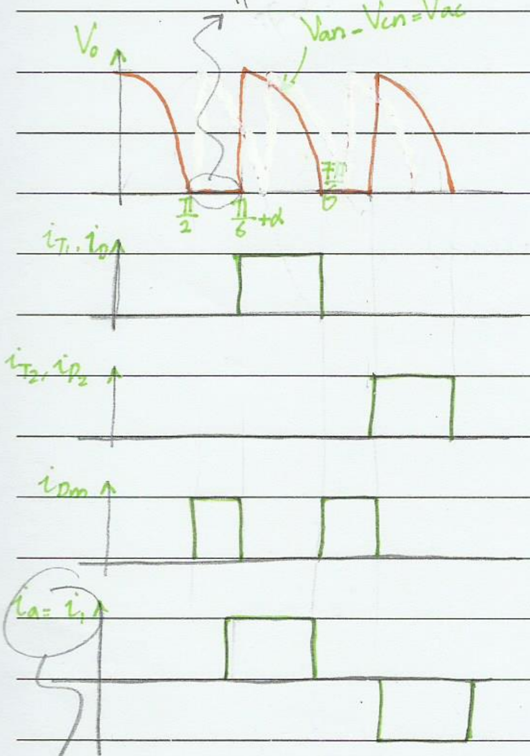
power Factor decrease as the delay angle increase.

power Factor is better than that of 3 phase half-wave Converter..

if $\alpha < 60 \Rightarrow$ Continuous

if $\alpha > 60 \Rightarrow$ zero because there's no (-ve)

• Note that load voltage is line to line Not phase volt.

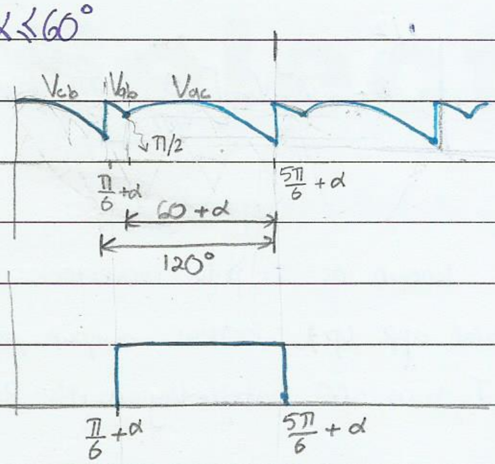


if the load is highly inductive, then the output is almost DC ⇒ the DC is seperated between D_1 & D_3 while D_m Complete the parts that there's no diode Operating.

في سلايدات ضيفهم قوانين و طبق خاصين

doubled current (in +ve & -ve), to calculate it ⇒ $\underline{\underline{\sqrt{2}\, I_s}}$

for $\alpha \leqslant 60°$



if

D_2 From $\frac{7\pi}{6}$ to $\frac{11\pi}{6}$; T_2 from $\frac{5\pi}{6} + \alpha$ to $\frac{9\pi}{6} + \alpha$

D_3 From 0 to $\frac{\pi}{2}$; T_3 from $\frac{9\pi}{6} + \alpha$ to $2\pi + \alpha$

D_1 From $\frac{\pi}{2}$ to $\frac{7\pi}{6}$, T for $\alpha > 60$ → Discontinuous Output :

$$V_{dc} = \frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{7\pi/6} \sqrt{3}\, V_m \sin\left(\omega t - \frac{\pi}{6}\right) d\omega t$$

$$\Rightarrow V_{dc} = \frac{3\sqrt{3}}{2\pi} V_m (1+\cos\alpha) = \frac{3 V_{mL}}{2\pi}(1+\cos\alpha).$$

max DC output at $\alpha = 0 \Rightarrow V_{dc} = \frac{3\sqrt{3}\, V_m}{\pi}$

$$\Rightarrow V_{rms} = \left[\frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{7\pi/6} V_{ac}^2 \, d\omega t\right]^{1/2}$$

$$= \sqrt{3}\, V_m \left[\frac{3}{4\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right]^{1/2}$$

for $\alpha < 60$ → Continuous:

$$V_{dc} = \frac{3}{2\pi}\left[\int_{\frac{\pi}{6}+\alpha}^{\pi/2} V_{ab}\, d\omega t + \int_{\pi/2}^{\frac{5\pi}{6}+\alpha} V_{ac}\, d\omega t\right] = \frac{3\sqrt{3}}{2\pi} V_m (1+\cos\alpha).$$

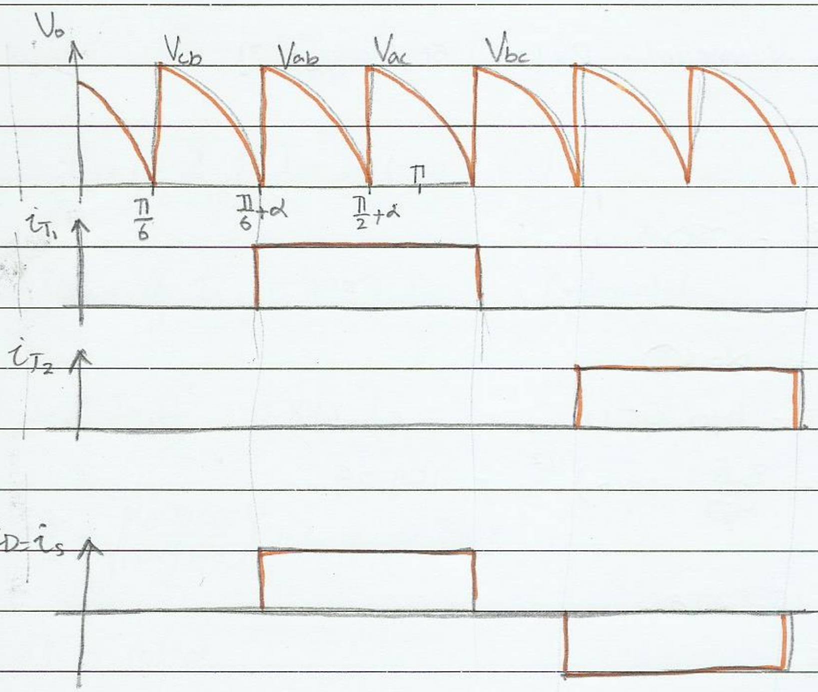
$$V_{rms} = \left[\frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\pi/2} V_{ac}^2\, d\omega t + \int_{\pi/2}^{\frac{5\pi}{6}+\alpha} V_{ac}^2\, d\omega t\right]^{1/2} = \sqrt{3}\, V_m \left[\frac{3}{4\pi}\left(\frac{2\pi}{3} + \sqrt{3}\cos^2\alpha\right)\right]^{1/2}$$

→ Three phase Full Converter : known as six pulse converter, used in industrial app. up to 120KW output power.

→ T_2 triggered at $\frac{\pi}{2}+\alpha$, T_6 turn off naturally as it's RB as soon as T_2 is triggered.

Thyristor Sequence of triggering :

12, 23, 34, 45, 56, 61, 12, 23, ...



i_o is constant

- Thyristor are triggered at interval of $\pi/3$
- the frequency of output ripple voltage is $6f_s$

$$V_{o(dc)} = \frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\pi/2+\alpha} v_o \, d\omega t$$

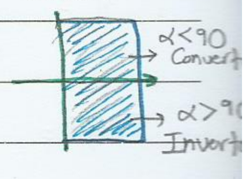
$$v_o = v_{ab} = \sqrt{3}\, V_m \sin\left(\omega t + \frac{\pi}{6}\right)$$

$$\Rightarrow V_{dc} = \frac{3\sqrt{3}}{\pi} V_m \cos\alpha = \frac{3 V_{mL}}{\pi} \cos\alpha$$

- $\alpha > 90 \rightarrow -ve$
- $\alpha < 90 \rightarrow +ve$
- $\alpha = 0 \rightarrow$ diode.

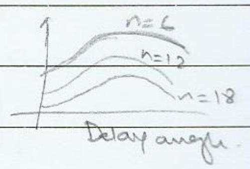
inverter OR converter

$$V_{rms} = \left(\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_o^2 \, d\omega t\right)^{1/2} = \sqrt{3}\, V_m \left(\frac{1}{2} + \frac{3\sqrt{3}}{4\pi} \cos 2\alpha\right)^{1/2}$$



- Note: increasing α will increase harmonic
  - $\Rightarrow$ min α is 6^{th} harmonic
  - max α is 18^{th} harmonic

$\Rightarrow$ Use the graph



Thursday 24th/Apr/2014

lecture 27

- Example : $V = 208\,v$, $60\,Hz$, Y connected, $R = 10\Omega$, 50% output ?!

$$V_m = \frac{208\sqrt{2}}{\sqrt{3}} = 169.83\ v$$

$$V_{dc(max)} = \frac{3\sqrt{3}\ 169.83}{\pi} = 280.9\ v.$$

$$\cos\alpha = 0.5 \Rightarrow \alpha = 60$$

$$V_{dc} = 280.9 \times 0.5 = 140.45\,V$$

$$V_{rms} = \sqrt{3}\,V_m\left(\frac{1}{2} + \frac{3\sqrt{3}}{4\pi}\cos\alpha\right)^{1/2} = 159.29.$$

$$I_{rms} = 159.29/10 = 15.929\,A.$$

each thyristor : $I_{dc}/\sqrt{3}$

$$I_{THDC} = \frac{14.045}{3} = 4.68\,A.$$

$$I_{THRMS} = \frac{15.929}{\sqrt{3}} = 9.2\,A.$$

$$I_s = 9.2\sqrt{2} = 13\,A.$$

$$\eta = \frac{14.045^2 \times 10}{15.929^2 \times 10} = 77\%.$$

$$TUF = \frac{14.045^2 \times 10}{\sqrt{3} \times 208 \times 9.2} = 0.421$$

$$PF = \frac{15.929^2 \times 10}{\sqrt{3} \times 208 \times 9.2} = 0.542\ \text{lags.}$$

- Now in the case of Highly Inductance :

$$a_0 = 0$$

$$a_n = \frac{1}{\pi}\left[\int_{\frac{\pi}{6}+\alpha}^{5\pi/6+\alpha} I_a \cos n\omega t\, d\omega t - \int_{\frac{7\pi}{6}+\alpha}^{11\pi/6+\alpha} I_a \cos n\omega t\, d\omega t\right]$$

$$= \left\{\begin{array}{ll} -4\,I_a \sin\frac{n\pi}{3}\sin n\alpha & n = 1, 3, 5, \ldots \\ 0 & n = 2, 4, 6, \ldots \end{array}\right] *$$

$$b_n = \frac{1}{\pi}\left[\int_{\frac{\pi}{6}+\alpha}^{5\pi/6+\alpha} \sin n\omega t\, d\omega t - \int_{\frac{7\pi}{6}+\alpha}^{11\pi/6+\alpha} I_a \sin n\omega t\, d\omega t\right]$$

$$= 4\,\frac{I_a}{n\pi}\sin\frac{n\pi}{3}\cos n\alpha \rightarrow *$$

$$I_{sn} = \frac{1}{\sqrt{2}} \sqrt{a_n^2 + b_n^2} = \frac{2\sqrt{2}\, I_a}{n\pi} \sin \frac{n\pi}{3}$$

$$\therefore i_s(t) = \sum_{n=1,5,7,\ldots} \sqrt{2}\, I_{sn} \sin(n\omega t + \phi_n).$$

$\Rightarrow I_{s1} = \frac{\sqrt{6}}{\pi} I_a = 0.7797\, I_a$;; fondemantel ..

$$I_s = I_a \sqrt{\frac{2}{3}} = 0.8165\, I_a$$

$$\Rightarrow HF = \sqrt{\left(\frac{0.81655}{0.7797}\right)^2 - 1} = 0.3108.$$

$$DF = \cos \alpha$$

$$PF = \frac{0.7797}{0.8165} \times \cos \alpha .$$ #

- Power Factor Improvement:

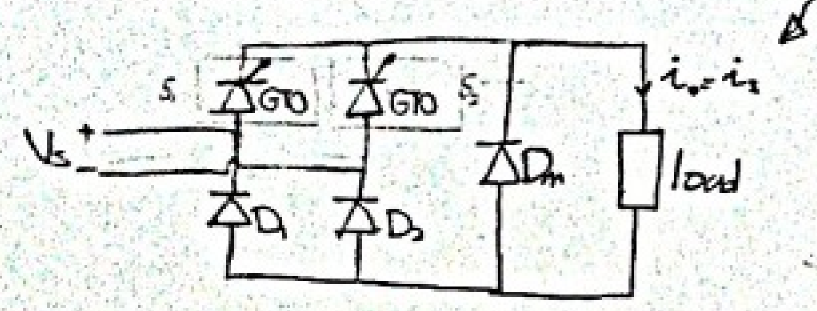
→ Extinction angle control

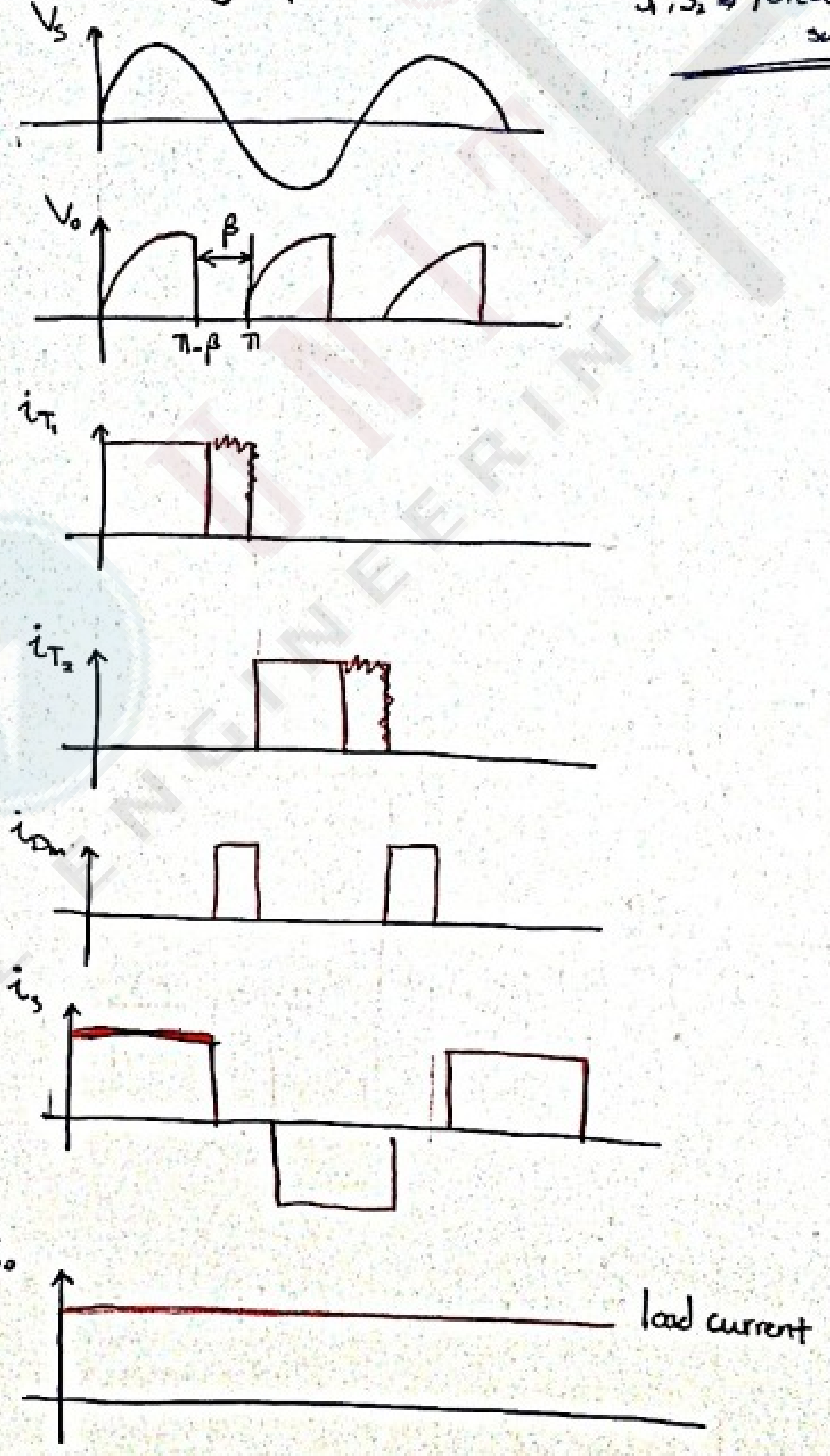
→ Symmetrical angel Control

→ pulse width modulation (PWM).

↳ Extinction angle Control: ≡ semi-converter, Single phase

S_1, S_2 ⇒ Forced-commutated switches.





$$V_{dc} = \frac{2}{2\pi}\int_0^{\pi-\beta} V_m \sin \omega t \, d\omega t = \frac{V_m}{\pi}(1+\cos\beta)$$

$$V_{rms} = \left[\frac{2}{2\pi}\int_0^{\pi-\beta} V_m^2 \sin^2 \omega t \, d\omega t\right]^{1/2}$$

$$= \frac{V_m}{\sqrt{2}}\left[\frac{1}{\pi}\left(\pi - \beta + \frac{\sin 2\beta}{2}\right)\right]^{1/2}$$

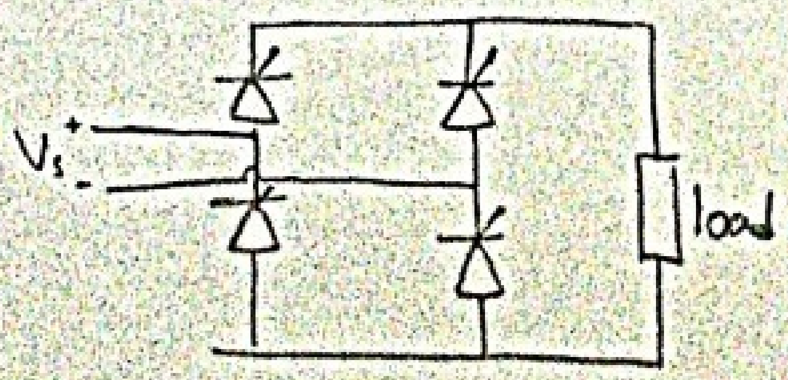
- the switching action of S_1 & S_2 can be performed by GTO [gate turn-OFF thyristor], the characterstic of GTOs can be turned on by applying short positive pulse to its gate as in case of normal thyristor, & turned off by applying short negative impluse to its gate.

⇒ the extinction angle control, S_1 & S_2:

S_1: turned on at $\omega t = 0$, turned OFF at $\omega t = \pi - \beta$

S_2: turned on at $\omega t = \pi$, turned off at $\omega t = 2\pi - \beta$

Full convertor ⇒ 4 GTO's [we get rid of the FWD 'Dm'].



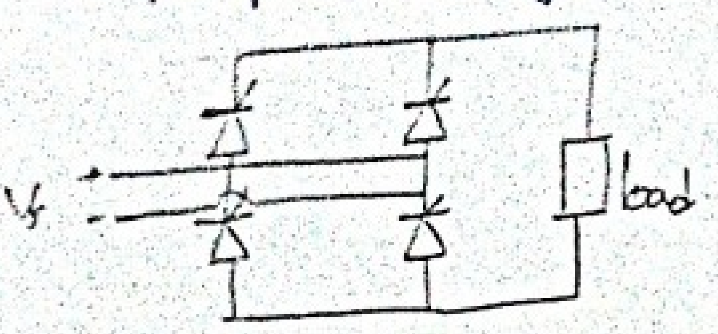
⇒ 2 GTO's works at a time.

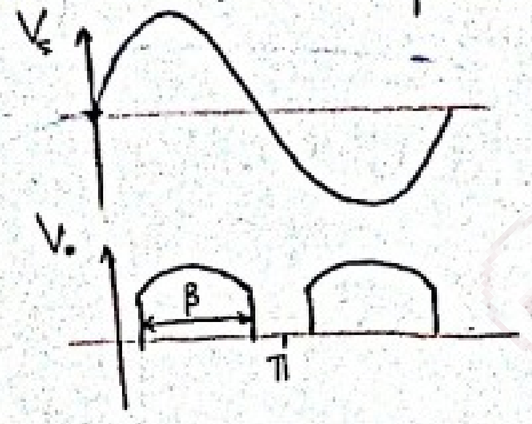
Note:

↳ check out the slide for sketches

↳ Symmetrical Angle Control: ≡ semi-converter with Free wheeling diode:

The symmetrical angle control allows one quadrant operation





$$V_{dc} = \frac{2}{2\pi}\int_{\frac{\pi-\beta}{2}}^{\frac{\pi+\beta}{2}} V_m \sin\omega t \, d\omega t = \frac{2V_m}{\pi}\sin\frac{\beta}{2}$$

$$V_{rms} = \frac{2}{2\pi}\int_{\frac{\pi-\beta}{2}}^{\frac{\pi+\beta}{2}} V_m^2 \sin^2\omega t \, d\omega t = \frac{V_m}{\sqrt{2}}\left[\frac{1}{\pi}(\beta + \sin\beta)\right]^{1/2}$$

→ Express the input current in Fourier series;

$$i_s(t) = I_{dc} + \sum_{n=1,2,\dots}^{\infty} a_n \cos n\omega t + b_n \sin n\omega t$$

$$a_0 = \frac{1}{2\pi}\int_{\frac{\pi-\beta}{2}}^{\frac{\pi+\beta}{2}} I_0 \, d\omega t - \frac{1}{2\pi}\int_{\frac{3\pi-\beta}{2}}^{\frac{3\pi+\beta}{2}} I_0 \, d\omega t = 0 \qquad a_n = \frac{1}{\pi}\int_0^{2\pi} i_s(t)\cos n\omega t \, d\omega t = 0$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} i_s(t)\sin n\omega t \, d\omega t = \frac{4I_a}{n\pi}\sin\frac{n\beta}{2} \quad \text{For } n \text{ odd}$$

$$= 0 \quad \text{For } n \text{ even}$$

$$\Rightarrow i_s(t) = \sum_{n=1,3,\dots}^{\infty} \sqrt{2}\, I_n \sin(n\omega t + \phi_n) \qquad \phi_n = \tan^{-1}\frac{a_n}{b_n} = 0$$

The rms value of the n^{th} harmonic input: $I_{sn} = \frac{1}{\sqrt{2}}(a_n^2 + b_n^2)^{1/2} = \frac{2\sqrt{2}}{n\pi} I_a \sin\frac{n\beta}{2}$

The rms value of the fundamental: $I_{s1} = \frac{2\sqrt{2}}{\pi} I_a \sin\frac{\beta}{2}$

The rms input current: $I_s = I_a\sqrt{\frac{\beta}{\pi}}$

$$HF = \left[\left(\frac{I_s}{I_{s1}}\right)^2 - 1\right]^{1/2}$$

$$DF = \cos\phi_1 = 1$$

$$PF = \left(\frac{I_{s1}}{I_s}\right) DF$$

↳ if $\beta = \frac{\pi}{3}$, $DF = 1$: Find V_{rms}, I_{s1}, I_s, HF, PF ?! $V_m = 169.83$

$$V_{rms} = \frac{V_m}{\sqrt{2}}\left[\frac{1}{\pi}(\beta + \sin\beta)\right]^{1/2} = \frac{169.83}{\sqrt{2}}\left[\frac{1}{\pi}\left(\frac{\pi}{3} + \sin 60\right)\right]^{1/2} = 93.72\ V$$

$$V_{dc} = \frac{2V_m}{\pi}\sin\frac{\beta}{2} = \frac{2 \times 169.83}{\pi}\sin 30 = 54.06\ V$$

$$I_s = I_a\sqrt{\frac{\beta}{\pi}} = 0.5774\, I_a$$

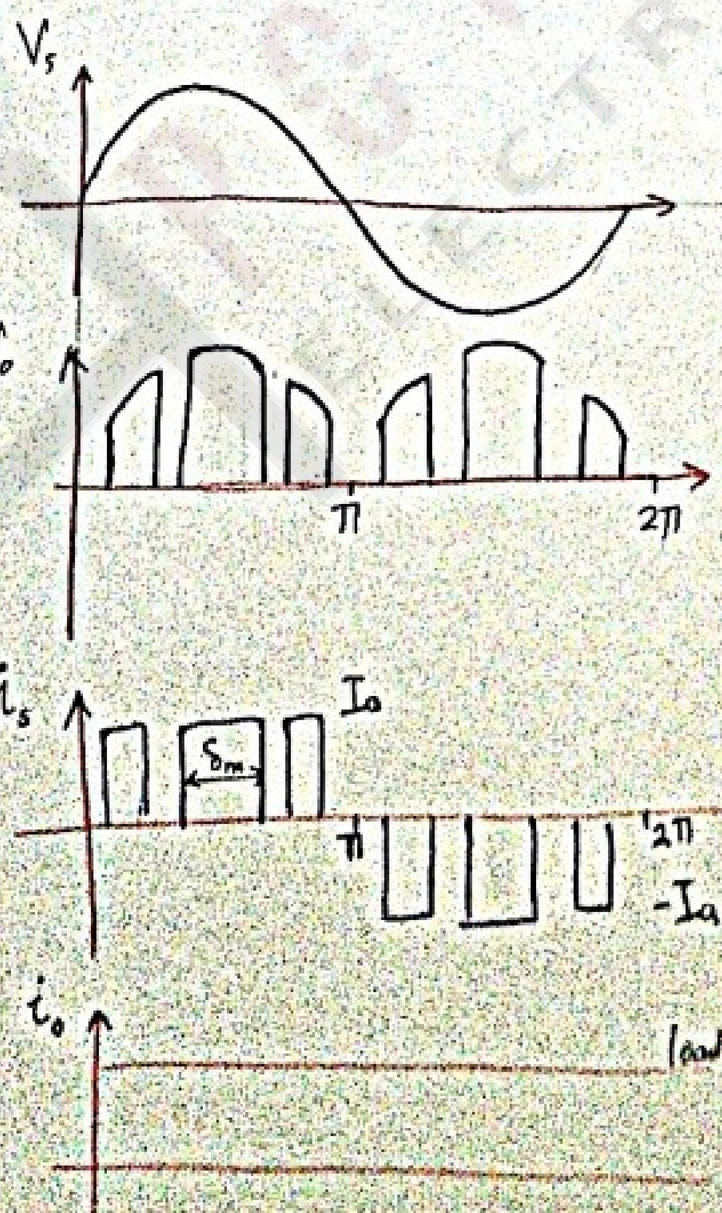
$$I_{s1} = \frac{2\sqrt{2}}{n\pi} I_a \sin\frac{n\beta}{2} = \frac{2\sqrt{2}}{\pi} I_a \sin\frac{\beta}{2} = 0.4502\ I_a.$$

$$\Rightarrow HF = \left[\left(\frac{I_s}{I_{s1}}\right)^2 - 1\right]^{1/2} = 0.803$$

$$PF = \left(\frac{I_{s1}}{I_s}\right) DF = 0.7797 \text{ lagging}$$ #

↳ Pulse Width Modulation :

