Advanced power Electronics. (APEC)

Date 13/03/2022

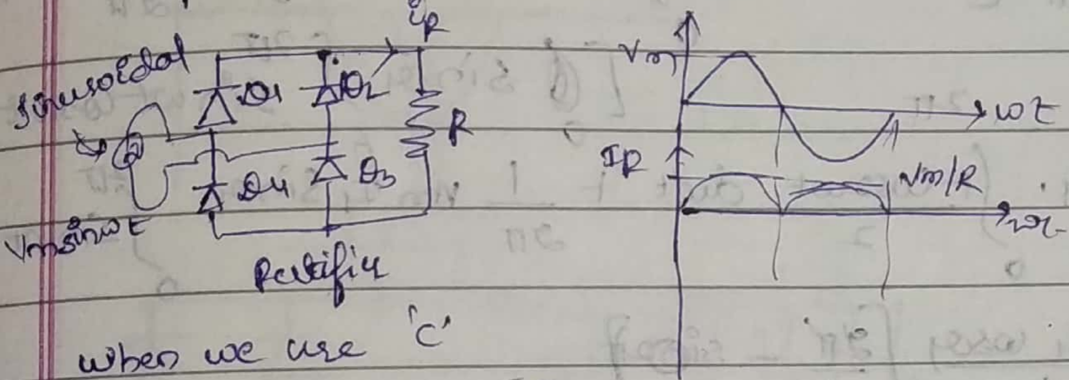
Module - 3

APFC

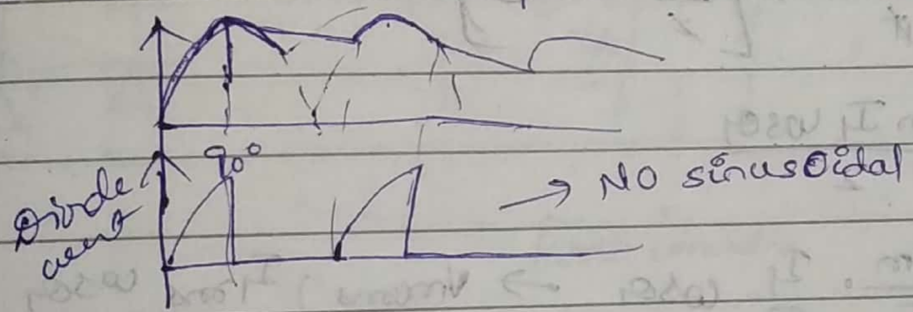
power factor $(\cos\phi)$ = (Active power $(VI\cos\phi)$) / (Appalant power (VI)) $\rightarrow \cos\phi$

Power = $VI\cos\phi$

Assumption → we have assumed V & I are pure sinusoidal



when we use 'C'



PF = $\frac{\text{Active power}}{\text{Appalant power}}$

first power

$p(t) = v(t) \cdot i(t)$

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

$i(t) = \sum_n I_n \sin(n\omega t + \theta_n)$

$p(t) = V_m \sin\omega t \times \sum_n \sin(n\omega t + \theta_n)$

$= V_m \left[(\sin\omega t \sin n\omega t \cdot \cos\theta_n) I_n + \sum_n (\sin\omega t \cos n\omega t \sin\theta_n) I_n \right]$

consider $n=1$ & take the average value

$$p(t) = V_m I_1 [\sin\omega t \sin\omega t \cos\theta_1 + \sin\omega t \cos\omega t \sin\theta_1]$$

$$p(t) = V_m I_1 [\sin^2\omega t \cos\theta_1 + \sin\omega t \cos\omega t \sin\theta_1]$$

Average value

$$\text{avg } P = \frac{1}{2\pi}\int_0^{2\pi} (V_m I_1 \sin^2\omega t \cos\theta_1 \, d\omega t + \frac{1}{2\pi}\int_0^{2\pi} V_m I_1 \sin\omega t \cos\omega t \sin\theta_1 \, d\omega t$$

$$P_{avg} = \frac{1}{2\pi}\left[V_m I_1 \cos\theta_1 \int_0^{2\pi} \sin^2\omega t \, d\omega t\right] + \frac{1}{2\pi} V_m I_1 \left[\sin\theta_1 \int_0^{2\pi} \sin\omega t \cos\omega t\right]$$

$$P_{avg} = \frac{V_m I_1 \cos\theta_1}{2\pi} \int_0^{2\pi} \frac{1-\cos 2\omega t}{2} \, d\omega t + \frac{1}{2\pi} V_m I_1 \sin\theta_1 \int_0^{2\pi} \sin\omega t \cos\omega t$$

$$\Rightarrow \frac{V_m I_1 \cos\theta_1}{2\pi}\left[\frac{2\pi}{2} - \sin 0\right]$$

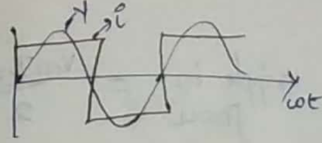
$$P_{avg} \Rightarrow \frac{V_m I_1 \cos\theta_1}{2}$$

$$P_{avg} \Rightarrow \frac{V_m}{\sqrt{2}} \cdot \frac{I_1}{\sqrt{2}} \cos\theta_1 \rightarrow V_{m(rms)} I_{1rms} \cos\theta_1$$

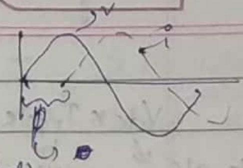
Apparant power = $V_{rms} I_{rms}$ → (harmonic not for so one is not there)

$$pf = \frac{V_{rms} I_{1rms} \cos\theta_1}{V_{rms} I_{rms}} \Rightarrow \underbrace{\frac{I_{1rms}}{I_{rms}}}_{\text{Distortion factor}} \underbrace{\cos\theta_1}_{\text{Displacement factor}}$$

$$pf = (\text{Distortion factor} \times \text{Displacement factor})$$

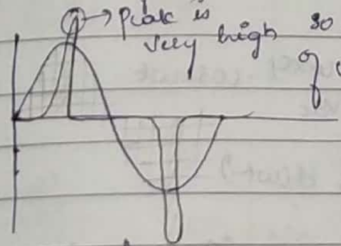


Displacement factor = 1

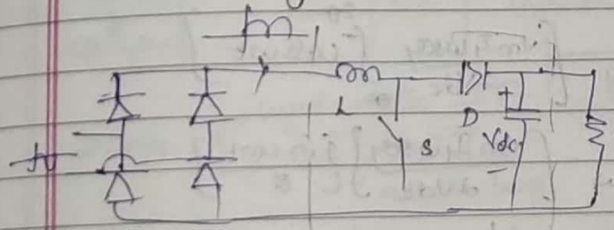


(Displacement → phase difference)

(by improving pf we can reduce the rms value of source current required)



Peak is very high so damage the equipments so shaping of current is important



Boost converter

Boost PFC
1) Vdc controlled by duty ratio
2) shaping of current.

Design of capacitor :-

→ using capacitor to reduce (or) eliminate the ripple in Vg & current i.e instantaneous power

$$p(t) = V_m I_1 \cos\theta_1 * \sin^2\omega t$$

$$\Rightarrow V_m I_1 \cos\theta_1 \frac{(1-\cos 2\omega t)}{2}$$

$$\Rightarrow \underbrace{\frac{V_m I_1 \cos\theta_1}{2}}_{\text{constant } P_0} - \underbrace{\frac{V_m I_1 \cos\theta_1}{2} \cdot \cos 2\omega t}_{\text{avg val} = 0}$$

$P_{avg} = \frac{V_m I_1 \cos\phi_1}{2}$ ripple in power $= \frac{V_m I_1 \cos\phi}{2} \cos 2\omega t$