If the output voltage of a single phase semi- or full converters is controlled by varying the delay angle, extinction angle or symmetrical angle, there's only one pulse per half cycle and as a result the lowest order harmonic is the third. In pulse width modulation, the converter switches are turned on and off several times during a half-cycle.



$$V_{dc} = \sum_{m=1}^{p} \frac{2}{2\pi}\int_{\alpha_m}^{\alpha_m + \delta_m} V_m \sin\omega t \, d\omega t$$

$$= \frac{V_m}{\pi}\sum_{m=1}^{p}\left[\cos\alpha_m - \cos(\alpha_m + \delta_m)\right]$$

$$i_s(t) = A_0 + \sum_{n=1,3,\dots}^{\infty} A_n \cos n\omega t + B_n \sin n\omega t$$

$A_0 = \frac{V_m}{\pi}$, A_n: zero

$$B_n = \frac{1}{\pi}\int_0^{2\pi} i_s(t) \sin n\omega t \, d\omega t$$

For odd n $\Rightarrow$ $\frac{4 I_a}{n\pi}\sum \sin\left(\frac{2\delta_m}{4}\right)\left[\sin\left(n\left(\alpha_m + \frac{3\delta_m}{4}\right)\right) - \sin\left[n\left(\alpha_m + \frac{\delta_m}{4} + \pi\right)\right]\right]$

For even n $\Rightarrow$ zero

$$\Rightarrow i_s(t) = \sum_{n=1,3,\dots}^{\infty} \sqrt{2}\, I_n \sin(n\omega t + \phi_n)$$

$\phi_n = \tan^{-1}\frac{A_n}{B_n}$

$I_n = \frac{1}{\sqrt{2}}(A_n^2 + B_n^2)^{1/2} = \frac{B_n}{\sqrt{2}}$

↳ **Sinusoidal Pulse Width Modulation:** the same as pulse width modulation, but instead of comparing it with DC, compare it with a Full wave rectifier sinusoidal.

يكون عنا قطع قطع في الفتح
فيكون في البداية والنهاية قليل و
في الوسط كبير.

- In a sinusoidal PWM control, the DF is unity & PF is improved, the lower order harmonics are eliminated or reduced, For example: with Four pulses per half cycle the lowest order harmonic is the fifth; and with six pulses per half cycle the lowest order harmonic is the seventh.

※ Modulation Index $\equiv M = \frac{A_c}{A_r}$

A_c: carrier voltage

A_r: refrence voltage

$0 < M < 1$

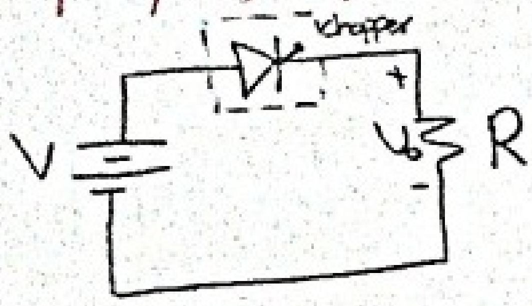
DC Chopper : [DC → DC] converter

- two types of Choppers :

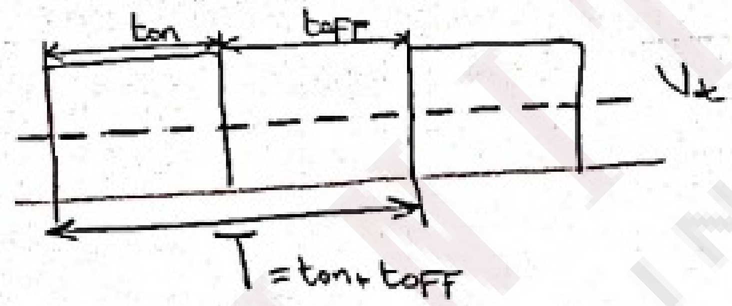
1. step-up :
$V_{out} \gg V_{in}$

2. step-Down :
$V_{out} < V_{in}$

→ principle of step-Down Chopper :



- the thyristor acts as a switch
  → when thyristor is ON ⇒ $V_o = V$
  → when thyristor is OFF ⇒ $V_o = 0$



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

Duty cycle ≡ D

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^{t_{ON}} V_o^2\,dt} = \sqrt{D}\,V$$

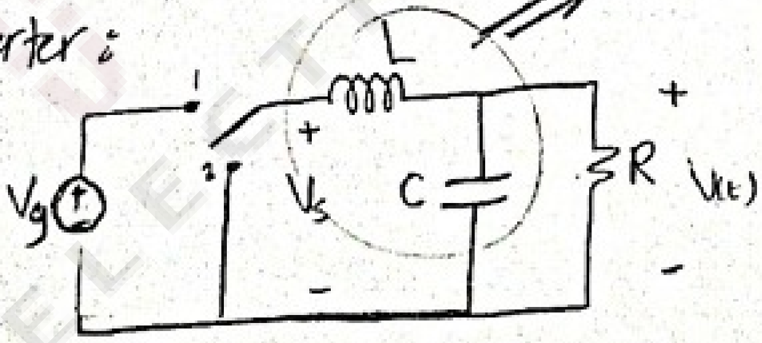
Note :
the output voltage can be varied by the duty cycle.

$$P_{output} = \frac{DV^2}{R}$$

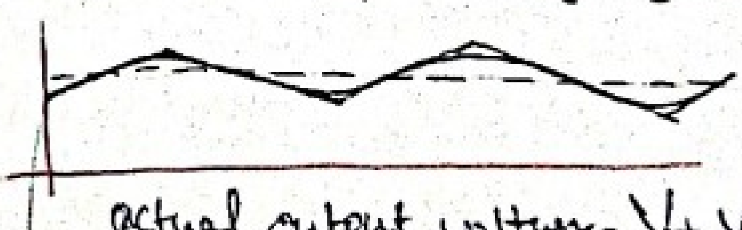
the effective input Resistance of chopper : $R_i = \frac{R}{D}$

- Basic DC to DC converter :

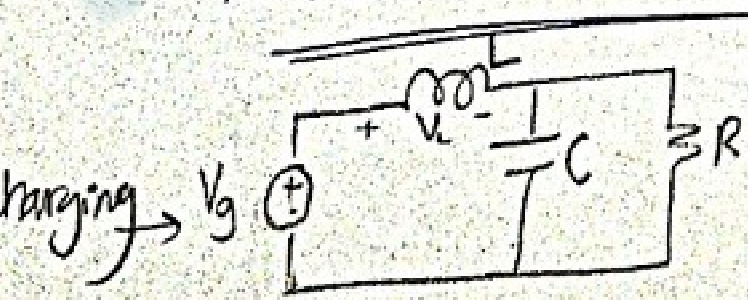
1. Buck Converter :



insertion of low pass Filter ⇒ to remove switching harmonic & pass only DC component



→ Buck converter analysis :

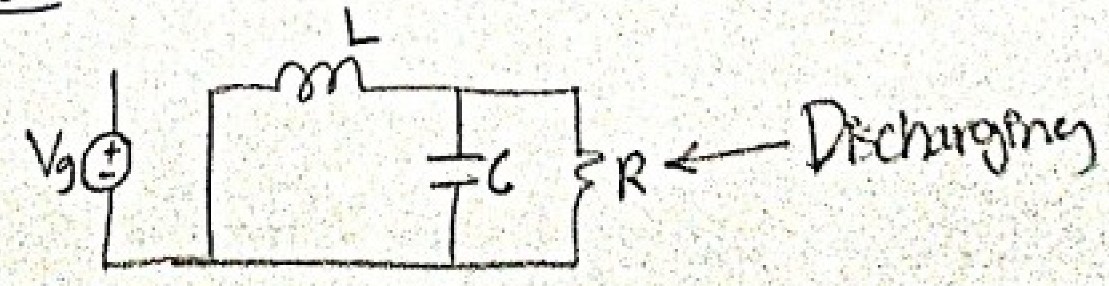


switch at position 1

$V_L = V_g - V(t)$

small ripple approximation : $V_L = V_g - V$

$$\Rightarrow V_L(t) = L\frac{di(t)}{dt} \Rightarrow di/dt = V_L(t)/L = (V_g - V)/L$$

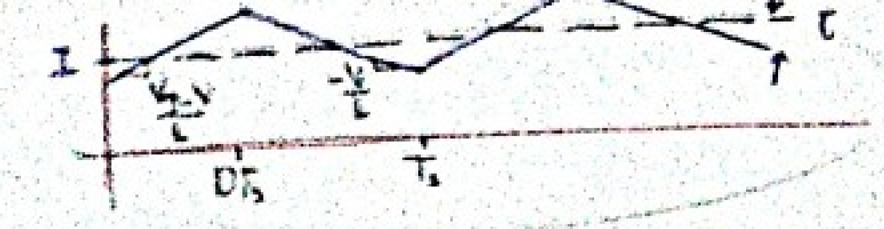


switch at position 2

$V_L = -V(t)$

small ripple approximation : ΔV

$$\Rightarrow \frac{di_L}{dt} = \frac{-V}{L}$$



transient

$$2\tau = \left(\frac{V_g - V}{L}\right)(DT_s)$$

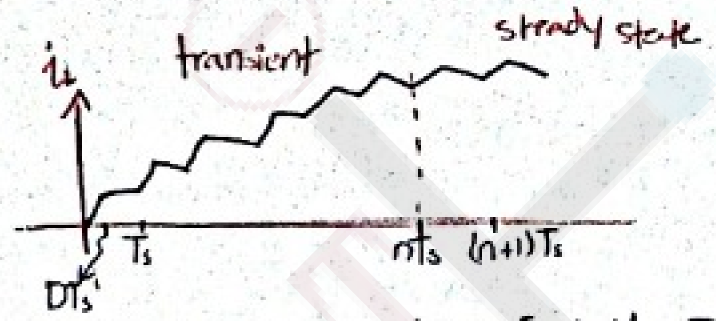
$$\Rightarrow \tau = \frac{V_g - V}{2L}(DT_s)$$

$$\Rightarrow L = \frac{V_g - V}{2\tau} DT_s$$

the inductance if we want a fixed ripple

→ when converter operates in equilibrium:

$i_L((n+1)T_s) = i_L(nT_s) \Rightarrow$ steady state

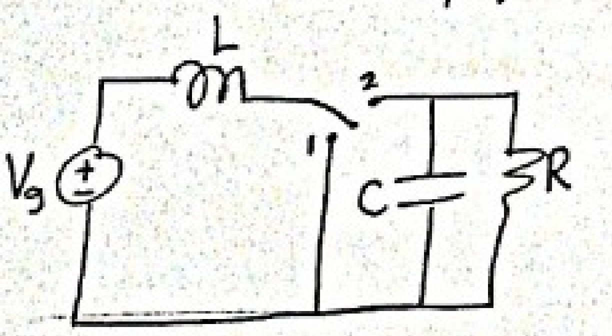


← المساحة تحت المنحنى هي "DQ" يعني هي الشحنة المخزنة في inductor

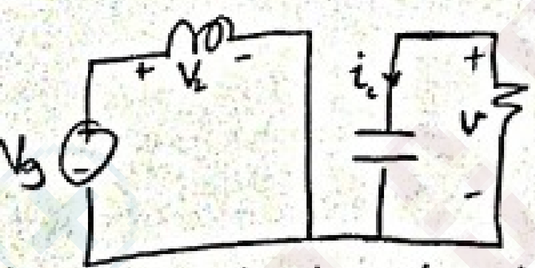
whenever the converter operates in steady state

→ total area (volt/sec) under the inductor voltage waveform is zero.

2. Boost Converter:



↳ Boost Converter analysis:



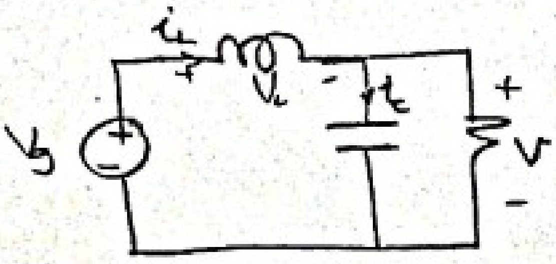
Charging

switch at position 1

$V_L = V_g$

$i_c = -\frac{V}{R}$

small ripple approximation: $V_L = V_g$



Discharging

switch at position 2

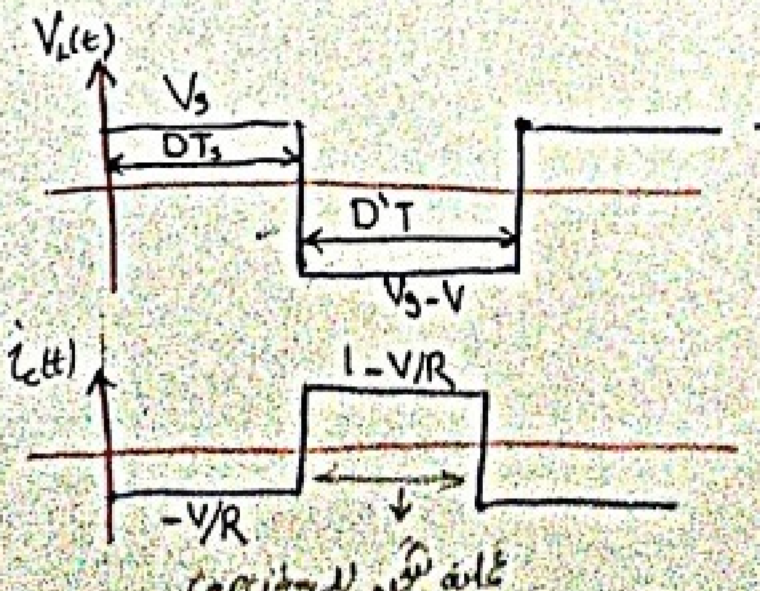
$V_L = V_g - v$

$i_c = i_L - \frac{v}{R}$

small ripple approximation: $V_L = V_g - V$

V: avg. value (const)

v: function of time



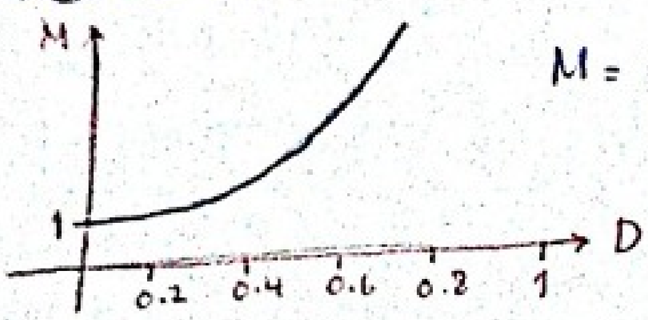
$\Rightarrow$ inductor volt/sec: $\int_0^{T_s} V_L(t)\,dt = V_g DT_s + (V_g - V)D'T_s = 0$

$$\Rightarrow V = \frac{V_g}{D'} = \frac{V_g}{1-D}$$

the voltage conversion ratio

$$M = \frac{V}{V_g} = \frac{1}{D'} = \frac{1}{1-D}$$

→ Conversion ratio M(D) of the boost Converter:



$$M = \frac{1}{D'} = \frac{1}{1-D}$$

"starts from zero → ∞"

- practically $D \neq 0$ & $D \neq 1$ ⇒ so M will never reach 1 or ∞, since the switch isn't ideal.

→ ~~Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM):~~

↳ Methods CF Control:

the output DC voltage can be varied by:

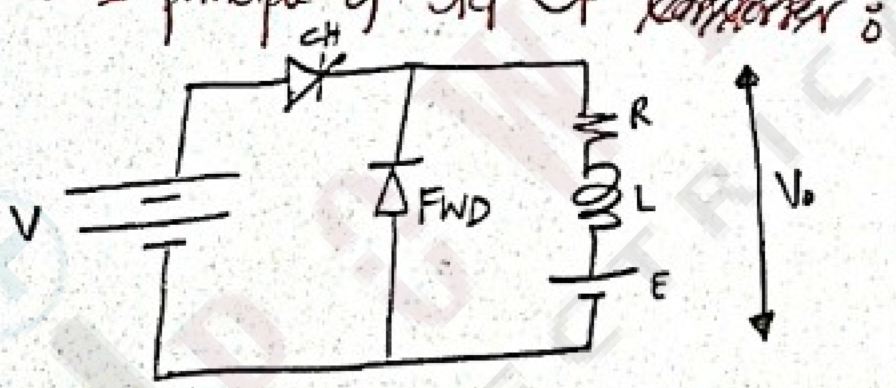
1. PWM control or constant frequency Operation
2. Variable frequency Control.

↳ 1. PWM: Output voltage is varied by varying the ON time.

↳ 2. Variable Frequency Control: • chopping freq. is varied keeping ton or toff constant.

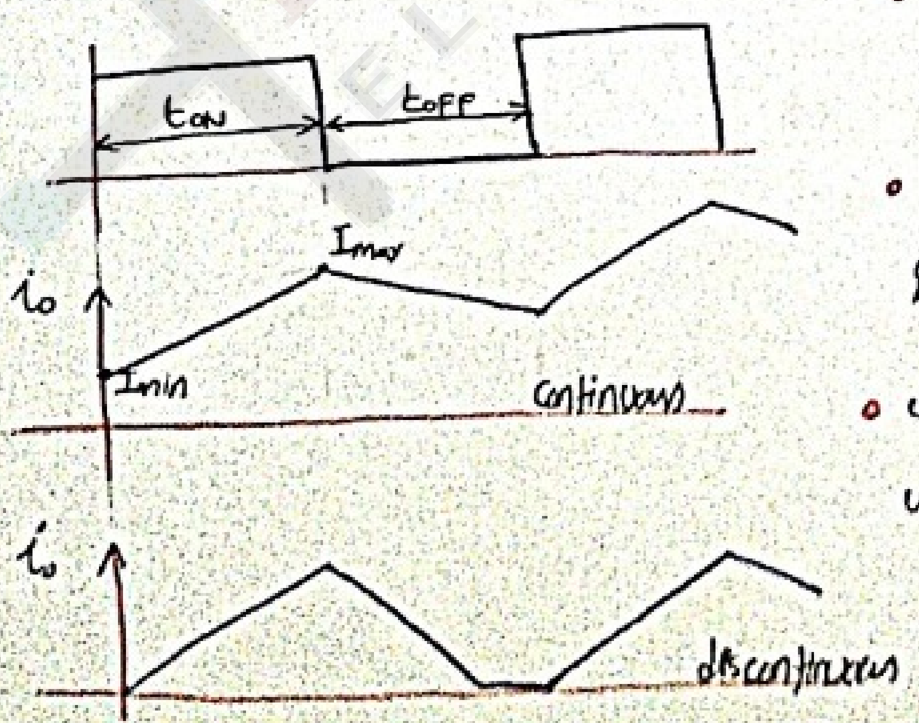
- to obtain full output voltage range ⇒ freq. has to be varied over a wide range.
- this method produces harmonic in the output & for large toff load current ⇒ it may be discontinuous.

→ principle of Step Up Chopper ~~Converter~~:

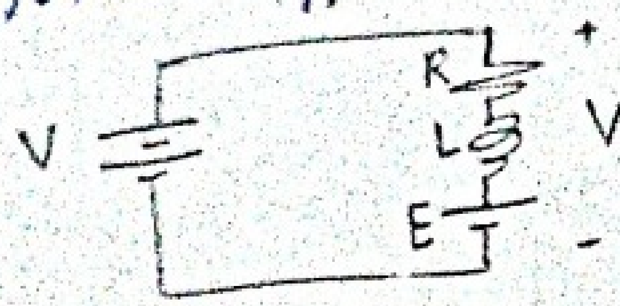


- when chopper is ON ⇒ supply is connected across the load current flows from supply → load.
- when chopper is off ⇒ load current continues flow in the same direction through FWD
- load current can be continues or Discontinues depends on: Value of L & Duty cycle.
- For Continuous current operation. load current varies between Imax & Imin
- when I = Imax ⇒ the Chopper turned off.

  when I reduces to Imin ⇒ chopper is ON.



↳ when Chopper is ON: $0 < t_{on} < t_{on}$



$$V = i_o R + L \frac{di_o}{dt} + E$$

⇒ taking laplace transform: $\frac{V}{S} = R I_o(s) + L[S I_o(s) + i_o^-] + \frac{E}{S}$

at $t=0$, $i_o(0^-) = I_{min}$:

$$I_o(s) = \frac{V - E}{LS(S + \frac{R}{L})} + \frac{I_{min}}{S + \frac{R}{L}}$$

↳ taking the Inverse:

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

↳ when chopper is OFF: $0 < t < t_{OFF}$

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

Check out the derivation

to find I_{max} & I_{min}:

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

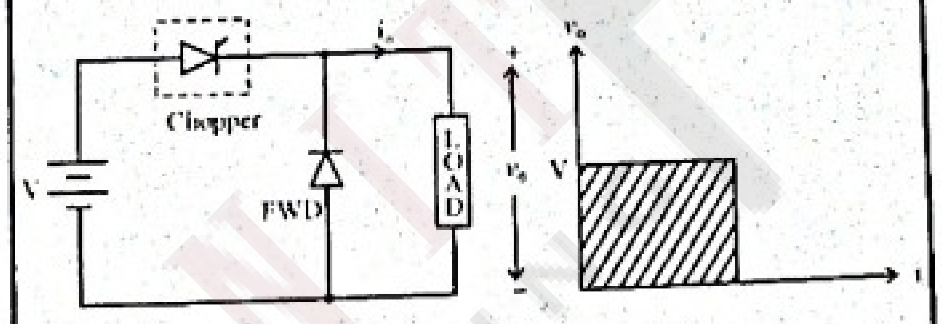
→ $(I_{max} - I_{min})$ known as steady state ripple.