2nd harmonic content

$V_{dc} \times I_{ripple} = \frac{V_m I_1 \cos\phi_1}{2} \cos 2\omega t$

V_{dc}: vg a/c capacitor; I_{ripple}: current flowing to C

$I_{ripple} = \frac{V_m I_1 \cos\phi_1}{2 V_{dc}} \cdot \cos 2\omega t$

$\Delta V_{dc} = \frac{1}{C\omega} \int_0^{2\pi} I_{ripple}\, d(\omega t)$

$= \frac{1}{C\omega} \left[\frac{V_m I_1 \cos\phi_1}{2 V_{dc}} \int_0^{2\pi} \cos 2\omega t \right]$

$\Rightarrow \frac{1}{C\omega} \left[\frac{V_m I_1 \cos\phi_1}{2 V_{dc}} \right] \left[\frac{\sin 2\omega t}{2} \right]$

$\Delta V_{dc(max)} = \frac{1}{4C\omega} \times \frac{V_m I_1 \cos\phi_1}{V_{dc}}$

$C \geq \frac{V_m \cdot I_1 \cos\phi_1}{4\omega \cdot \Delta V_{dc(max)} \cdot V_{dc}}$

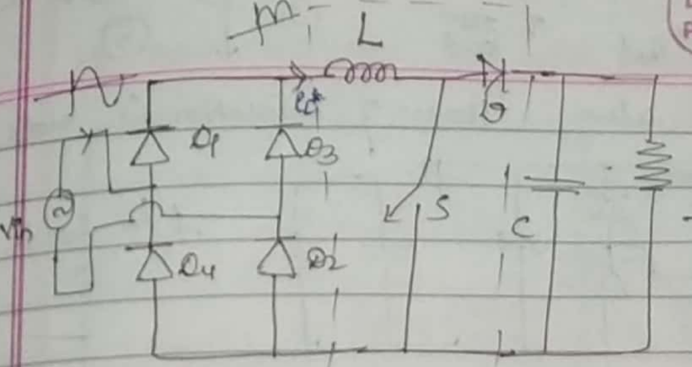
$I_{ripple} = C\frac{dv}{dt}$

$I_c = C\frac{dv}{dt}$

$\Delta V = \frac{1}{C} \int I_c\, dt$

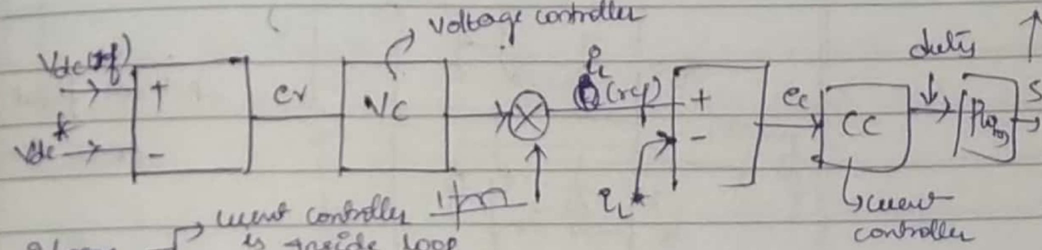
15/3/22

Date: Page:

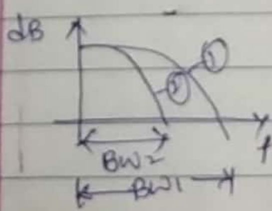


1) DC Voltage regulation
2) current shaping

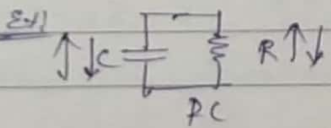
Snubber



2 loops —
- current controller is inside loop
- Voltage controller outside loop



2nd one is faster compared to 1st

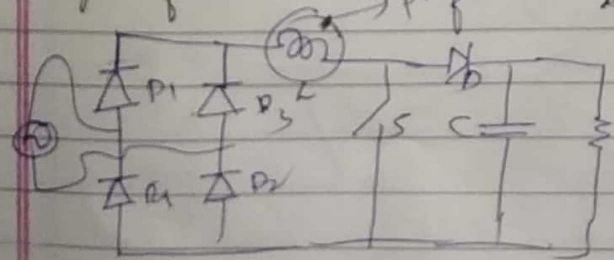


$\uparrow \tau = RC \downarrow$

$\tau = RC \downarrow \rightarrow$ constant

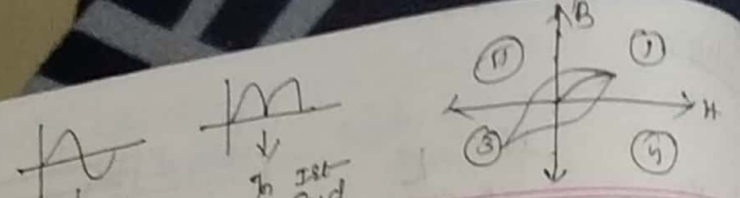
$\downarrow BW = \frac{1}{\tau \uparrow}$ $\uparrow BW = 1/\tau \downarrow$