$V_{dc} = VD$ $\qquad I_{dc} = \frac{I_{max} + I_{min}}{2}$ $\qquad \Delta I = I_{max} - I_{min}$

Classification Of Choppers

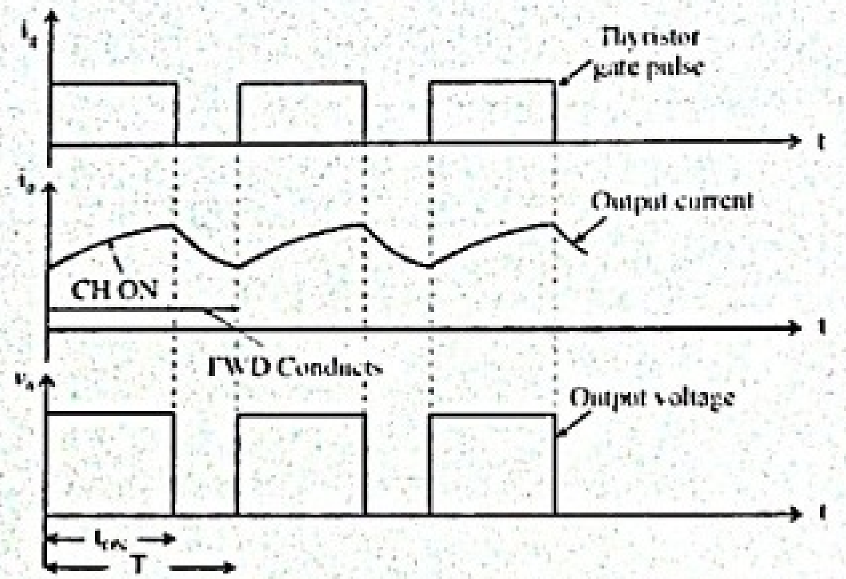
- Choppers are classified as
  - Class A Chopper
  - Class B Chopper
  - Class C Chopper
  - Class D Chopper
  - Class E Chopper

Class A Chopper

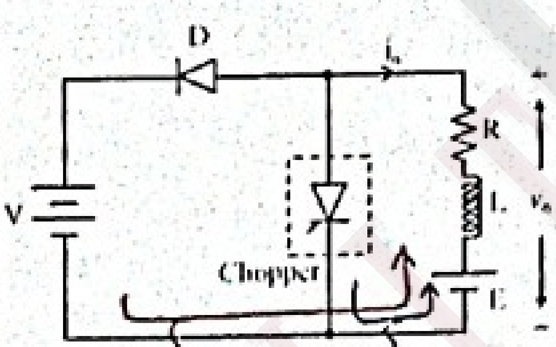


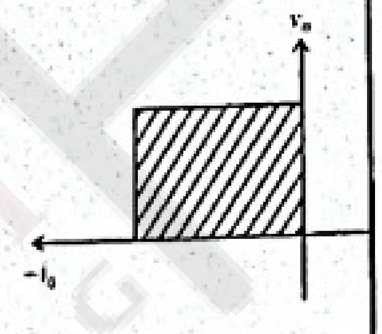
- When chopper is *ON*, supply voltage *V* is connected across the load.
- When chopper is OFF, $v_O = 0$ and the load current continues to flow in the same direction through the FWD.
- The average values of output voltage and current are always positive.
- *Class A Chopper* is a first quadrant chopper .

- *Class A Chopper* is a step-down chopper in which power always flows form source to load.
- It is used to control the speed of dc motor.
- The output current equations obtained in step down chopper with *R-L* load can be used to study the performance of *Class A Chopper.*



Class B Chopper



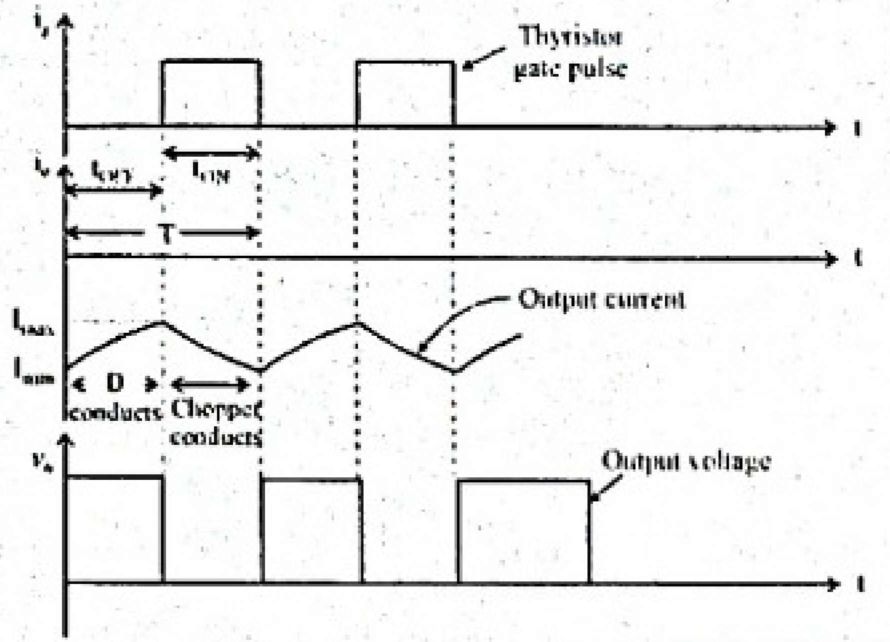


if chopper in OFF, stored power in L will be discharged and return to the source.

if chopper is ON → current always -ve & voltage +ve
→ then E will work as generator and keep the generated power in L

- When chopper is ON, *E* drives a current through *L* and R in a direction opposite to that shown in figure.
- During the ON period of the chopper, the inductance *L* stores energy.
- When Chopper is OFF, diode *D* conducts, and part of the energy stored in inductor *L* is returned to the supply.

- Average output voltage is positive.
- Average output current is negative.
- Therefore *Class B Chopper* operates in second quadrant.
- In this chopper, power flows from load to source.
- *Class B Chopper* is used for regenerative braking of dc motor. يخزنها في (L) ثم يعطيها إلى (source)
- *Class B Chopper* is a step-up chopper.



Expression for Output Current

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

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

For the initial condition i.e.,

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

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

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

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

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

During the interval chopper is ON voltage equation is given by

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

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

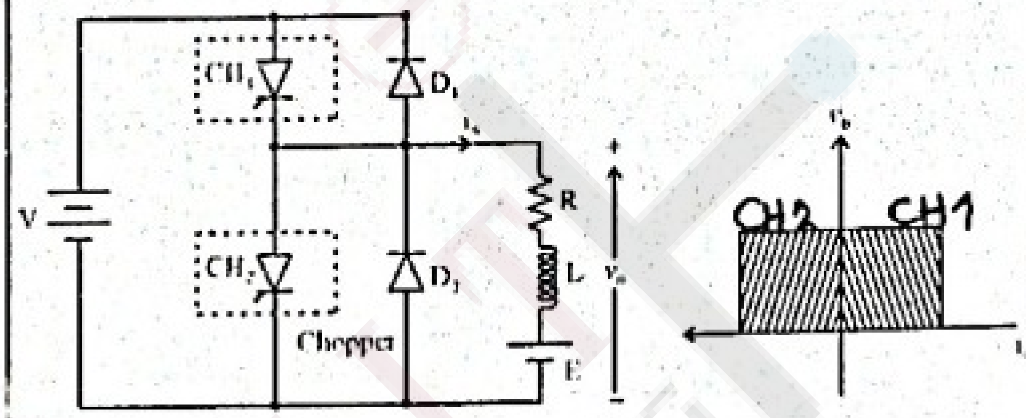
The solution for the stated initial condition is

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

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

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

Class C Chopper = class A + class B



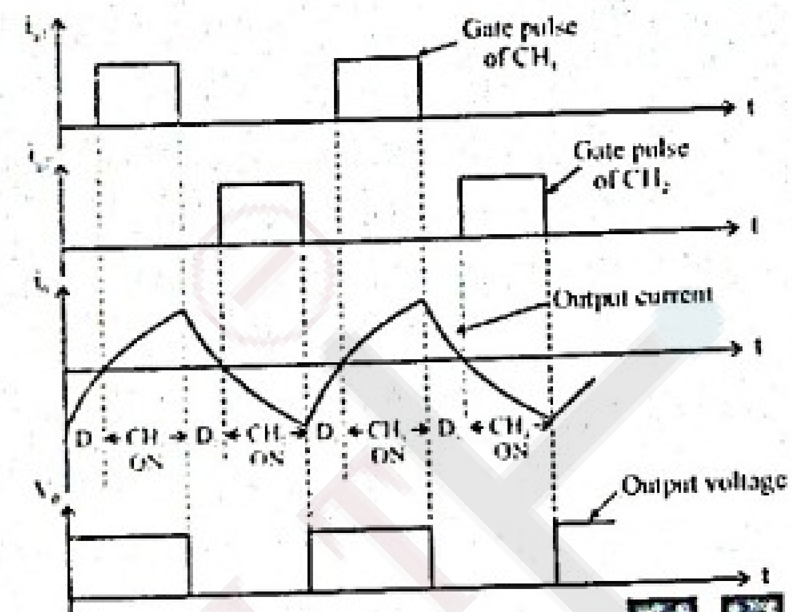
- *Class C Chopper* is a combination of *Class A* and *Class B Choppers.*
- For first quadrant operation, CH_1 is ON or D_2 conducts. class A
- For second quadrant operation, CH_2 is ON or D_1 conducts.
- When CH_1 is ON, the load current is positive.
- The output voltage is equal to 'V' & the load receives power from the source.
- When CH_1 is turned OFF, energy stored in inductance L forces current to flow through the diode D_2 and the output voltage is zero.

Free wheeling Diode

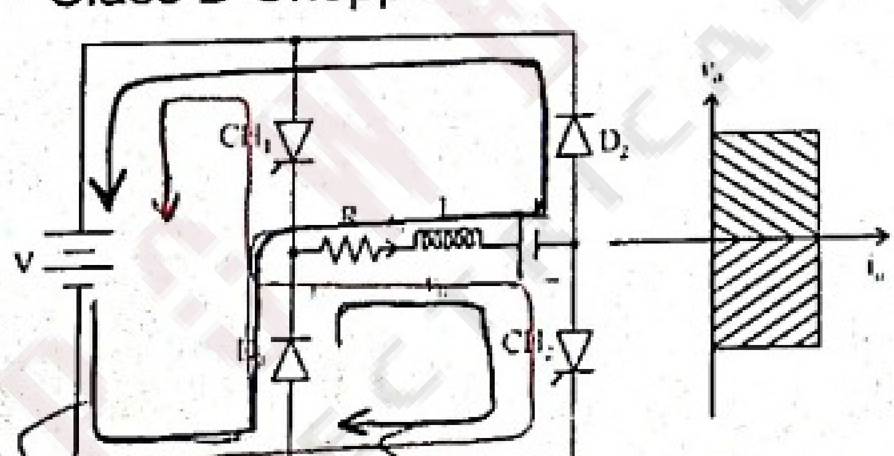
- Current continues to flow in positive direction.
- When CH_2 is triggered, the voltage E forces current to flow in opposite direction through L and CH_2.
- The output voltage is zero.
- On turning OFF CH_2, the energy stored in the inductance drives current through diode D_1 and the supply
- Output voltage is V, the input current becomes negative and power flows from load to source.

class C → class A : Motor
class B : Regenerator.

- Average output voltage is positive
- Average output current can take both positive and negative values.
- Choppers CH_1 & CH_2 should not be turned ON simultaneously as it would result in short circuiting the supply.
- *Class C Chopper* can be used both for dc motor control and regenerative braking of dc motor.
- *Class C Chopper* can be used as a step-up or step-down chopper.



Class D Chopper



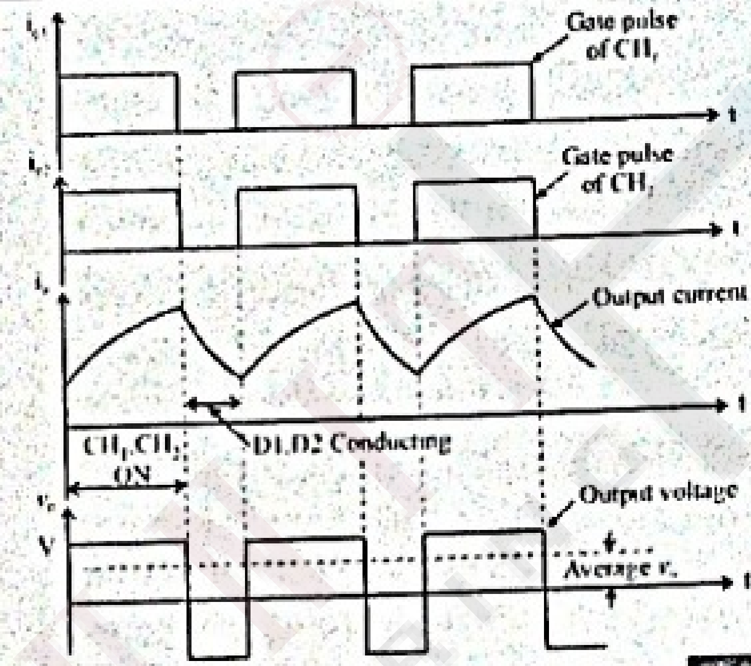
If CH1 is OFF

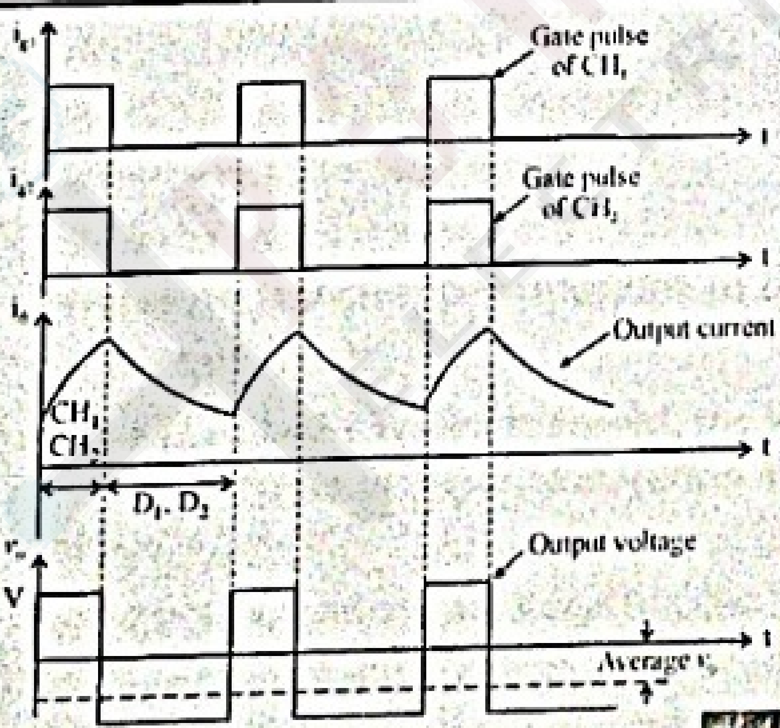
If CH1 & CH2 works at the same tim

If CH1 & CH2 are OFF ∴ voltage will be negative, current flows in the same direction as before.

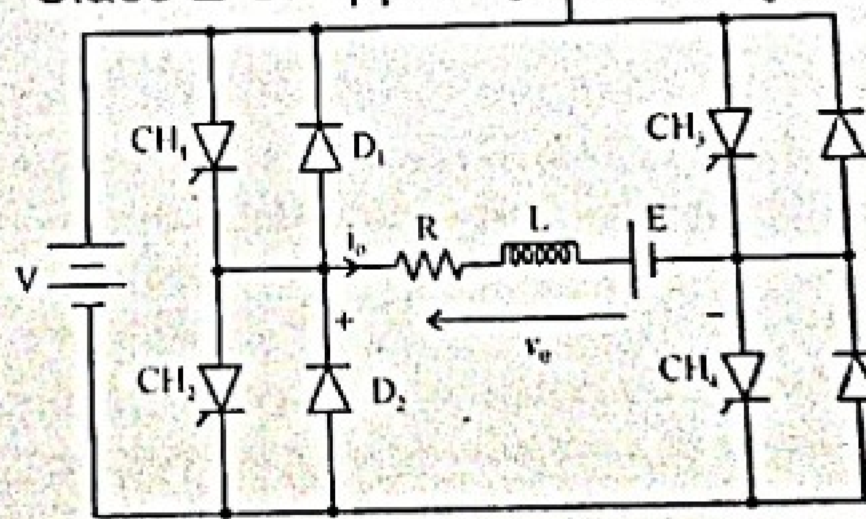
- Class D is a two quadrant chopper.
- When both CH_1 and CH_2 are triggered simultaneously, the output voltage $v_O = V$ and output current flows through the load.
- When CH_1 and CH_2 are turned OFF, the load current continues to flow in the same direction through load, D_1 and D_2, due to the energy stored in the inductor L.
- Output voltage $v_O = -V$.

- Average load voltage is positive if chopper ON time is more than the OFF time
- Average output voltage becomes negative if $t_{ON} < t_{OFF}$.
- Hence the direction of load current is always positive but load voltage can be positive or negative.





Class E Chopper comparation of class D & C



for each quadrant there are two equivalent ckts
→ so we have 8 equivalent.

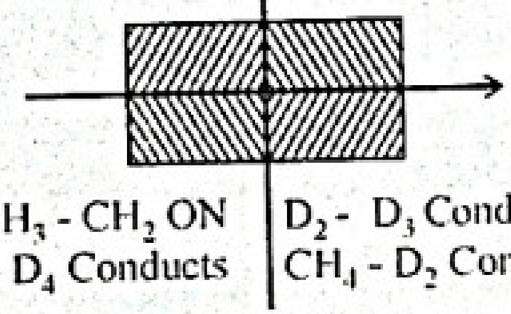
Four Quadrant Operation

v_0

+ve V
-ve I

CH_2 - D_4 Conducts
D_1 - D_4 Conducts

CH_1 - CH_4 ON +Ve I
CH_4 - D_2 Conducts +Ve V



i_0

-ve V
-ve I

CH_3 - CH_2 ON
CH_2 - D_4 Conducts

D_2 - D_3 Conducts -Ve V
CH_4 - D_2 Conducts +Ve I

Prof. T.K. Anantha Kumar, E&E Dept., MSRIT

1 and 3 are opposite

- Class E is a four quadrant chopper
- When CH_1 and CH_4 are triggered, output current i_O flows in positive direction through CH_1 and CH_4, and with output voltage $v_O = V$.
- This gives the first quadrant operation.
- When both CH_1 and CH_4 are OFF, the energy stored in the inductor L drives i_O through D_2 and D_3 in the same direction, but output voltage $v_O = -V$.

Prof. T.K. Anantha Kumar, E&E Dept., MSRIT

- Therefore the chopper operates in the fourth quadrant.
- When CH_2 and CH_3 are triggered, the load current i_O flows in opposite direction & output voltage $v_O = -V$.
- Since both i_O and v_O are negative, the chopper operates in third quadrant.

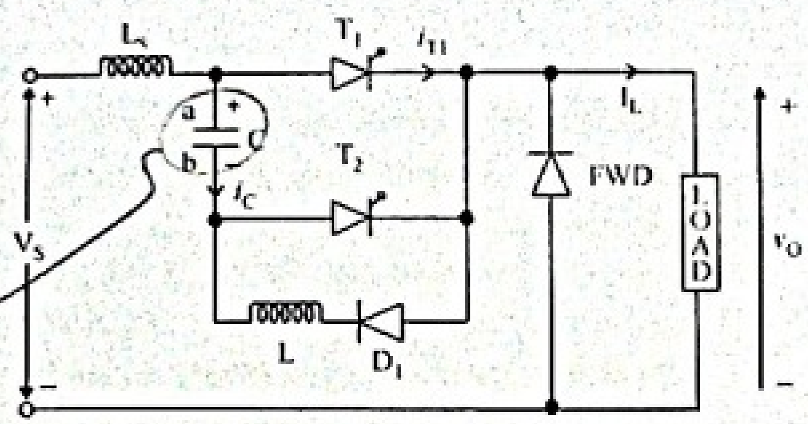
Prof. T.K. Anantha Kumar, E&E Dept., MSRIT

- When both CH_2 and CH_3 are OFF, the load current i_O continues to flow in the same direction D_1 and D_4 and the output voltage $v_O = V$.
- Therefore the chopper operates in second quadrant as v_O is positive but i_O is negative.

Prof. T.K. Anantha Kumar, E&E Dept., MSRIT

Impulse Commutated chopper :

⇒ a way to force the thyristor to stop.



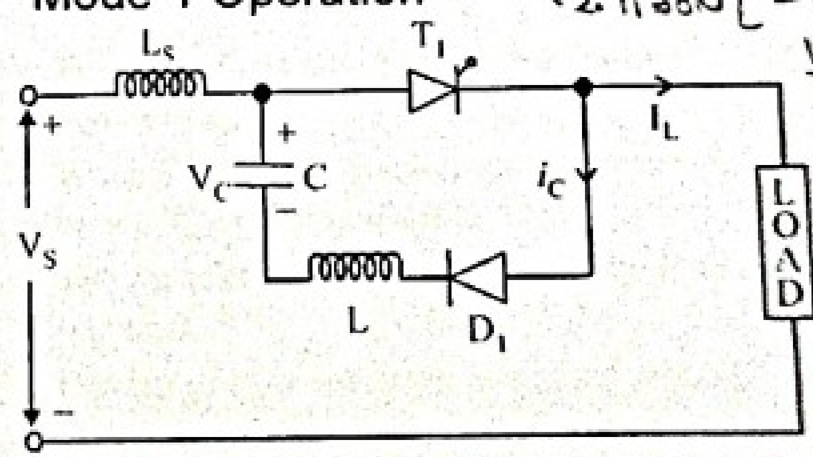
بيطلع تيار الذي زيه لإطفاء thyristor

- To start the circuit, capacitor *'C'* is initially charged with polarity (with plate 'a' positive) by triggering the thyristor T_2.
- Capacitor *'C'* gets charged through V_S, C, T_2 and load.
- As the charging current decays to zero thyristor T_2 will be turned-off.
- With capacitor charged with plate 'a' positive the circuit is ready for operation.
- Assume that the load current remains constant during the commutation process.

- For convenience the chopper operation is divided into five modes.
  - Mode-1
  - Mode-2
  - Mode-3
  - Mode-4
  - Mode-5

Mode-1 Operation

1. عكس شحنة الـcapacitor من خلال L
2. T_1 ON [لاتصال التيار — الى الـ load]



- Thyristor T_1 is fired at $t = 0$.
- The supply voltage comes across the load.
- Load current I_L flows through T_1 and load.
- At the same time capacitor discharges through T_1, D_1, L_1, & 'C' and the capacitor reverses its voltage.
- This reverse voltage on capacitor is held constant by diode D_1.

Capacitor Discharge Current

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

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

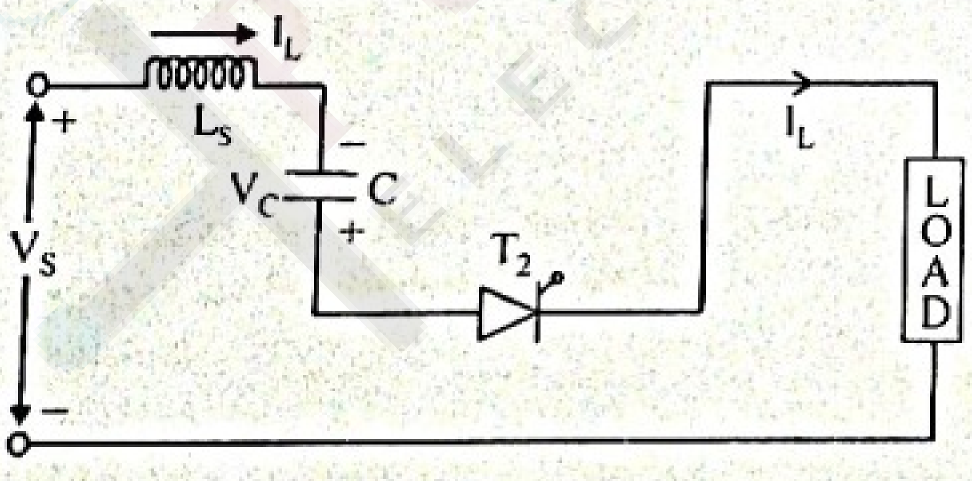
& Capacitor Voltage

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

mode 1 → ON
mode 2 }
mode 3 } مرحلة انتقالية للتجهيز لـ OFF
mode 4 }
mode 5 → OFF

Mode-2 Operation

$T_1 \to$ OFF
$T_2 \Rightarrow$ ON



- Thyristor T_2 is now fired to commutate thyristor T_1.
- When T_2 is ON capacitor voltage reverse biases T_1 and turns if off.
- The capacitor discharges through the load from $-V$ to 0.
- Discharge time is known as circuit turn-off time.

Circuit turn-off time is given by

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

max max → gives min time for this mode.

Where I_L is load current.

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

- Capacitor recharges back to the supply voltage (with plate 'a' positive).
- This time is called the recharging time and is given by

$$t_d = \frac{V_S \times C}{I_L}$$

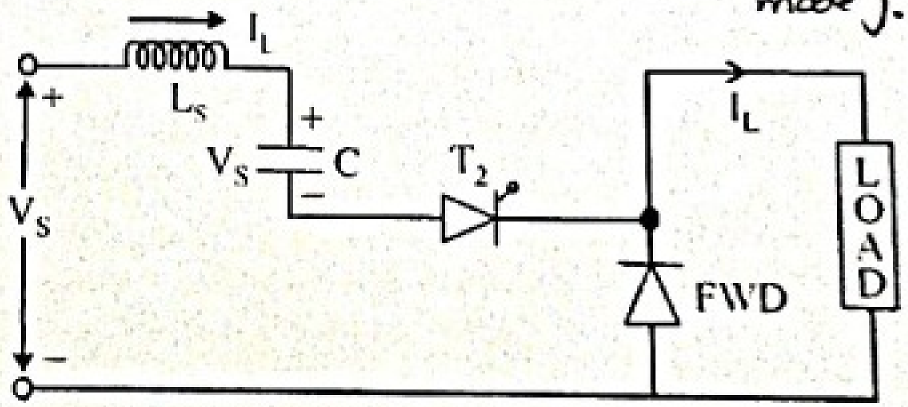
- The total time required for the capacitor to discharge and recharge is called the commutation time and it is given by $t_r = t_C + t_d$

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

FWD ⇒ ON حتى يصير التيار بنفس الاتجاه.

Mode-3 Operation

T_2 ⇒ OFF [at the end of this mode].



- *FWD* starts conducting and the load current decays.
- The energy stored in source inductance L_S is transferred to capacitor.
- Hence capacitor charges to a voltage higher than supply voltage, T_2 naturally turns off.

The instantaneous capacitor voltage is

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

Where

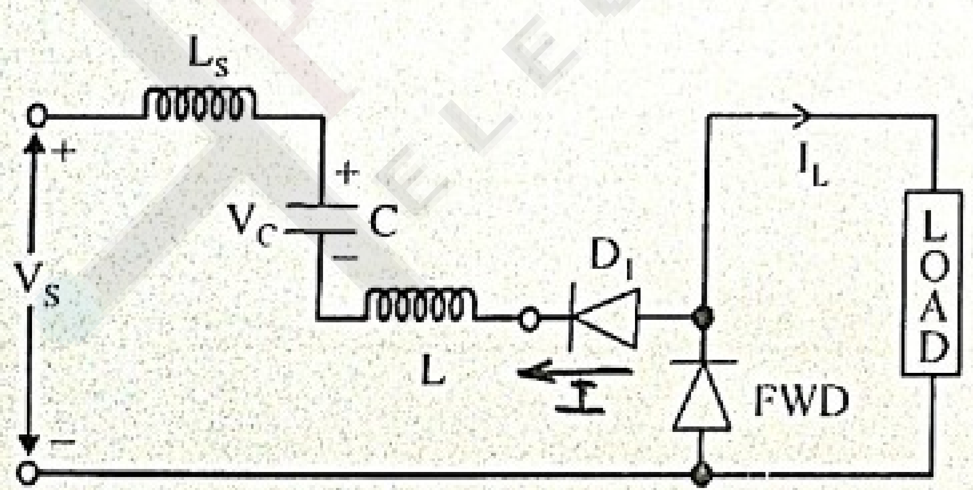
$$\omega_S = \frac{1}{\sqrt{L_S C}}$$

because the capacitor charge larger than the supply.

$D_1 \Rightarrow ON$

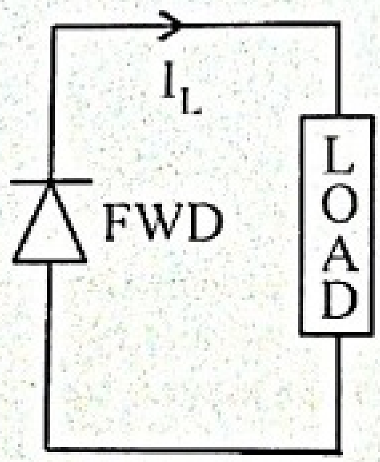
$T_2 \Rightarrow OFF$

Mode-4 Operation

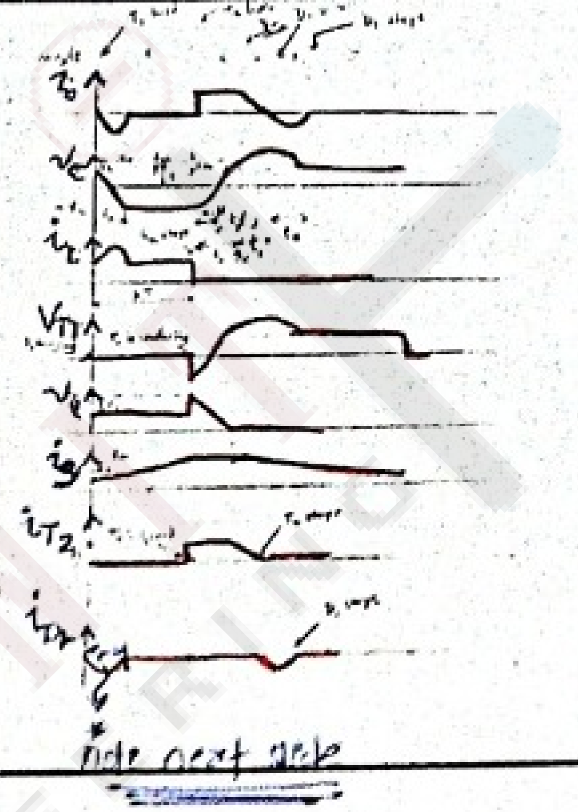


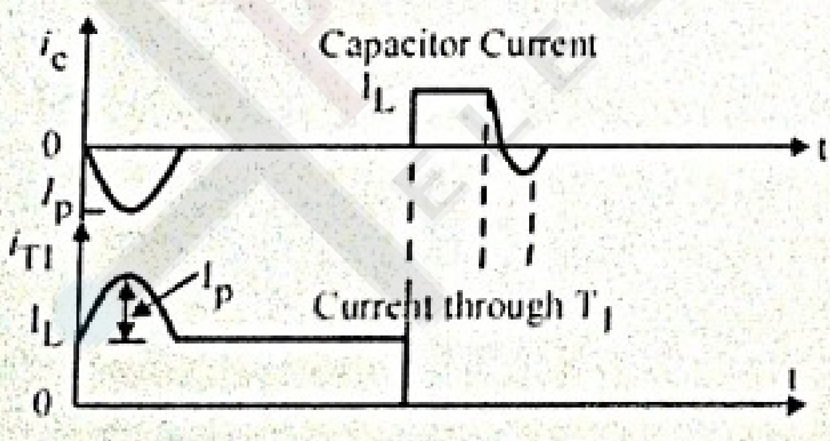
- Capacitor has been overcharged i.e. its voltage is above supply voltage.
- Capacitor starts discharging in reverse direction.
- Hence capacitor current becomes negative.
- The capacitor discharges through L_S, V_S, *FWD*, D_1 *and L*.
- When this current reduces to zero D_1 will stop conducting and the capacitor voltage will be same as the supply voltage

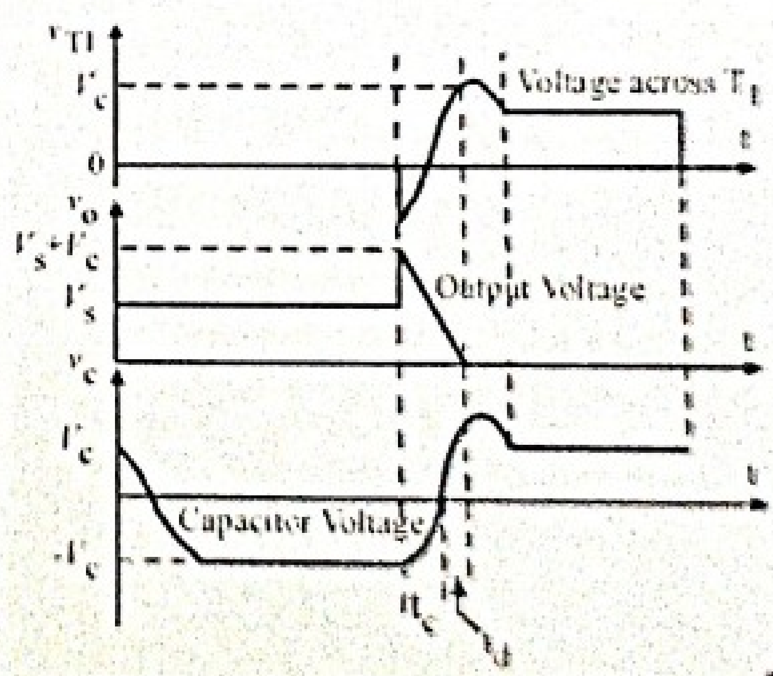
Mode-5 Operation



- Both thyristors are off and the load current flows through the FWD.
- This mode will end once thyristor T_1 is fired.







Disadvantages

- A starting circuit is required and the starting circuit should be such that it triggers thyristor T_2 first.
- Load voltage jumps to almost twice the supply voltage when the commutation is initiated.
- The discharging and charging time of commutation capacitor are dependent on the load current and this limits high frequency operation, especially at low load current.

- Chopper cannot be tested without connecting load.
- Thyristor T_1 has to carry load current as well as resonant current resulting in increasing its peak current rating.

$t_{on} \Rightarrow$ time for mode 1 $\Rightarrow t_{on\,min}$ = time of mode 1

$t_{OFF} \Rightarrow$ time for mode 2, 3, 4, 5 $\Rightarrow t_{OFF\,min}$ = time for 3+2+4

so duty cycle can't be less than 5%, if * in graph (i_a) in 5%

Chapter 4 AC to AC Converters

Outline

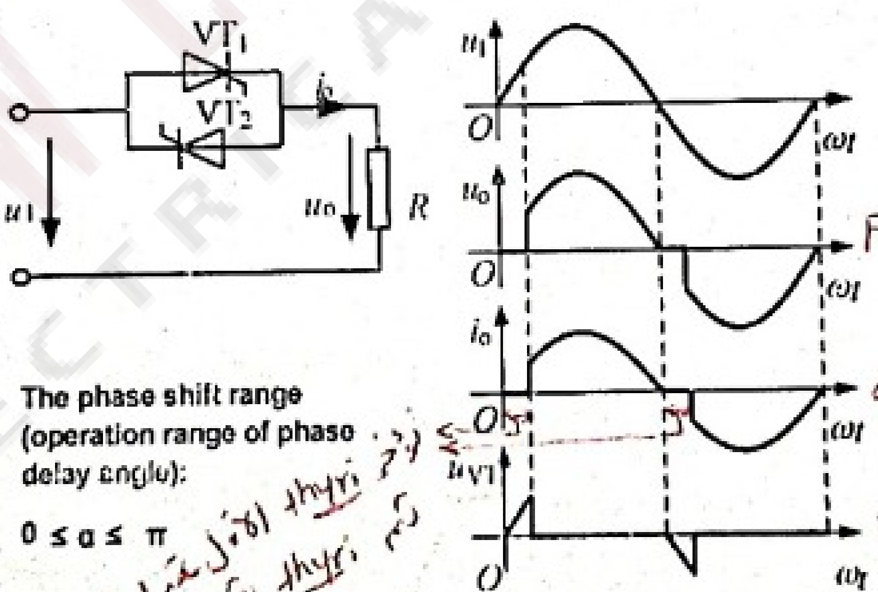
4.1 AC voltage controllers

4.2 Other AC controllers

input : AC Fixed

output : AC variable

4.1.1 Single-phase AC voltage controller

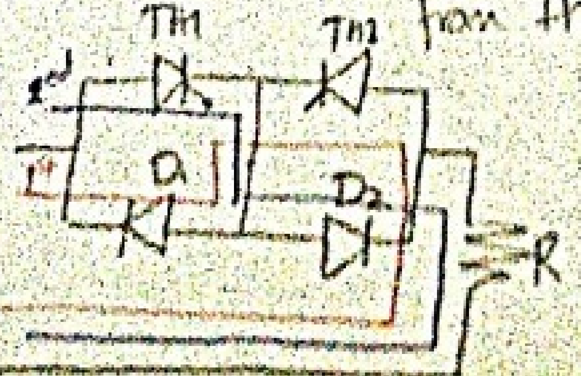


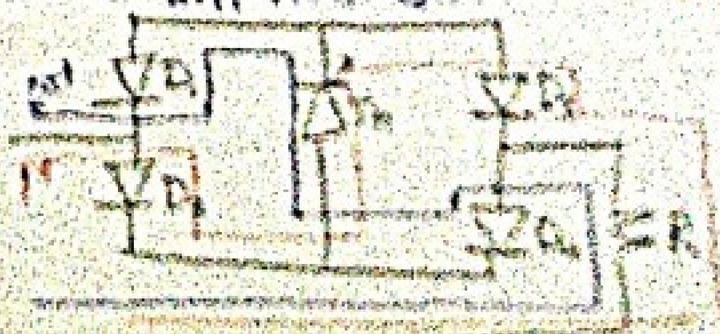
The phase shift range (operation range of phase delay angle):

$0 \le \alpha \le \pi$

• aproblem occurs for this type of ckts & cathode for the 1st thyrister is connected for anode of the 2nd [when Firing happens we'll give current for the gate (cathode)]
⇒ so the problem in that we can't give current for two thyristor from the same source [different source, different earth each].

1





Resistive load, quantitative analysis

RMS value of output voltage

$$U_o = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}\left(\sqrt{2}U_1 \sin\omega t\right)^2 d(\omega t)} = U_1\sqrt{\frac{1}{2\pi}\sin 2\alpha + \frac{\pi-\alpha}{\pi}} \quad (4\text{-}1)$$

same as Full wave rectifier just that 2nd thyristor is (-ve)

RMS value of output current

$$I_o = \frac{U_o}{R} \quad (4\text{-}2)$$

RMS value of thyristor current

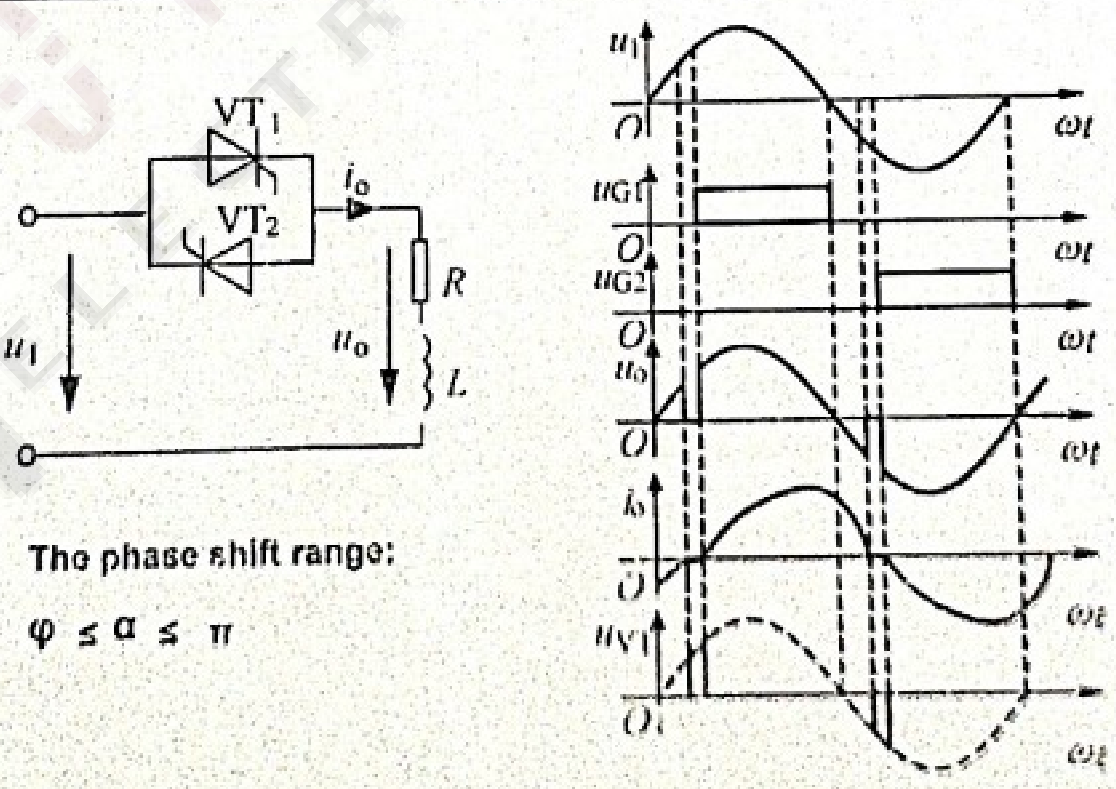
$$I_T = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi}\left(\frac{\sqrt{2}U_1 \sin\omega t}{R}\right)^2 d(\omega t)} = \frac{U_1}{R}\sqrt{\frac{1}{2}\left(1-\frac{\alpha}{\pi}+\frac{\sin 2\alpha}{2\pi}\right)} \quad (4\text{-}3)$$

Power factor of the circuit

$$\lambda = \frac{P}{S} = \frac{U_o I_o}{U_1 I_o} = \frac{U_o}{U_1} = \sqrt{\frac{1}{2\pi}\sin 2\alpha + \frac{\pi-\alpha}{\pi}} \quad (4\text{-}4)$$

so a delay occurs

Inductive (Inductor- resistor) load , operation principle



The phase shift range:

$\varphi \le \alpha \le \pi$

if θ large & α small ⇒ Continuous Output

Inductive load, quantitative analysis

Same as full wave but here there's a +ve part & a -ve part [in full wave it's always +ve]

Differential equation

$$L\frac{\mathrm{d}i_o}{\mathrm{d}t}+Ri_o=\sqrt{2}U_1\sin\omega t$$

$$i_o\big|_{\omega t=\alpha}=0 \qquad (4\text{-}5)$$

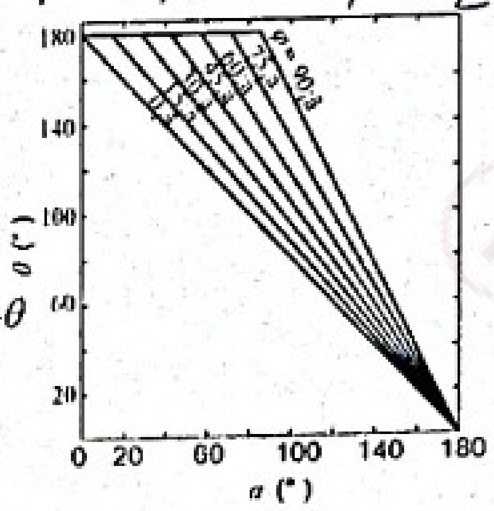
Solution

$$i_o=\frac{\sqrt{2}U_1}{Z}\left[\sin(\omega t-\varphi)-\sin(\alpha-\varphi)e^{\frac{\alpha-\omega t}{\tan\varphi}}\right] \qquad \alpha\le\omega t\le\alpha+\theta \qquad (4\text{-}6)$$

Considering $i_o=0$ when $\omega t=\alpha+\theta$

We have

$$\sin(\alpha+\theta-\varphi)=\sin(\alpha-\varphi)e^{\frac{-\theta}{\tan\varphi}} \qquad (4\text{-}7)$$

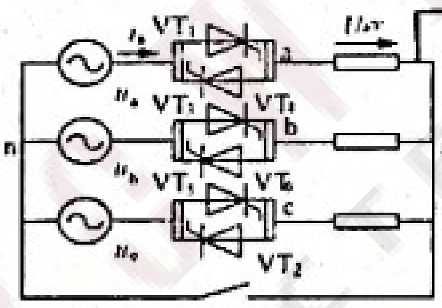


The RMS value of output voltage, output current, and thyristor current can then be calculated.

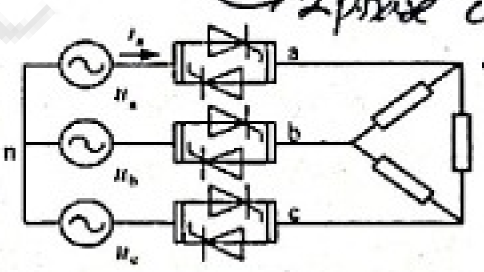
4.1.2 Three-phase AC voltage controller

Classification of three- phase circuits

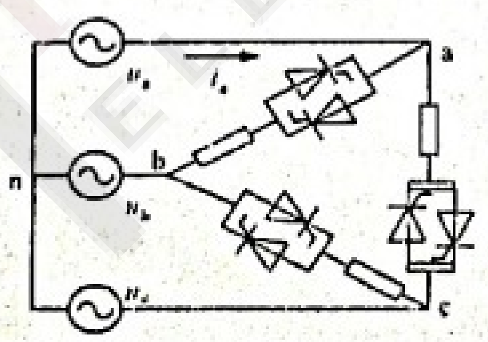
لو أحد thyristor تعطل بتصير كأنو
2phase connected line to line



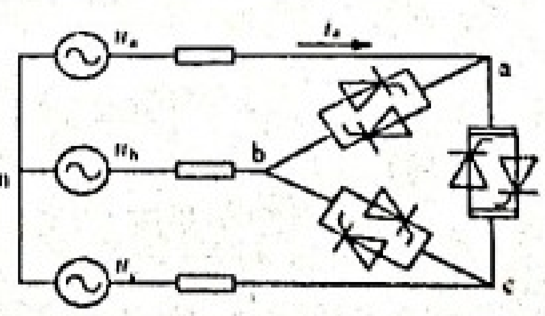
Y connection



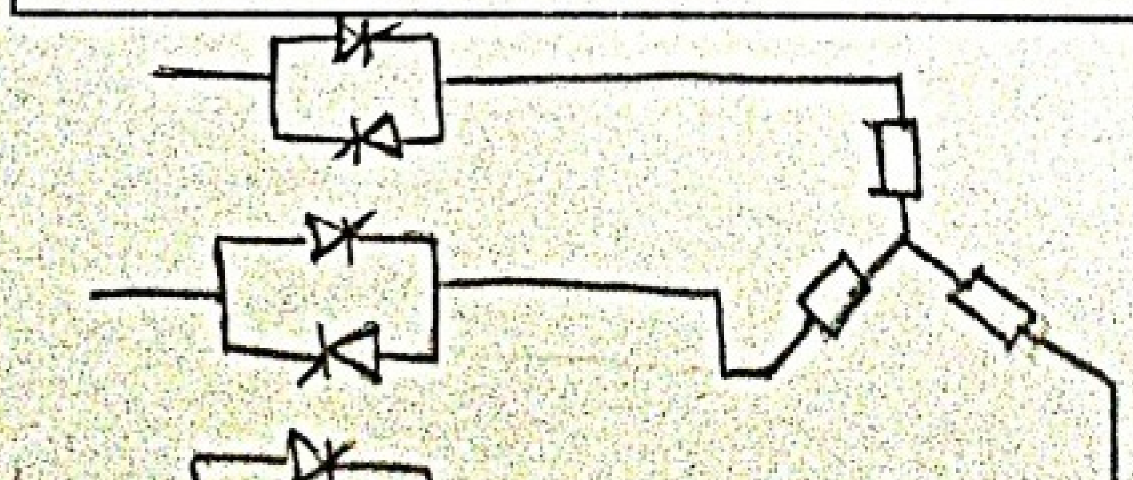
Line- controlled Δ connection



Branch-controlled Δ connection



Neutral-point controlled Δ connection



If one thyristor doesn't work it won't be three phase any more
⇒ it will be two phase connected line to line.