Design of Inductor :- preferred dc side b/oz size requirement is less



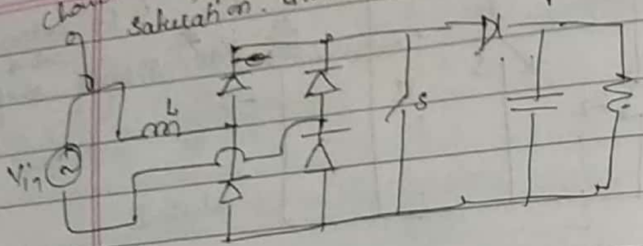
AC → ↓ size

DC →

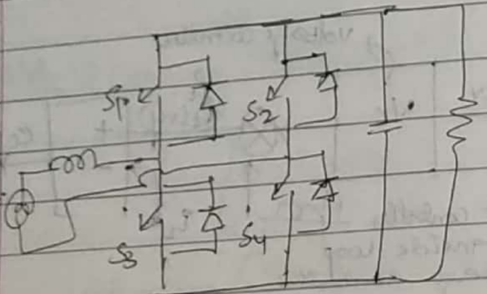


I^{st} + 3^{rd} Quad → charges saturation is less

In I^{st} Quad → charges of saturation is more



f ↑, Size ↓

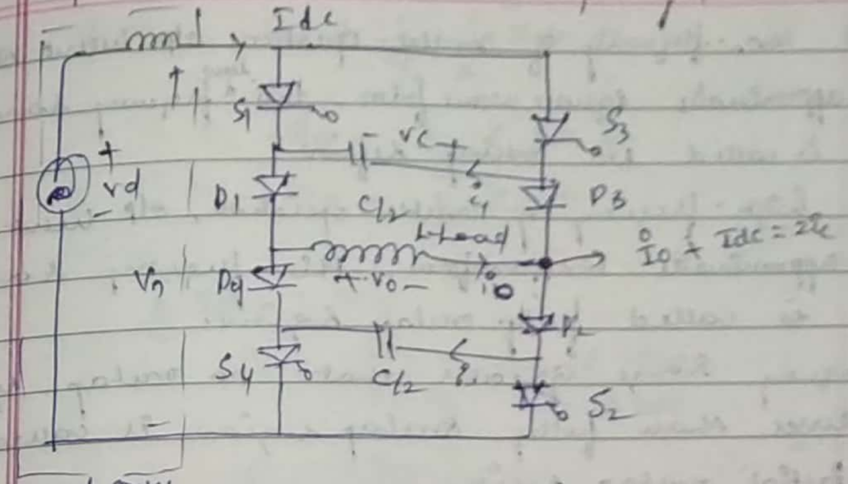


Actual front end pfc circuit

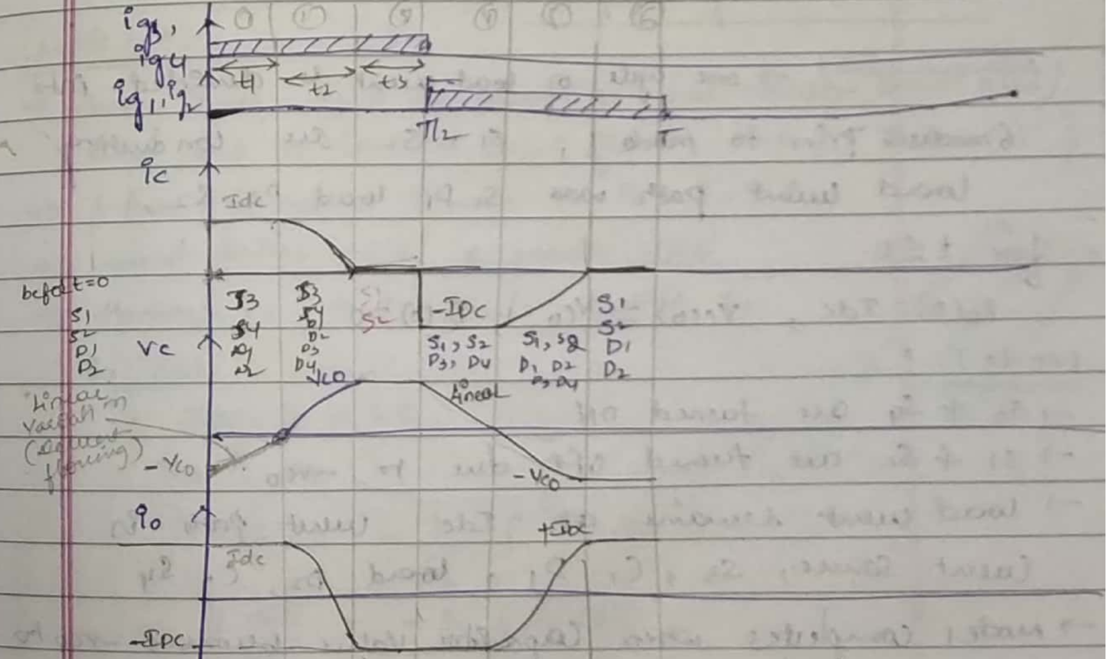
ac → dc	dc − ac
S3 → +v	S1 → +ve
S4 → −v	S2 → −ve

22/03/22

1ϕ load commutated CSI with purely inductive load.



current source



→ At low frequency of inverter operations o/p current will approximately square wave form. This low frequency range is called No overlap region.

→ At high frequency of inverter operation, o/p current approximately sinewaveform. This frequency range is called fully overlap region.

→ frequency range greater than no overlap region and lesser than fully overlap region is called partial overlap region

CSI in No overlap region :-

(Diagram same) → one cycle of load current is divided into 6 modes. Prior to mode 1, S_1, S_2 are conducting load current path was S_1 D_1 load D_2 S_2.

for $t \leq 0$

$i_o(0) = I_{dc}$, $V_C(0) = -V_{CO}$, $i_C(0) = 0$

Mode 1 :-

→ S_3 & S_4 are turned ON

→ S_1 & S_2 are turned OFF due to $-V_{CO}$

→ load current remains at I_{dc} current path is current source, S_3, C_1 D_1, load D_2, C, S_4

→ Mode 1 completes when capacitor value becomes $-V_{CO}$ to zero.

$$V_C(t) = -V_{CO} + \frac{1}{C/2}\int_0^t I_{dc}\,dt$$

$$= -V_{CO} + \frac{2}{C}\int_0^t I_{dc}\,dt$$

$$\Rightarrow -V_{CO} + \frac{2}{C} I_{dc}\, t$$

$t_1 \Rightarrow$ duration of mode 1.