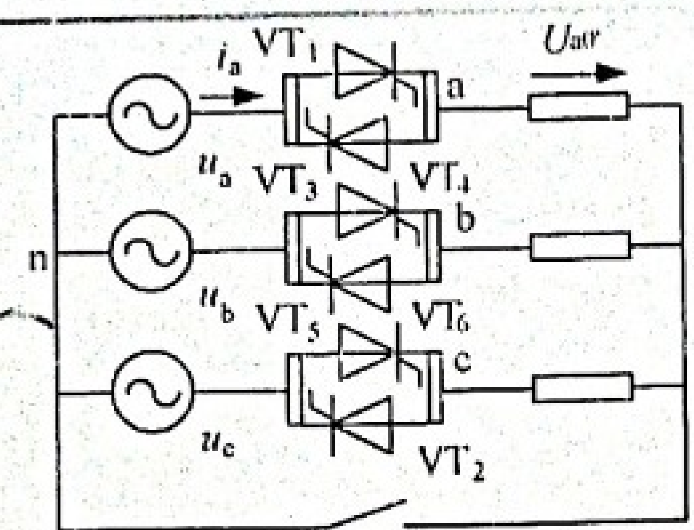
3

3ON → 3φ → $V_P = V_c$

2ON → line to line /2 → $V_P = V_L/2$

- **3- phase 3- wire Y connection AC voltage controller**

called semi-controller
if it was like this



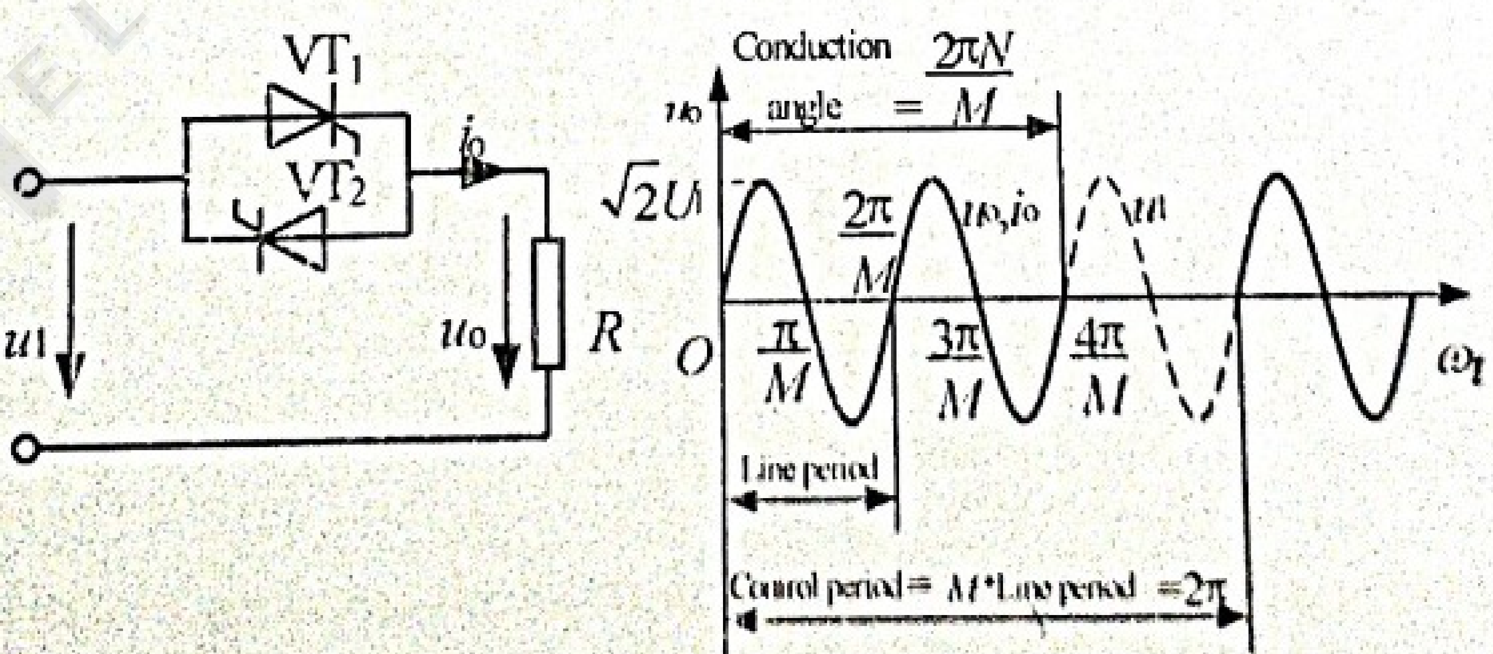
For a time instant, there are 2 possible conduction states:

–Each phase has a thyristor conducting. Load voltages are the same as the source voltages.

–There are only 2 thyristors conducting, each from a phase. The load voltages of the two conducting phases are half of the corresponding line to line voltage, while the load voltage of the other phase is 0.

4.2 Other AC controllers

4.2.1 Integral cycle control—AC power controller



Circuit topologies are the same as AC voltage controllers.

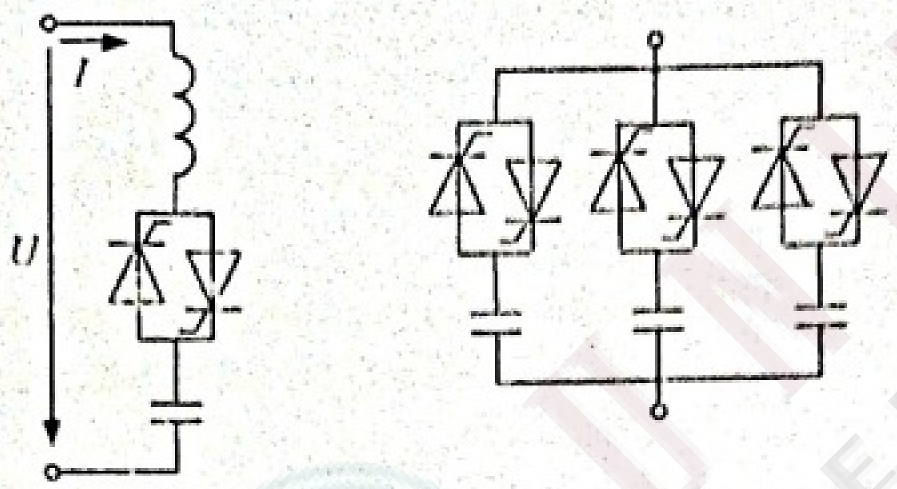
Only the control method is different.

Load voltage and current are both sinusoidal when thyristors are conducting.

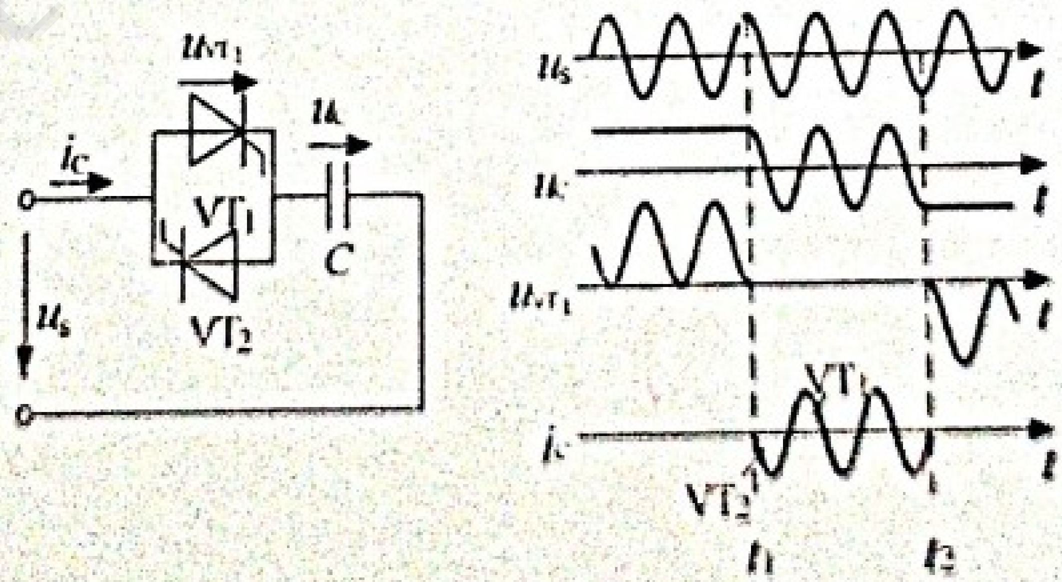
4.2.2 Electronic AC switch

Circuit topologies are the same as AC voltage controllers. But the back- to- back thyristors are just used like a switch to turn the equipment on or off.

Application—Thyristor-switched capacitor (TSC)



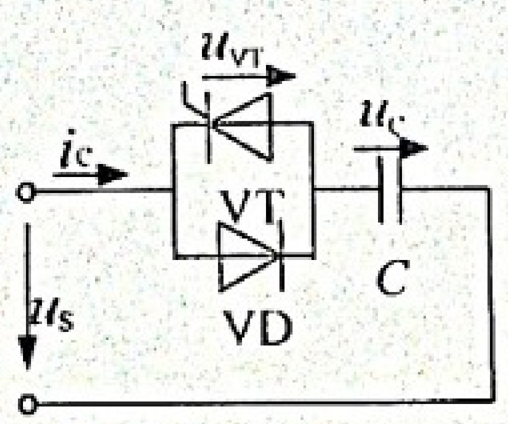
- TSC waveforms when the capacitor is switched in/out

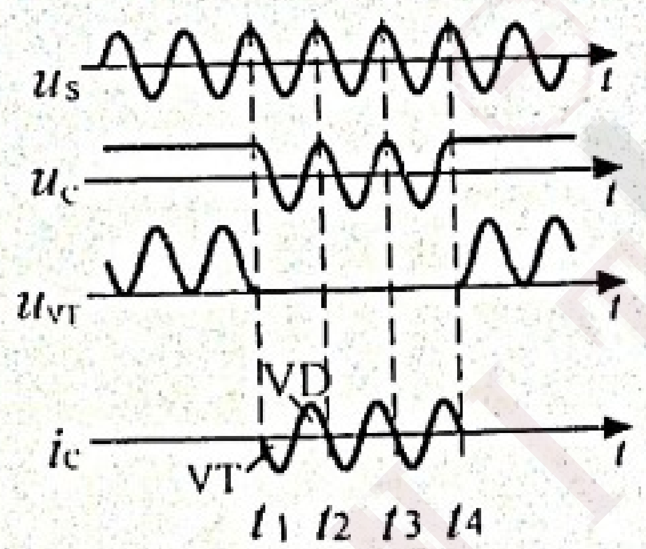


The voltage across the thyristor must be nearly zero when switching in the capacitor, and the current of the thyristor must be zero when switching out the capacitor.

V. → zero Switch on
i → zero Switch off

- **TSC with the electronic switch realized by a thyristor and an anti-parallel diode**





The capacitor voltage will be always charged up to the peak of source voltage.

The response to switching- out command could be a little slower (maximum delay is one line-cycle).

ECE 8830 - Electric Drives

Topic 10: Cycloconverters

AC Fixed Frequency → AC variable Frequency

Introduction

Cycloconverters directly convert ac signals of one frequency (usually line frequency) to ac signals of variable frequency. These variable frequency ac signals can then be used to directly control the speed of ac motors.

Thyristor-based cycloconverters are typically used in low speed, high power (multi-MW) applications for driving induction and wound field synchronous motors.

Phase-Controlled Cycloconverters

The basic principle of cycloconversion is illustrated by the single phase-to-single phase converter shown below.

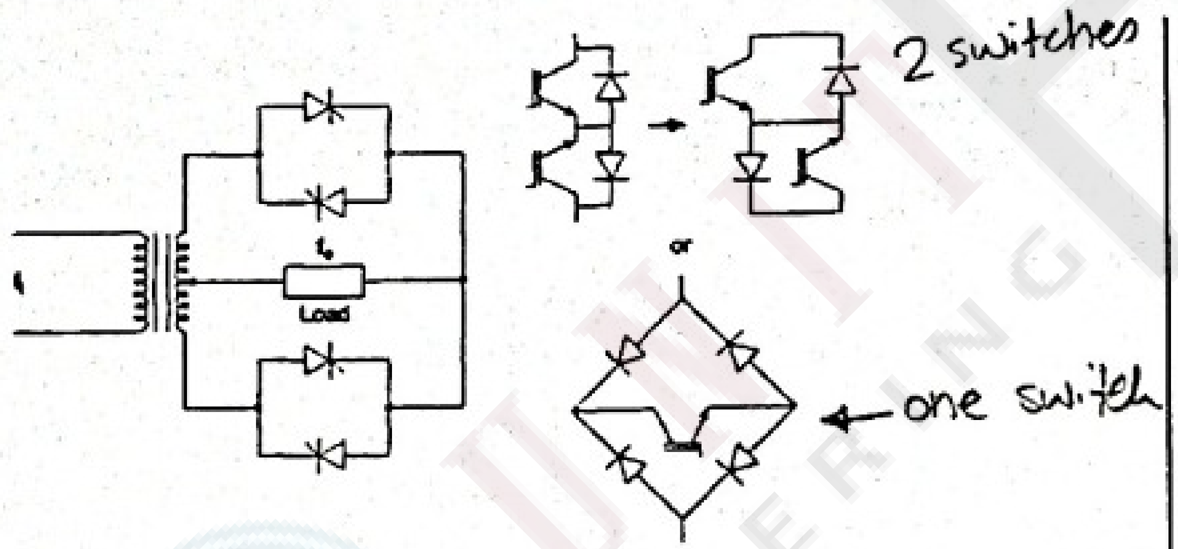


Figure 4.3 Single-phase-to-single-phase cycloconverter circuit showing ac switch configurations

Phase-Controlled Cycloconverters (cont'd)

A positive center-tap thyristor converter is connected in anti-parallel with a negative converter of the same type. This allows current/voltage of either polarity to be controlled in the load.

The waveforms are shown on the next slide.

Phase-Controlled Cycloconverters (cont'd)

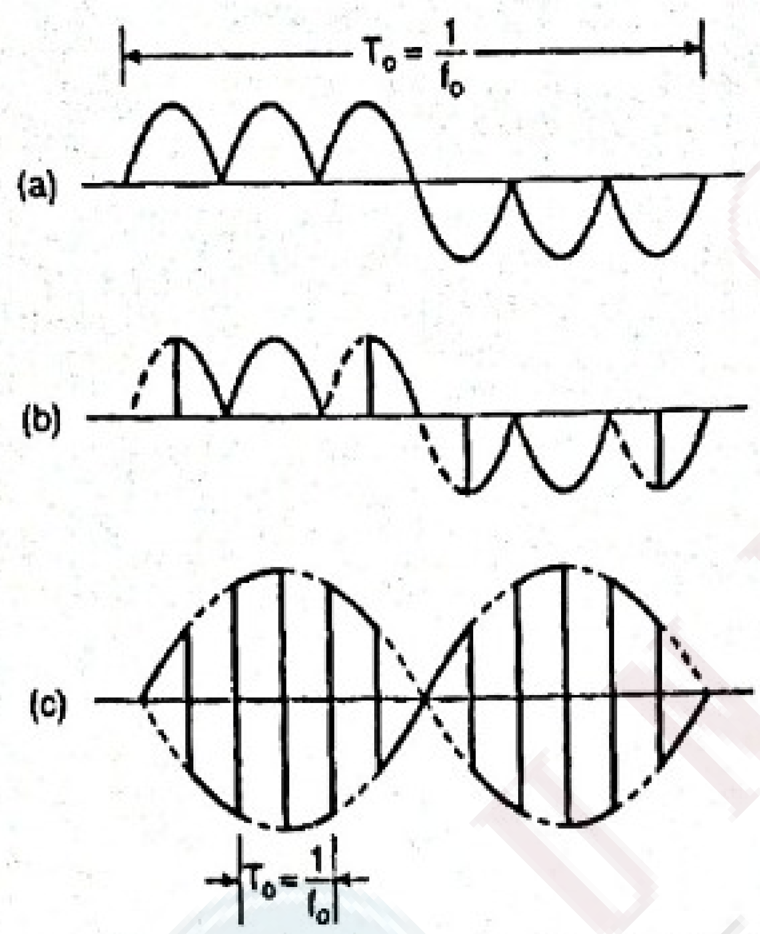


Figure 4.4 Fabricated waveforms for Figure 4.3 (a) Integral half-cycle control, (b) Waveform with firing angle modulation, (c) Waveform with step-up cycloconversion

Phase-Controlled Cycloconverters (cont'd)

An integral half-cycle output wave is created which has a fundamental frequency $f_0=(1/n)\ f_i$ where n is the number of input half-cycles per half-cycle of the output. The thyristor firing angle can be set to control the fundamental component of the output signal. Step-up frequency conversion can be achieved by alternately switching high frequency switching devices (e.g. IGBTs, instead of thyristors) between positive and negative limits at high frequency to generate carrier-frequency modulated output.

Phase-Controlled Cycloconverters (cont'd)

3Φ to single phase conversion can be achieved using either of the dual converter circuit topologies shown below:

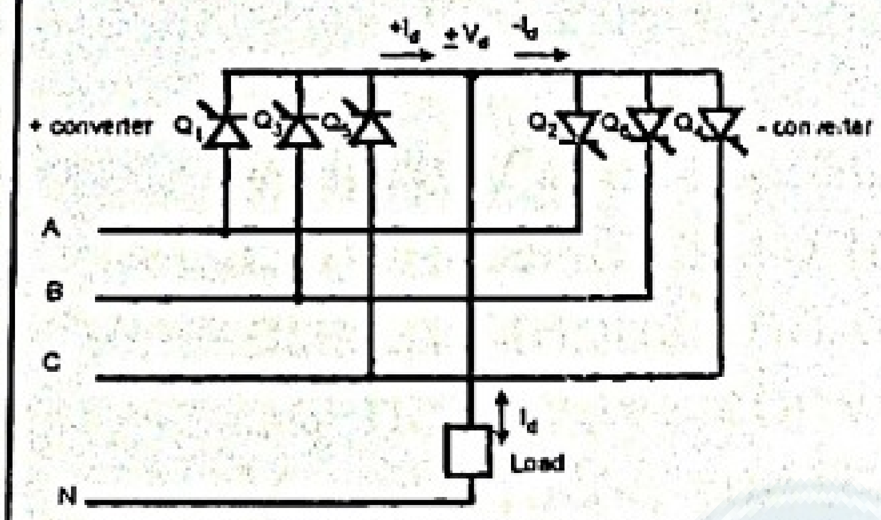


Figure 4.5 Three-phase, half-wave dual converter

$V_o = 0.675\,V_L$

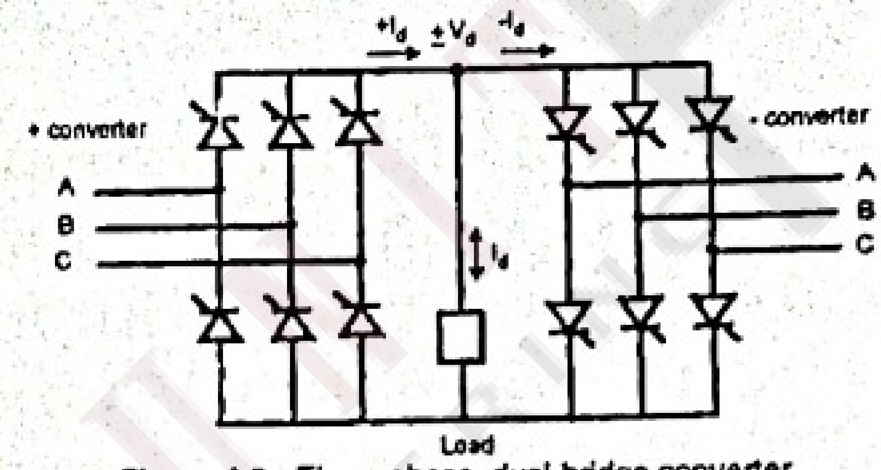


Figure 4.6 Three-phase, dual-bridge converter

$V_o = 1.35\,V_L$

where $V_L \equiv$ the rms line voltage

Phase-Controlled Cycloconverters (cont'd)

A Thevenin equivalent circuit for the dual converter is shown below:

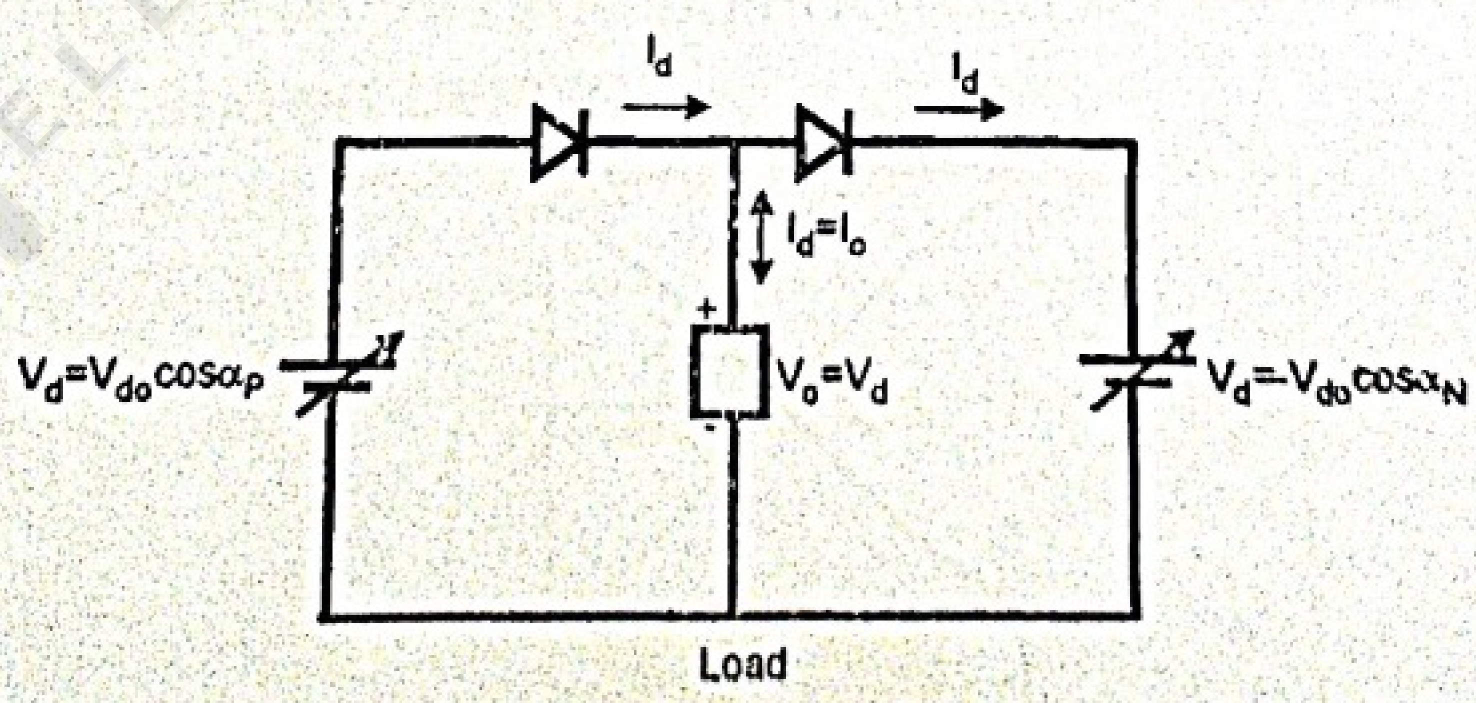


Figure 4.8 Thevenin-equivalent circuit of dual converter

Phase-Controlled Cycloconverters (cont'd)

The input and output voltages are adjusted to be equal and the load current can flow in either direction. Thus,

$$V_0 = V_d = V_{d0}\cos\alpha_p = -V_{d0}\cos\alpha_n$$

where V_{d0} is the dc output voltage of each converter at zero firing angle and α_p and α_N are the input and output firing angles. For a 3Φ half-wave converter $V_{d0} = 0.675V_L$ and $V_{d0} = 1.35V_L$ for the bridge converter (V_L is the rms line voltage).

Phase-Controlled Cycloconverters (cont'd)

Voltage-tracking between the input and output voltages is achieved by setting the sum of the firing angles to π. Positive or negative voltage polarity can be achieved as shown below:

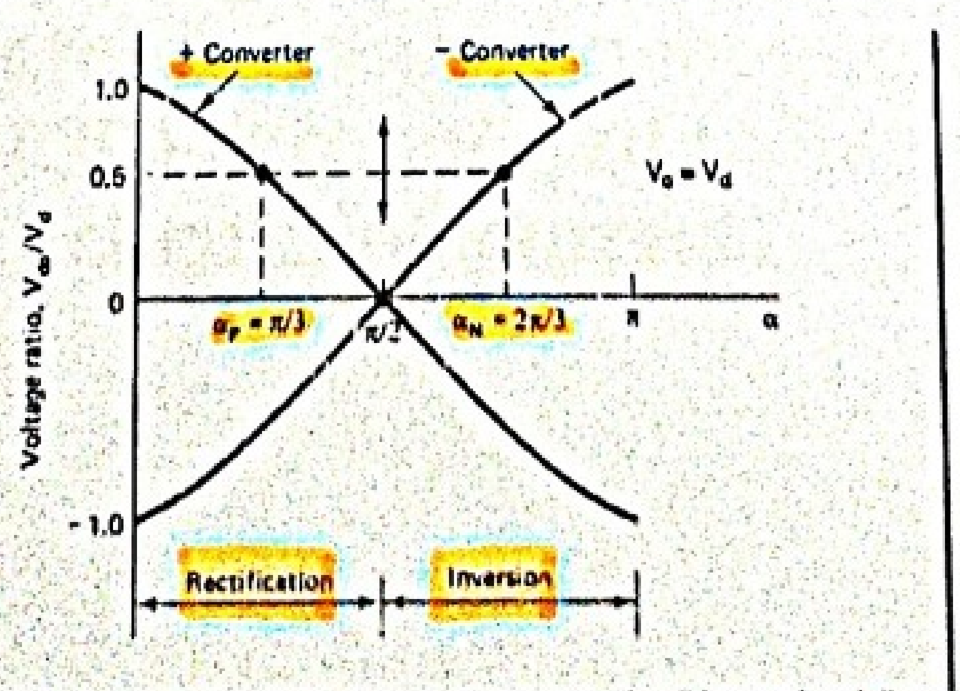


Figure 4.9 Voltage-tracking control in dual converter showing firing angle relations

$\alpha_n + \alpha_p = \pi$

Phase-Controlled Cycloconverters (cont'd)

A 3Φ to 3Φ cycloconverter can be implemented using 18 thyristors as shown below:

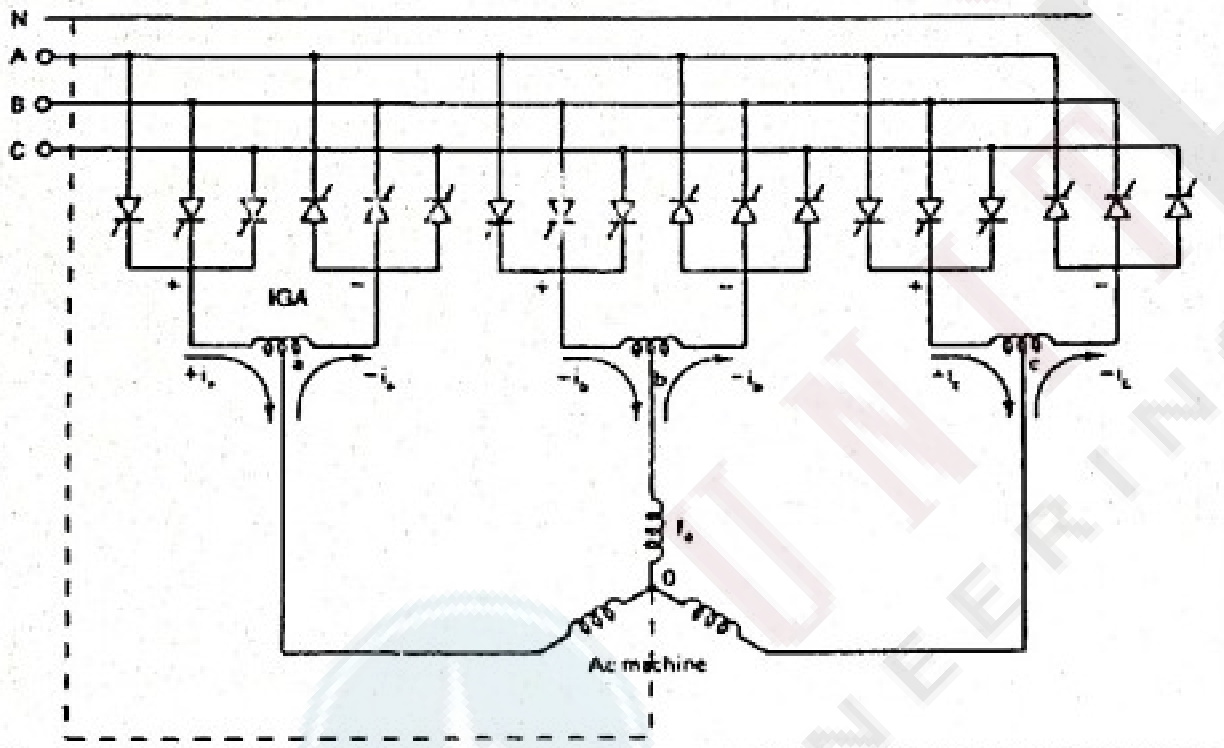


Figure 4.11 Three-phase-to-three-phase cycloconverter with 18 thyristors

Phase-Controlled Cycloconverters (cont'd)

Each phase group functions as a dual converter but the firing angle of each group is modulated sinusoidally with $2\pi/3$ phase angle shift -> 3Φ balanced voltage at the motor terminal. An inter-group reactor (IGR) is connected to each phase to restrict circulating current.

Phase-Controlled Cycloconverters (cont'd)

An output phase wave is achieved by sinusoidal modulation of the thyristor firing angles.

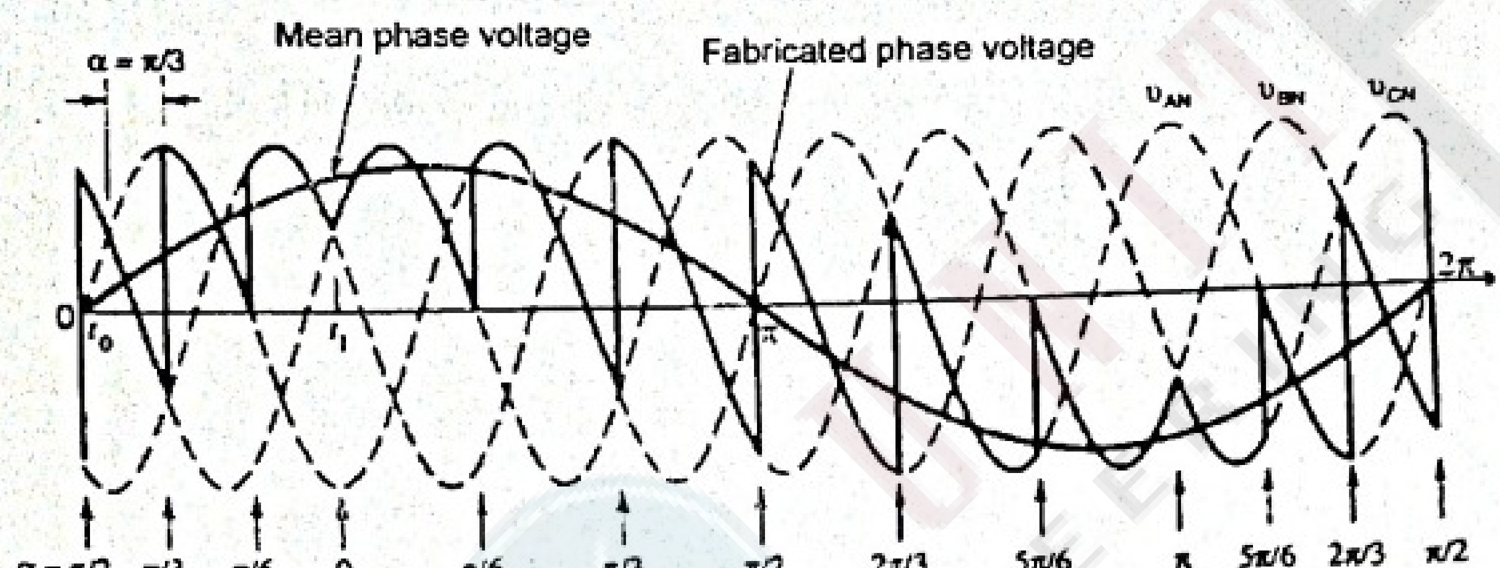


Figure 4.12 Phase-controlled fabrication of output voltage wave in three-phase, half-wave cycloconverter

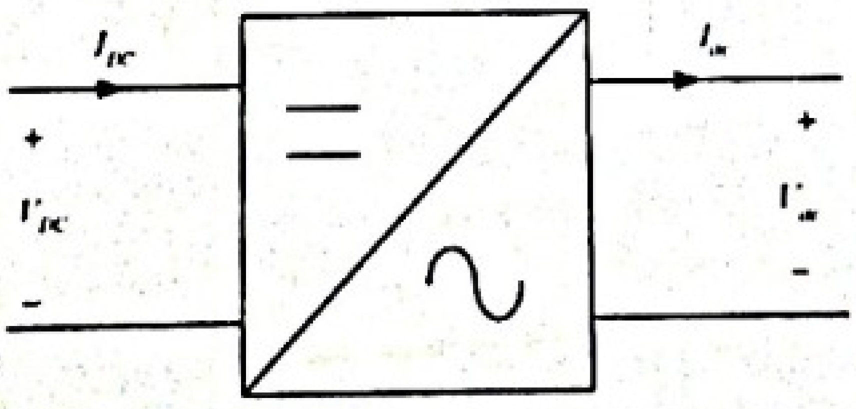
Chapter 4
DC to AC Conversion
(INVERTER)

- General concept
- Single-phase inverter
- Harmonics
- Modulation
- Three-phase inverter

DC to AC Converter (Inverter)

- DEFINITION: Converts DC to AC power by switching the *DC input voltage (or current)* in a pre-determined sequence so as to generate *AC voltage (or current) output.*

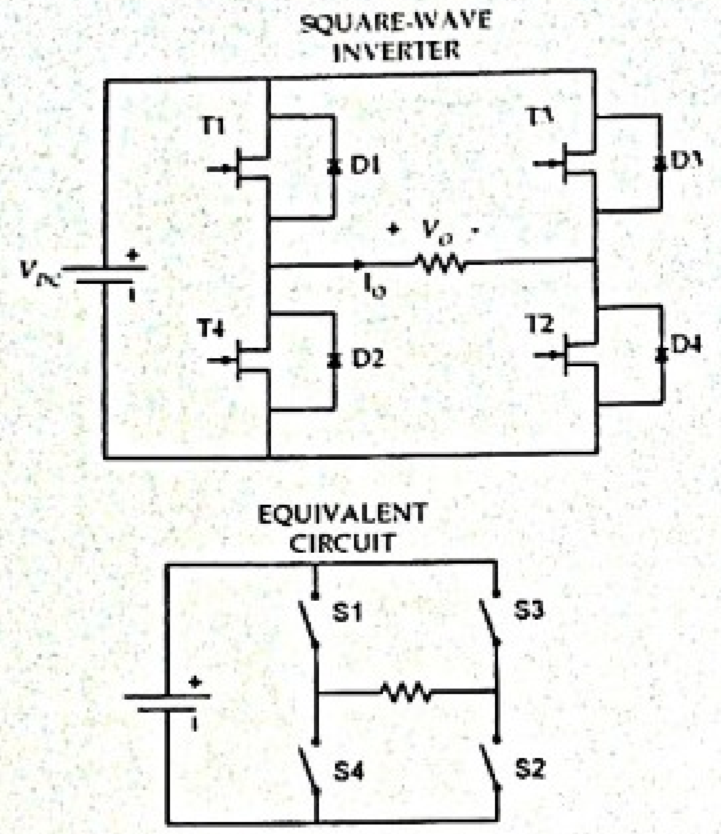
- General block diagram



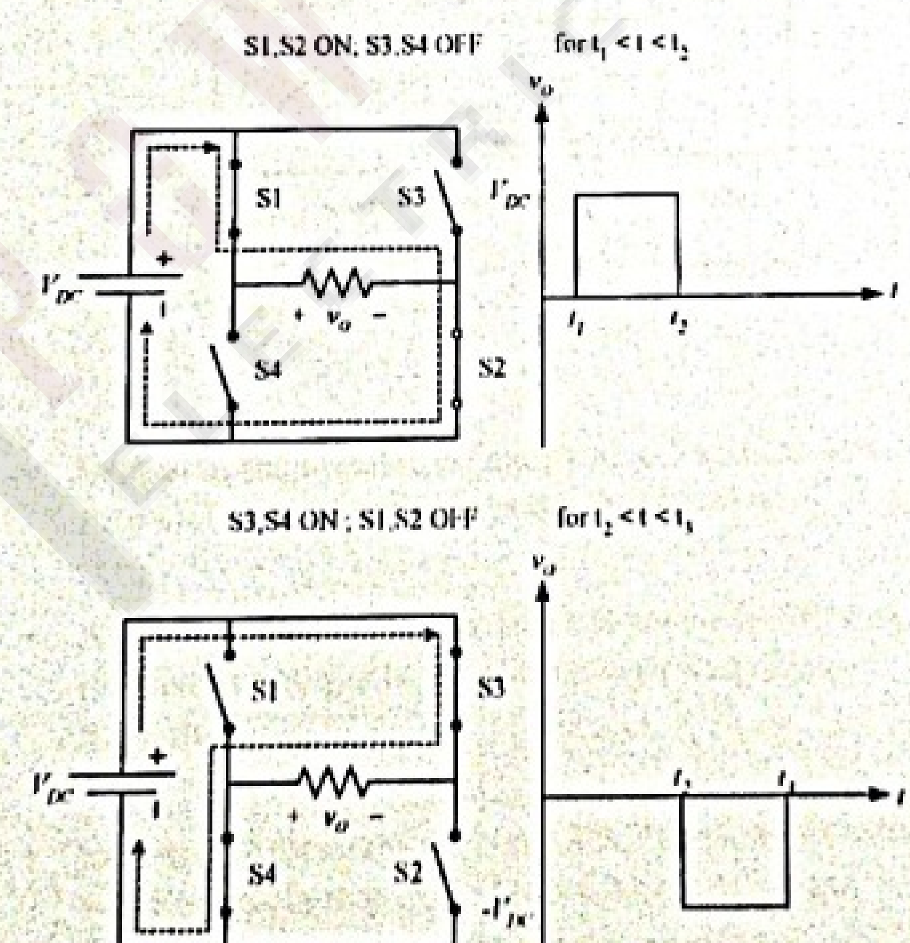
- TYPICAL APPLICATIONS:
  - Un-interruptible power supply (UPS), Industrial (induction motor) drives, Traction, HVDC

Simple square-wave inverter (1)

- To illustrate the concept of AC waveform generation

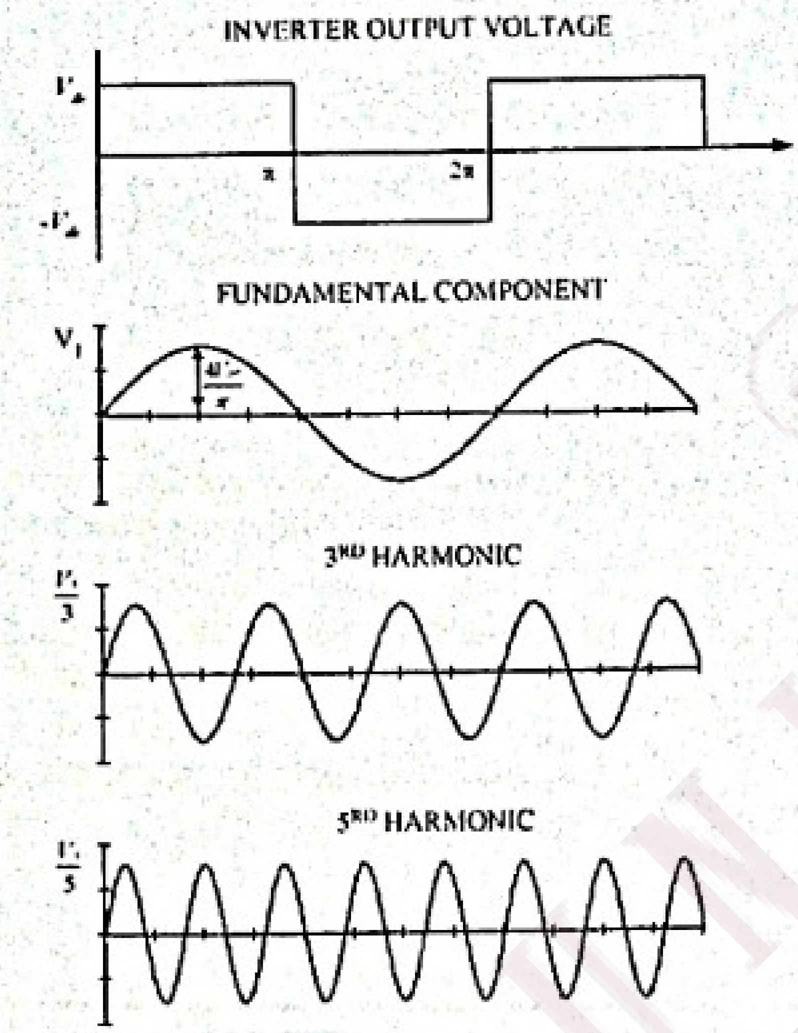


AC Waveform Generation

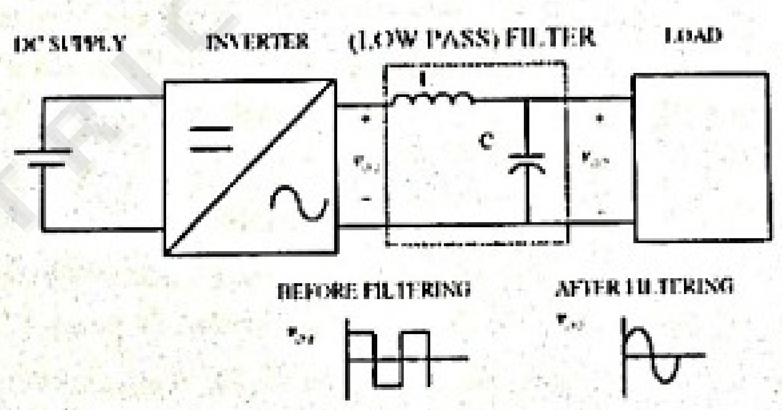


if t_2 both at the same moment it'll produce square wave.

AC Waveforms

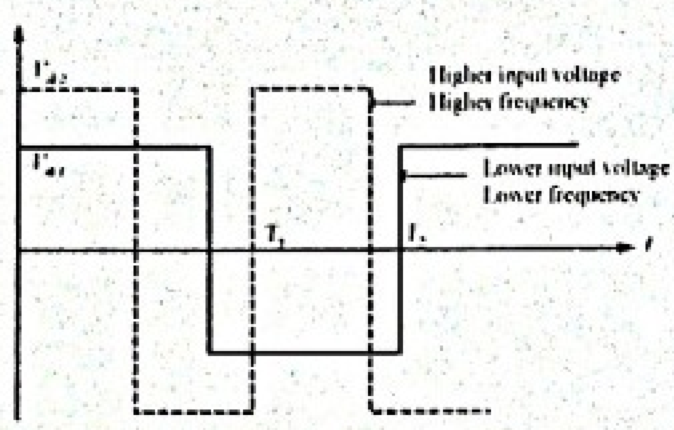


Harmonics Filtering



- Output of the inverter is "chopped AC voltage with zero DC component". It contain **harmonics.**
- An **LC section low-pass filter** is normally fitted at the inverter output to reduce the high frequency harmonics.
- In some applications such as UPS, "*high purity*" sine wave output is required. Good filtering is a must.
- In some applications such as AC motor drive, filtering is not required.

Variable Voltage Variable Frequency Capability



- Output voltage frequency can be varied by "period" of the square-wave pulse.
- Output voltage amplitude can be varied by varying the "magnitude" of the DC input voltage.
- Very useful: e.g. variable speed induction motor drive

Output voltage harmonics/ distortion

- Harmonics cause distortion on the output voltage.
- Lower order harmonics (3rd, 5th etc) are very difficult to filter, due to the filter size and high filter order. They can cause serious voltage distortion.
- Why need to consider harmonics?
  - Sinusoidal waveform quality.
  - "Power Quality" issue.
  - Harmonics may cause degradation of equipment. Equipment need to be "de-rated".
- Total Harmonic Distortion (THD) is a measure to determine the "quality" of a given waveform.

Fourier Series

- Study of harmonics requires understanding of wave shapes. Fourier Series is a tool to analyse wave shapes.

Fourier Series

$$a_o = \frac{1}{\pi}\int_0^{2\pi} f(v)d\theta \quad (\text{"DC" term})$$

$$a_n = \frac{1}{\pi}\int_0^{2\pi} f(v)\cos(n\theta)d\theta \quad (\text{"cos" term})$$

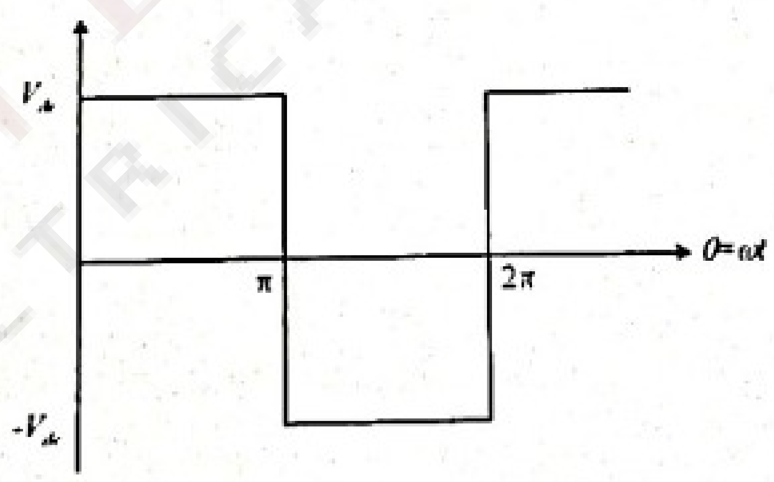
$$b_n = \frac{1}{\pi}\int_0^{2\pi} f(v)\sin(n\theta)d\theta \quad (\text{"sin" term})$$

Inverse Fourier

$$f(v) = \frac{1}{2}a_o + \sum_{n=1}^{\infty}(a_n \cos n\theta + b_n \sin n\theta)$$

where $\theta = \omega t$

Harmonics of square-wave (1)



$$a_o = \frac{1}{\pi}\left[\int_0^{\pi} V_{dc} d\theta + \int_{\pi}^{2\pi} -V_{dc} d\theta\right] = 0$$

$$a_n = \frac{V_{dc}}{\pi}\left[\int_0^{\pi} \cos(n\theta)d\theta - \int_{\pi}^{2\pi} \cos(n\theta)d\theta\right] = 0$$

$$b_n = \frac{V_{dc}}{\pi}\left[\int_0^{\pi} \sin(n\theta)d\theta - \int_{\pi}^{2\pi} \sin(n\theta)d\theta\right]$$

Harmonics of square wave (2)

Solving,

$$b_n = \frac{V_{dc}}{n\pi}\left[-\cos(n\theta)\Big|_0^{\pi} + \cos(n\theta)\Big|_{\pi}^{2\pi}\right]$$

$$= \frac{V_{dc}}{n\pi}\left[(\cos 0 - \cos n\pi) + (\cos 2n\pi - \cos n\pi)\right]$$

$$= \frac{V_{dc}}{n\pi}\left[(1 - \cos n\pi) + (1 - \cos n\pi)\right]$$

$$= \frac{2V_{dc}}{n\pi}\left[(1 - \cos n\pi)\right]$$

When n is even, $\cos n\pi = 1$

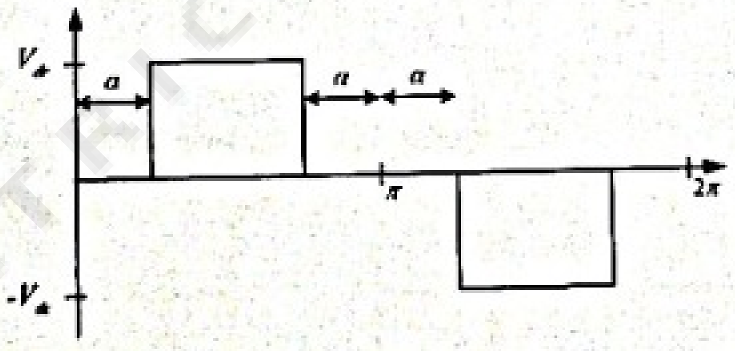
$b_{n=}0$

(i.e. even harmonics do not exist)

When n is odd, $\cos n\pi = -1$

$$b_{n=}\frac{4V_{dc}}{n\pi}$$

Quasi-square wave (QSW)



Note that $a_n = 0$. (due to half - wave symmetry)

$$b_n = 2\left[\frac{1}{\pi}\int_{\alpha}^{\pi-\alpha} V_{dc}\sin(n\theta)d\theta\right] = \frac{2V_{dc}}{n\pi}\left[-\cos n\theta\Big|_{\alpha}^{\pi-\alpha}\right]$$

$$= \frac{2V_{dc}}{n\pi}\left[\cos(n\alpha) - \cos n(\pi - \alpha)\right]$$

Expanding:

$$\cos n(\pi-\alpha) = \cos(n\pi - n\alpha)$$

$$= \cos n\pi \cos n\alpha + \sin n\pi \sin n\alpha = \cos n\pi \cos n\alpha$$

$$\Rightarrow b_n = \frac{2V_{dc}}{n\pi}\left[\cos(n\alpha) - \cos n\pi \cos n\alpha\right]$$

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

Harmonics control

If n is even, $\Rightarrow b_n = 0$,

If n is odd, $\Rightarrow b_n = \frac{4V_{dc}}{n\pi}\cos(n\alpha)$

In particular, amplitude of the fundamental is :

$$b_1 = \frac{4V_{dc}}{\pi}\cos(\alpha)$$

Note:

The fundamental, b_1, is controlled by varying α

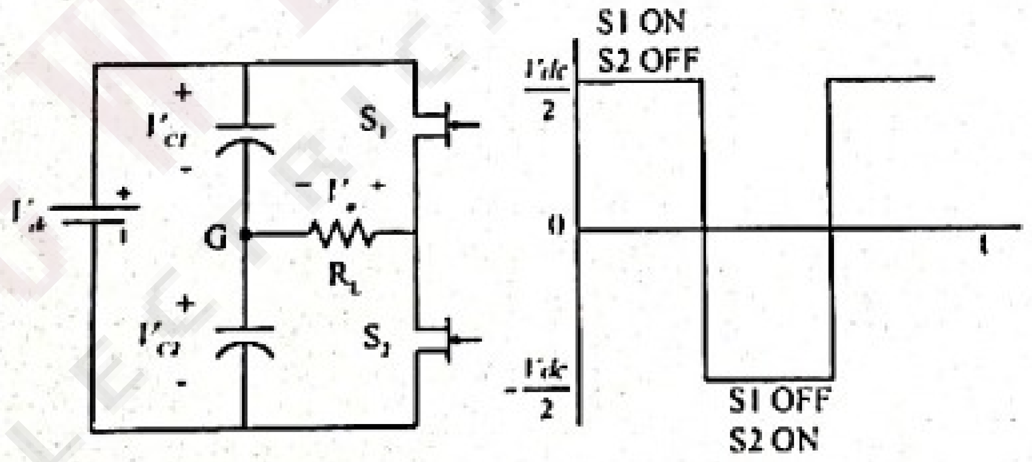
Harmonics can also be controlled by adjusting α,

Harmonics Elimination :

For example if $\alpha = 30^o$, then $b_3 = 0$, or the third harmonic is eliminated from the waveform. In general, harmonic n will be eliminated if :

$$\alpha = \frac{90^o}{n}$$

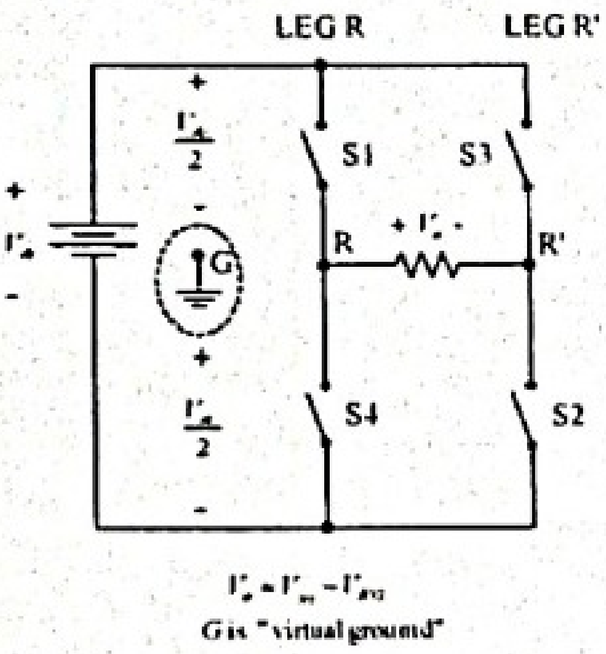
Half-bridge inverter (1)

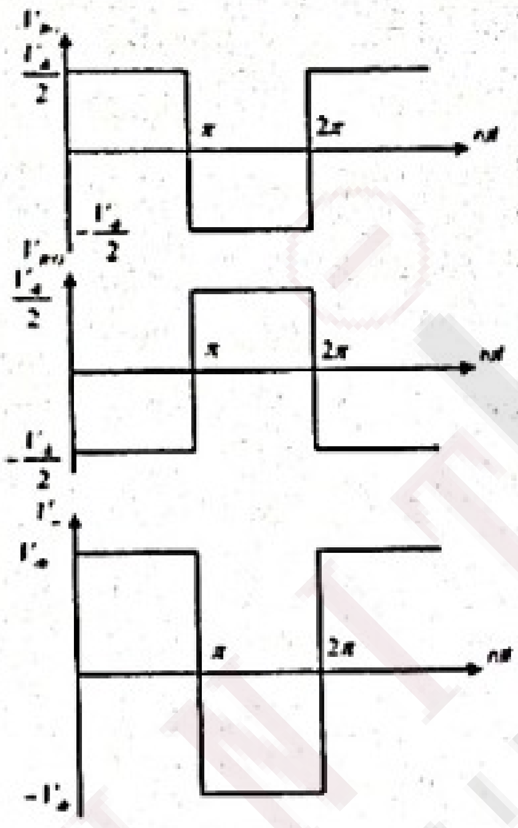


- Also known as the "inverter leg".
- Basic building block for full bridge, three phase and higher order inverters.
- G is the "centre point".
- Both capacitors have the same value. Thus the DC link is equally "spilt" into two.
- The top and bottom switch has to be "complementary", i.e. If the top switch is closed (on), the bottom must be off, and vice-versa.

Single-phase, full-bridge (1)

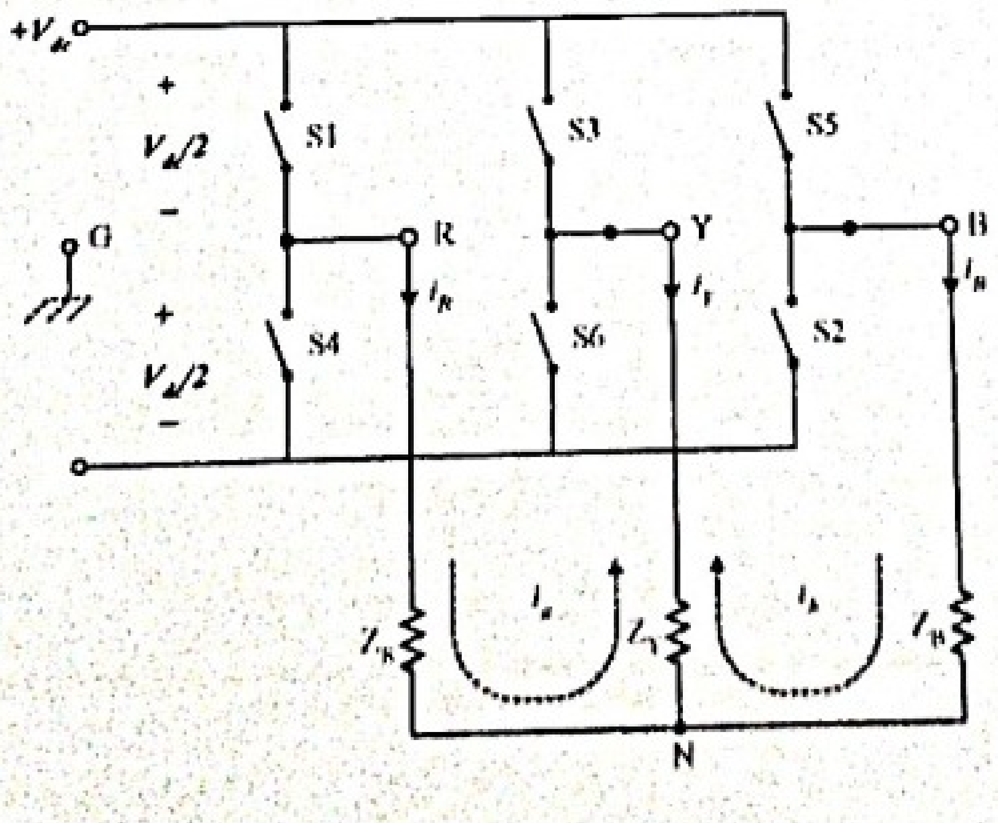
- Full bridge (single phase) is built from two half-bridge leg.
- The switching in the second leg is "delayed by 180 degrees" from the first leg.





Three-phase inverter

- Each leg (Red, Yellow, Blue) is delayed by 120 degrees.
- A three-phase inverter with star connected load is shown below



I. Voltage Source Inverter (VSI)
A. Six-Step VSI (1)

➢ **Six-Step three-phase Voltage Source Inverter**

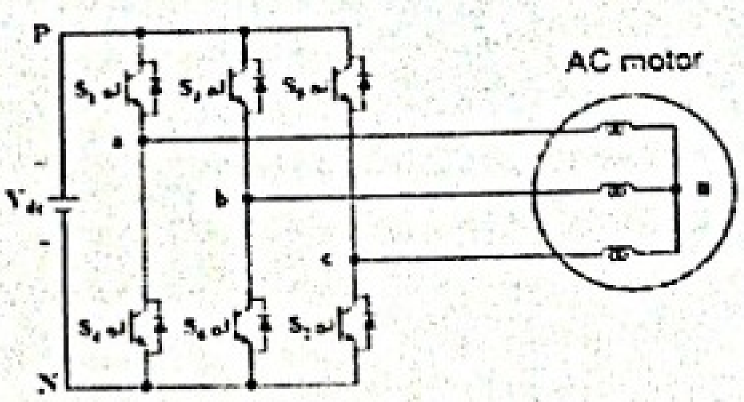


Fig. 1 Three-phase voltage source inverter.

I. Voltage Source Inverter (VSI)
A. Six-Step VSI (2)

➢ **Gating signals, switching sequence and line to negative v**

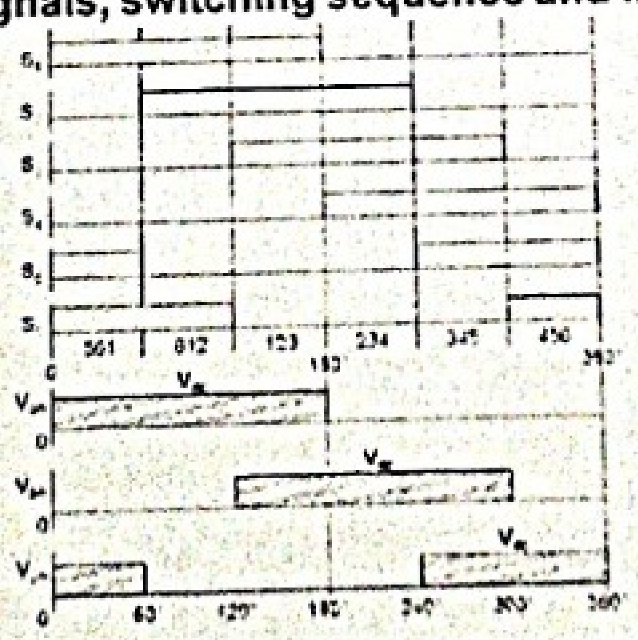


Fig. 2 Waveforms of gating signals, switching sequence, line to negative voltages for six-step voltage source inverter.

I. Voltage Source Inverter (VSI)

A. Six-Step VSI (3)

➢ **Switching Sequence:**

561 (V_1) → 612 (V_2) → 123 (V_3) → 234 (V_4) → 345 (V_5) → 456 (V_6) → 561 (V_1)

where, 561 means that S_5, S_6 and S_1 are switched on

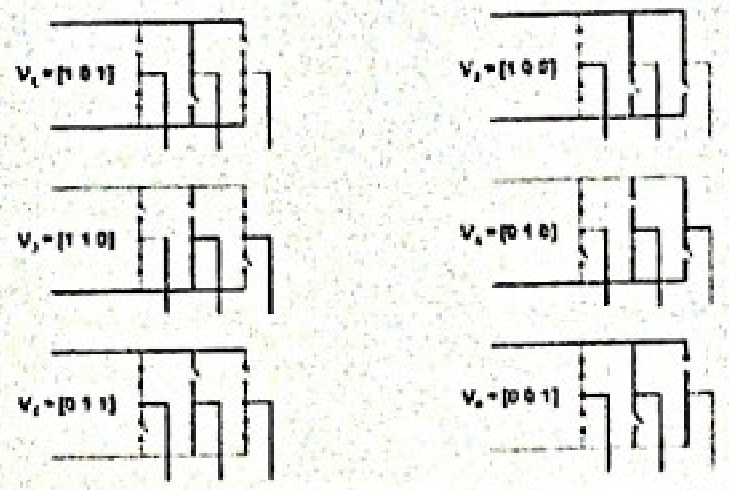


Fig. 3 Six inverter voltage vectors for six-step voltage source inverter.

5

I. Voltage Source Inverter (VSI)

A. Six-Step VSI (4)

➢ Line to line voltages (V_{ab}, V_{bc}, V_{ca})

➢ and line to neutral voltages (V_{an}, V_{bn}, V_{cn})

- Line to line voltages
  - $V_{ab} = V_{aN} - V_{bN}$
  - $V_{bc} = V_{bN} - V_{cN}$
  - $V_{ca} = V_{cN} - V_{aN}$
- Phase voltages
  - $V_{an} = 2/3V_{aN} - 1/3V_{bN} - 1/3V_{cN}$
  - $V_{bn} = -1/3V_{aN} + 2/3V_{bN} - 1/3V_{cN}$
  - $V_{cn} = -1/3V_{aN} - 1/3V_{bN} + 2/3V_{cN}$

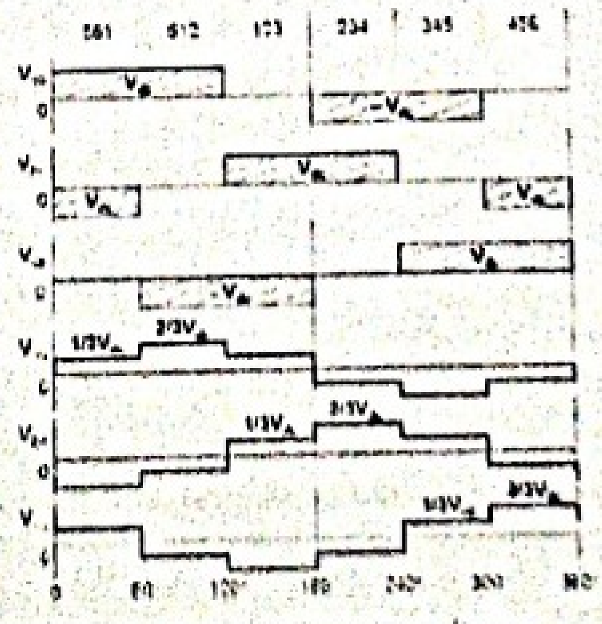
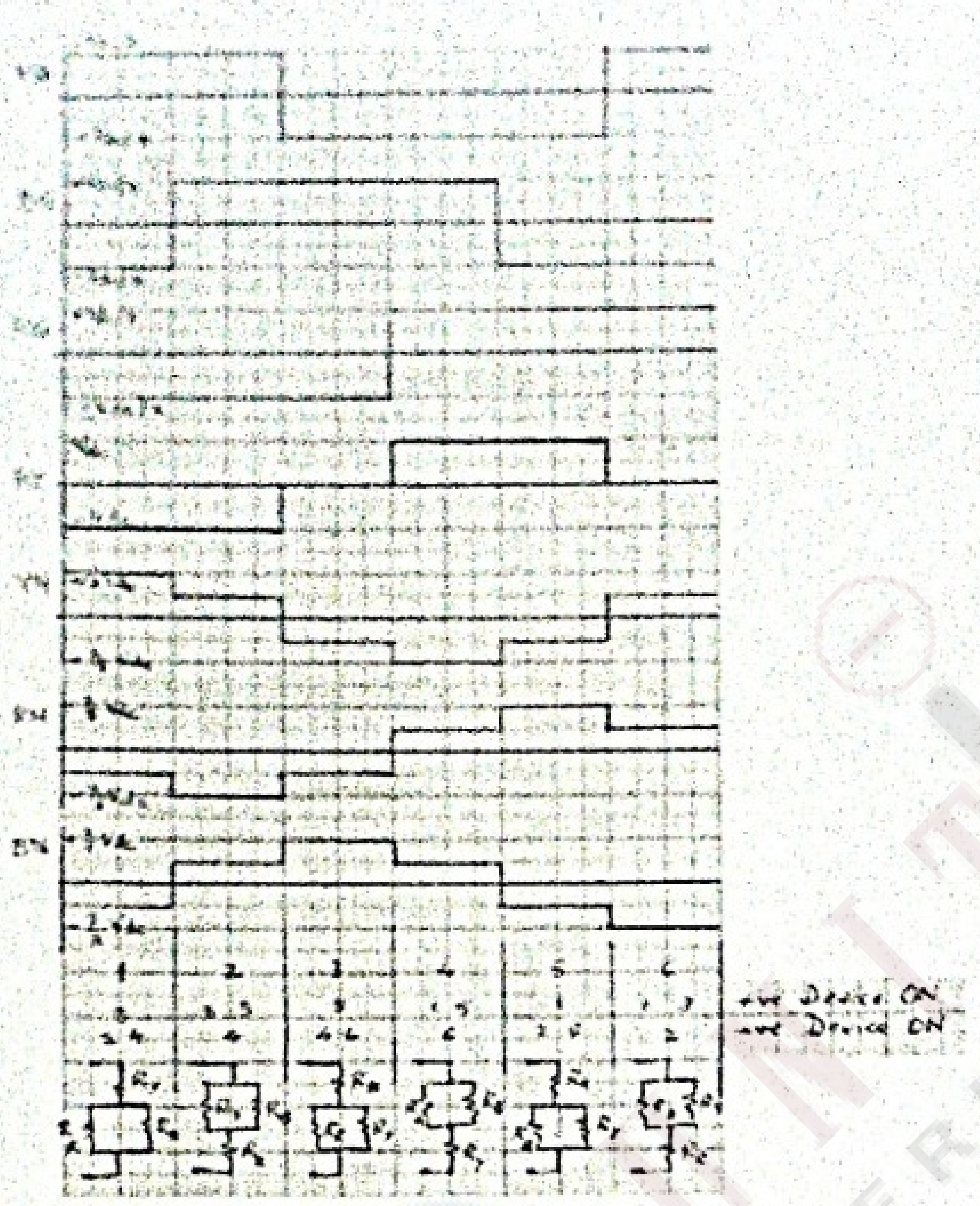


Fig. 4 Waveforms of line to neutral (phase) voltages and line to line voltages for six-step voltage source inverter.

6

Three phase inverter waveforms



I. Voltage Source Inverter (VSI)

A. Six-Step VSI (5)

➢ **Amplitude of line to line voltages (V_{ab}, V_{bc}, V_{ca})**

- **Fundamental Frequency Component $(V_{ab})_1$**

$$(V_{ab})_1(rms) = \frac{\sqrt{3}}{\sqrt{2}}\frac{4}{\pi}\frac{V_{dc}}{2} = \frac{\sqrt{6}}{\pi}V_{dc} \approx 0.78V_{dc}$$

- **Harmonic Frequency Components $(V_{ab})_h$**

: amplitudes of harmonics decrease inversely proportional to their harmonic order

$$(V_{ab})_h(rms) = \frac{0.78}{h}V_{dc}$$

where, $h = 6n \pm 1 \quad (n = 1, 2, 3, \ldots)$

I. Voltage Source Inverter (VSI)
A. Six-Step VSI (6)

➢ **Characteristics of Six-step VSI**

- It is called "six-step inverter" because of the presence of six "steps" in the line to neutral (phase) voltage waveform
- Harmonics of order three and multiples of three are absent from both the line to line and the line to neutral voltages and consequently absent from the currents
- Output amplitude in a three-phase inverter can be controlled by only change of DC-link voltage (V_{dc})

I. Voltage Source Inverter (VSI)
B. Pulse-Width Modulated VSI (1)

➢ **Objective of PWM**

- Control of inverter output voltage
- Reduction of harmonics

➢ **Disadvantages of PWM**

- Increase of switching losses due to high PWM frequency
- Reduction of available voltage
- EMI problems due to high-order harmonics

I. Voltage Source Inverter (VSI)
B. Pulse-Width Modulated VSI (2)

➢ **Pulse-Width Modulation (PWM)**

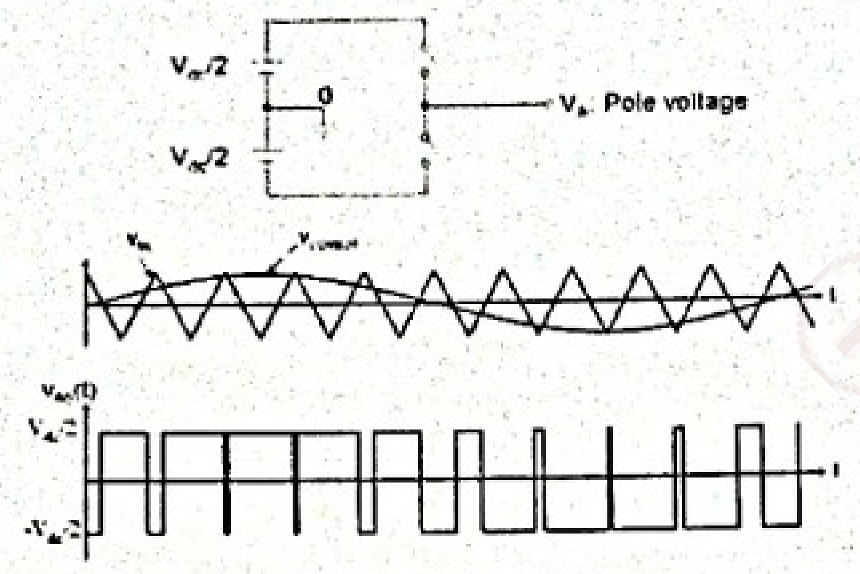


Fig. 5 Pulse-width modulation.

I. Voltage Source Inverter (VSI)
B. Pulse-Width Modulated VSI (3)

➢ **Inverter output voltage**

- When $v_{control} > v_{tri}$, $V_{A0} = V_{dc}/2$
- When $v_{control} < v_{tri}$, $V_{A0} = -V_{dc}/2$

➢ **Control of inverter output voltage**

- PWM frequency is the same as the frequency of v_{tri}
- Amplitude is controlled by the peak value of $v_{control}$
- Fundamental frequency is controlled by the frequency of $v_{control}$

➢ **Modulation Index (m)**

$$\therefore m = \frac{v_{control}}{v_{tri}} = \frac{peak\ \ of\ \ (V_{A0})_1}{V_{dc}/2},$$

where, $(V_{A0})_1$: fundamental frequecny component of V_{A0}

II. PWM METHODS
A. Sine PWM (1)

➢ Three-phase inverter

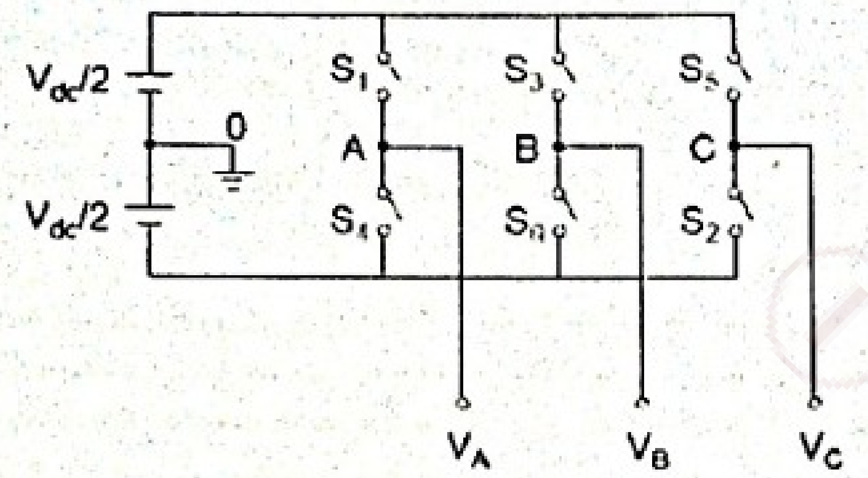


Fig. 6 Three-phase Sine PWM Inverter.

II. PWM METHODS
A. Sine PWM (2)

➢ Three-phase sine PWM waveforms

- Frequency of v_{tri} and $v_{control}$
  - ⇨ Frequency of v_{tri} = f_s
  - ⇨ Frequency of $v_{control}$ = f_1

  where, f_s = PWM frequency
  f_1 = Fundamental frequency

- Inverter output voltage
  - ⇨ When $v_{control} > v_{tri}$, $V_{AB} = V_{dc}/2$
  - ⇨ When $v_{control} < v_{tri}$, $V_{AB} = -V_{dc}/2$

  where, $V_{AB} = V_{A0} - V_{B0}$
  $V_{BC} = V_{B0} - V_{C0}$
  $V_{CA} = V_{C0} - V_{A0}$

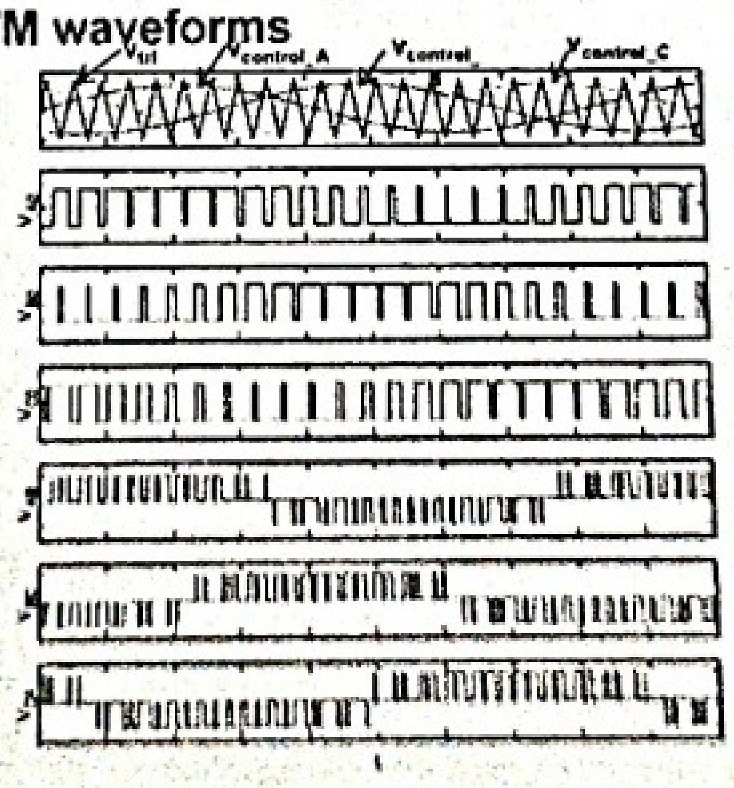


Fig. 7 Waveforms of three-phase sine PWM inverter.

II. PWM METHODS

A. Sine PWM (3)

➢ **Amplitude modulation ratio (m_a)**

$$\therefore m_a = \frac{peak \;\; amplitude \;\; of \;\; v_{control}}{amplitude \;\; of \;\; v_{tri}} = \frac{peak \;\; value \;\; of \;\; (V_{A0})_1}{V_{dc}/2}$$

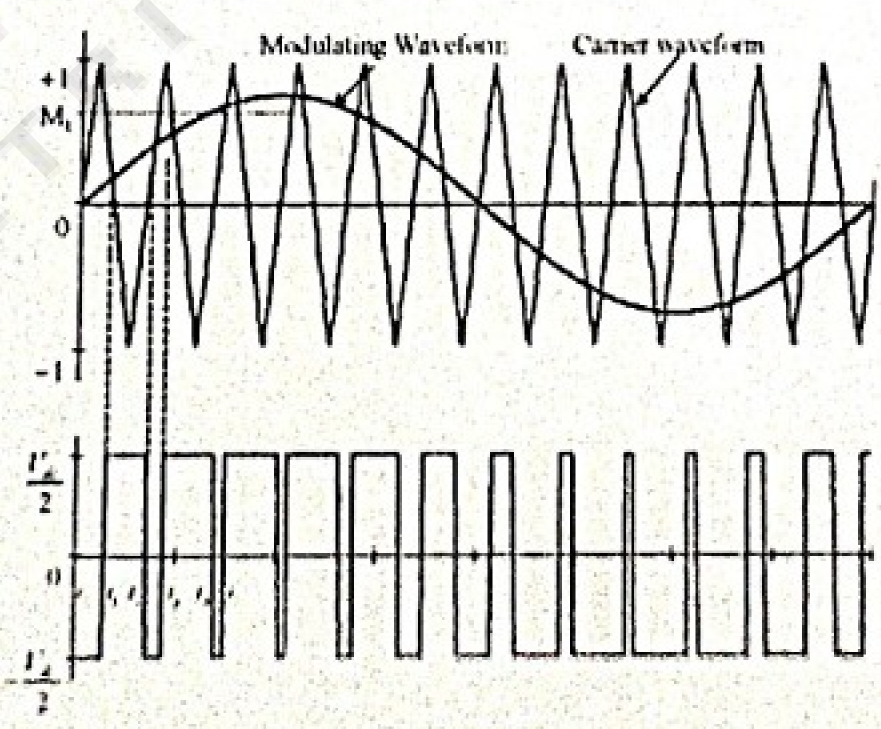
where, $(V_{A0})_1$: fundamental frequecny component of V_{A0}

➢ **Frequency modulation ratio (m_f)**

$m_f = \dfrac{f_s}{f_1}$, where, f_s = PWM frequency and f_1 = fundamental frequency

- m_f should be an odd integer
  - ⇨ If m_f is not an integer, there may exist sunharmonics at output voltage
  - ⇨ If m_f is not odd, DC component may exist and even harmonics are present at output voltage
- m_f should be a multiple of 3 for three-phase PWM inverter
  - ⇨ An odd multiple of 3 and even harmonics are suppressed

Pulse Width Modulation (PWM)

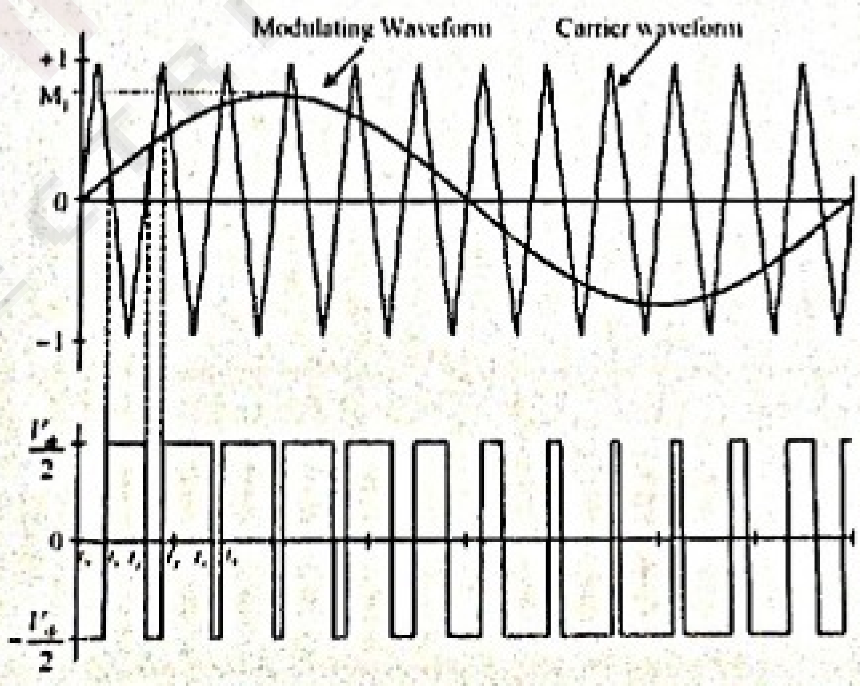


- Triangulation method (Natural sampling)
  - Amplitudes of the triangular wave (carrier) and sine wave (modulating) are compared to obtain PWM waveform. Simple analogue comparator can be used.
  - Basically an analogue method. Its digital version, known as REGULAR sampling is widely used in industry.

PWM types

- Natural (sinusoidal) sampling (as shown on previous slide)
  - Problems with analogue circuitry, e.g. Drift, sensitivity etc.
- Regular sampling
  - simplified version of natural sampling that results in simple digital implementation
- Optimised PWM
  - PWM waveform are constructed based on certain performance criteria, e.g. THD.
- Harmonic elimination/minimisation PWM
  - PWM waveforms are constructed to eliminate some undesirable harmonics from the output waveform spectra.
  - Highly mathematical in nature
- Space-vector modulation (SVM)
  - A simple technique based on volt-second that is normally used with three-phase inverter motor-drive

Modulation Index, Ratio



Modulation Index (Modulation Depth) = M_I :

$$M_I = \frac{\text{Amplitude of the modulating waveform}}{\text{Amplitude of the carrier waveform}}$$

Modulation Ratio (Frequency Ratio) = M_R (= p)

$$M_R = p = \frac{\text{Frequency of the carrier waveform}}{\text{Frequency of the modulating waveform}}$$

Modulation Index, Ratio

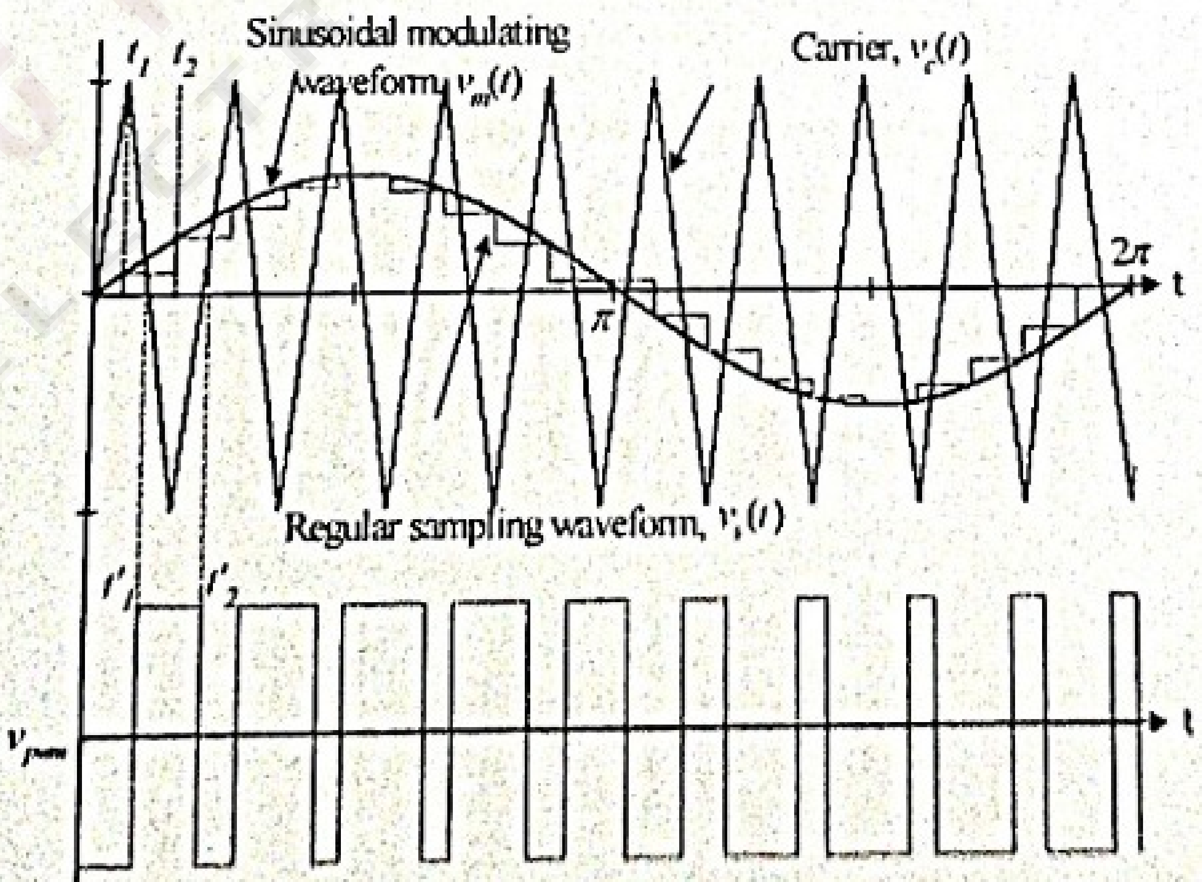
Modulation Index determines the output voltage fundamental component

If $0 < M_I < 1$,
$V_1 = M_I V_m$
where V_1, V_m are fundamental of the output voltage and input (DC) voltage, respectively.

Modulation ratio determines the incident (location) of harmonics in the spectra.

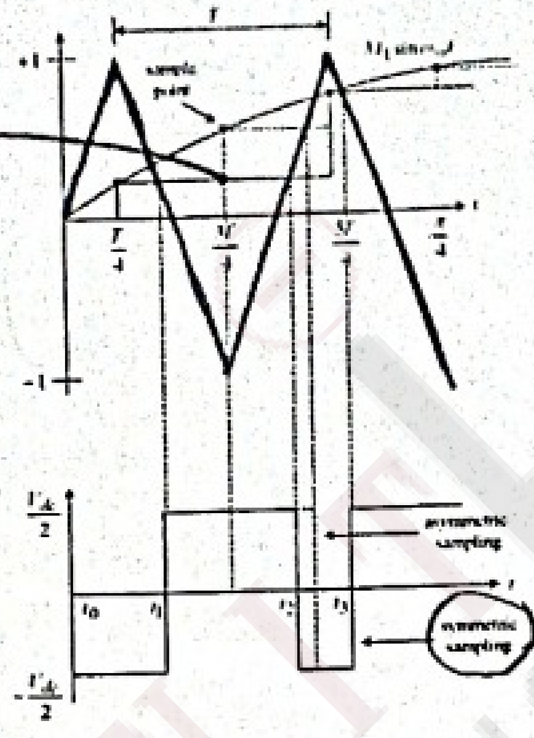
The harmonics are normally located at :
$f = kM_R(f_m)$
where f_m is the frequency of the modulating signal and k is an integer (1,2,3...)

Regular sampling



Regular sampling PWM

Asymmetric and symmetric regular sampling

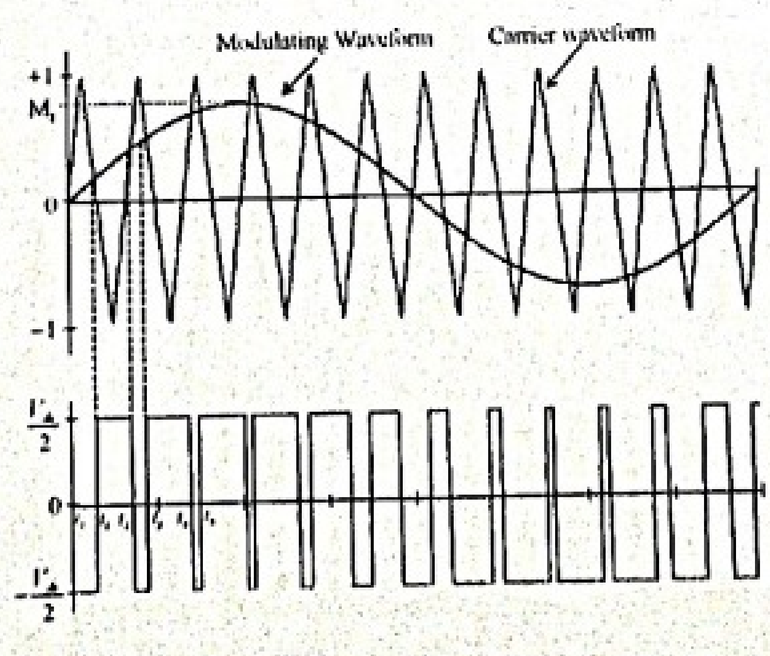


Generating of PWM waveform regular sampling

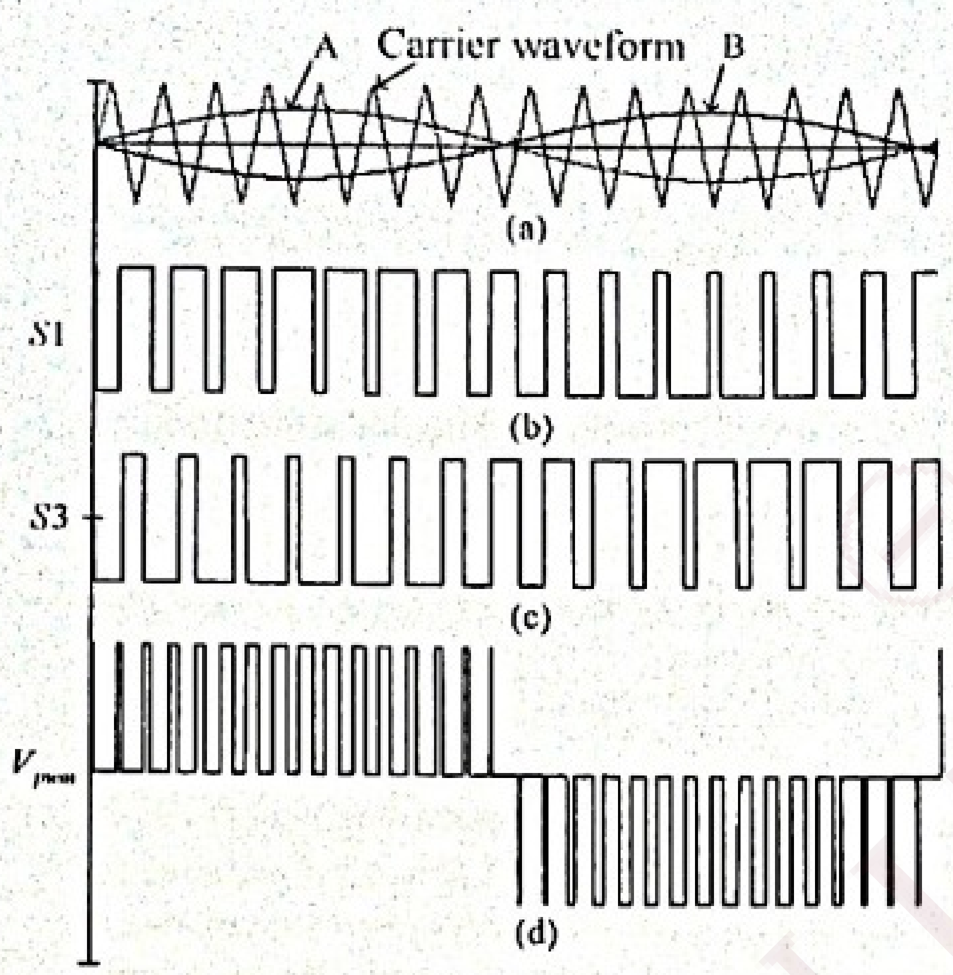
من منتصف المسافة نرسم خط ليتقاطع مع ال sine
على امتداد نقطة التقاطع (الامتداد الافقي)
فين مابيقطع ال carrier بناخذ ال
Asymmetrical لعندها .

intersection point between carrier & squre wave

Bipolar Switching

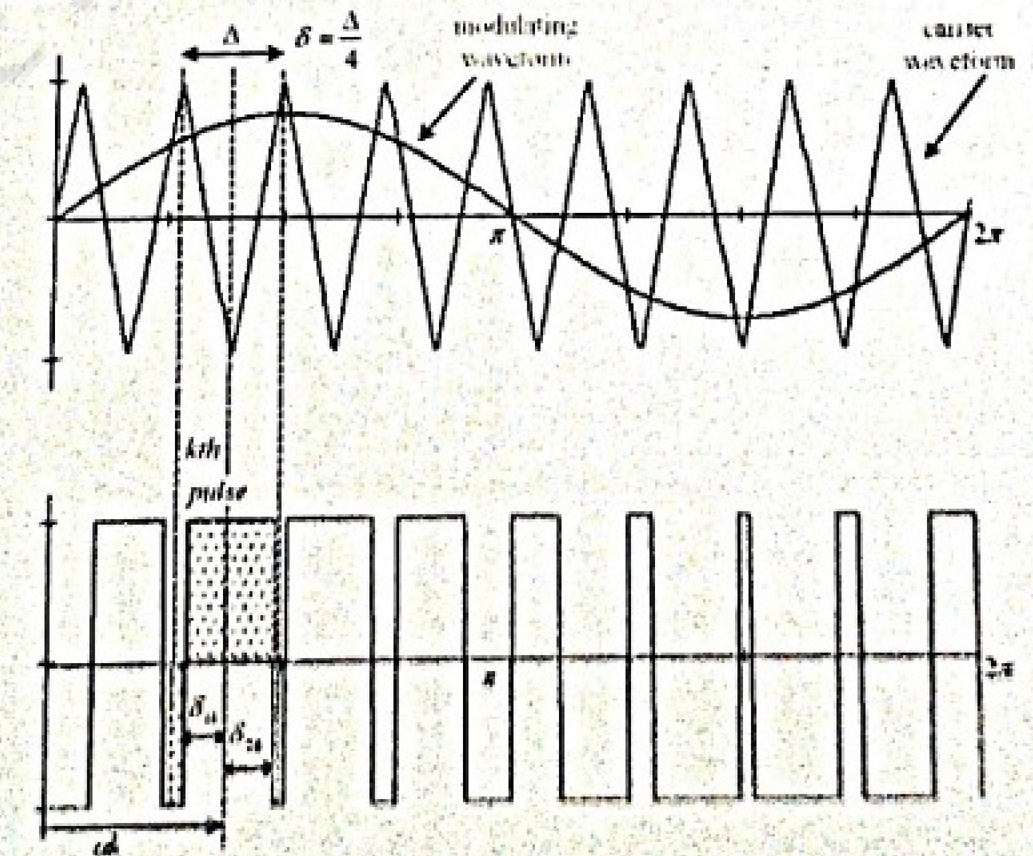


Unipolar switching



Unipolar switching scheme

Bipolar PWM switching: Pulse-width characterization



Three-phase harmonics

- For three-phase inverters, there is significant advantage if M_R is chosen to be:
  - **Odd:** All even harmonic will be eliminated from the pole-switching waveform.
  - **triplens** (multiple of three (e.g. 3,9,15,21, 27..): All triplens harmonics will be eliminated from the line-to-line output voltage.
- By observing the waveform, it can be seen that with odd M_R, the line-to-line voltage shape looks more "sinusoidal".
- As can be noted from the spectra, the phase voltage amplitude is 0.8 (normalised). This is because the modulation index is 0.8. The line voltage amplitude is square root three of phase voltage due to the three-phase relationship

Effect of odd and "triplens"

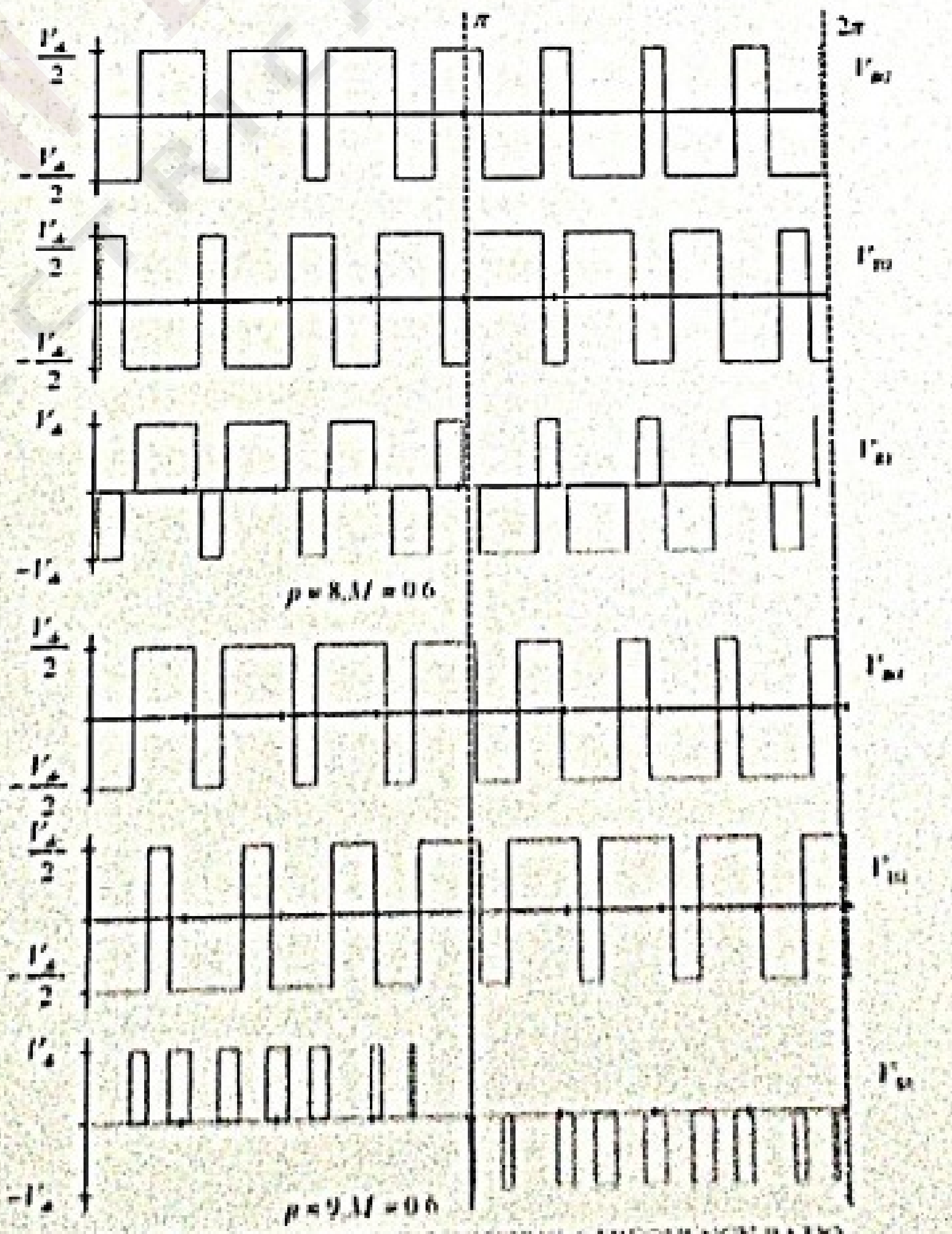


ILLUSTRATION OF BENEFITS OF USING A FREQUENCY RATIO THAT IS A MULTIPLE OF THREE IN A THREE PHASE INVERTER

Three phase inverter with RL load

- It is desirable to have M_R as large as possible.

- This will push the harmonic at higher frequencies on the spectrum. Thus filtering requirement is reduced.

- Although the voltage THD improvement is not significant, but the current THD will improve greatly because the load normally has some current filtering effect.

- However, higher M_R has side effects:
  - Higher switching frequency: More losses.
  - Pulse width may be too small to be constructed. "Pulse dropping" may be required.