$$\frac{2}{C} I_{dc} t = V_{CO}$$

$$t_1 = \frac{V_{CO}}{I_{dc}\,2/C} \Rightarrow \frac{C V_{CO}}{2 I_{dc}}$$

$$t_1 = \frac{C V_{CO}}{2 I_{dc}}$$

Mode 2 :-

→ when $V_C = 0$, D_3 & D_4 become ON. (as voltage all load also zero due to constant current flowing through the load 'L')

→ L & C are shorted through D_1, D_2, D_3 & D_4

→ current enters to L, C parallel ckt

→ through S_3 and leaves through S_4

(since all are conducting so load current is not constant)

By KCL

- $I_{dc} + i_o = 2 i_c$
- $V_o = -V_C$

$$L\frac{di_o}{dt} = -\frac{1}{C/2}\int_0^t i_c\,dt$$

$$L\frac{di_o}{dt} = -\frac{2}{C}\int_0 i_c(t)$$

$$\frac{di_o(t)}{dt} = -\frac{2}{LC} i_c(t)$$

$$\frac{di_0(t)}{dt} = -\frac{2}{LC} i_c \cdot t$$

$$\cancel{s\, I(s)} = \cancel{\frac{2}{LC}}$$

$$\left\{ \begin{array}{l} i_0(t) = -\frac{2}{LC} i_c \frac{t^2}{2} \\ i_0(t) = -\frac{i_c}{LC} t^2 \end{array} \right\} \times$$

$$\boxed{i_0(t) = I_{dc}(2\cos\omega_0 t - 1)}$$

$$\left\{ \begin{array}{l} L\frac{di_0(t)}{dt} = -\frac{2}{C}\int_0^t i_c\, dt \\ L\frac{di_0^2(t)}{dt^2} = -\frac{2}{C} i_c(t) \\ Ls^2 I_0(s) = -\frac{2}{C} I_c(s) \\ I_0(s) = \end{array} \right\} \times$$

$$L\frac{di_0}{dt} = -\frac{1}{C/2}\int_0^t i_c\, dt$$

$$= -\frac{1}{C/2}\int_0^t I_{dc} + i_0(t)\, dt$$

Initial conditions for mode 2

$i_0(0) = I_{DC}$

$$L\frac{di_0}{dt}\Big|_{t=0} = V_c\Big|_{t=0} = 0$$

25/03/22

Date......
Page......

$$L\frac{di_0}{dt} = -\frac{2}{C}\int_0^t \frac{I_{dc} + i_0(t)\, dt}{2}$$

$$L\frac{di_0^2}{dt^2} = -\frac{2}{C} I_{dc} + i_0(t)$$

$$L\frac{di_0^2}{dt^2} = -\frac{2}{C} I_{dc} + \frac{2}{C} i_0(t)$$

$$L\frac{di_0^2}{dt^2} + \frac{2}{C} i_0(t) = -2/C\, I_{dc}$$

$$Ls^2 I_0(s) + \frac{2}{C} I_0(s) = -2/C\, I_{dc}$$

$$I_0(s)\left[Ls^2 + \frac{1}{C}\right] = \frac{2}{C} I_{DC}$$

$$I_0(s) = \frac{-I_{DC}/C}{Ls^2 + 1/C}$$

$$\Rightarrow \frac{-I_{DC}/C}{\frac{LCs^2+1}{C}}$$

$$\Rightarrow -I_D\left[\frac{1}{(\cancel{LCs})^2 + s^2 + (1/\sqrt{LC})^2}\right]$$

$$\Rightarrow -I_{DC}\left[\right.$$

$$i_0(t) = I_{dc}[2\cos\omega_0 t - 1]$$

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

$$i_c(t) = I_{DC}(2\cos\omega_0 t - 1) + I_{DC}$$

Sulekha

$i_c(t) = \frac{I_{DC}}{\cancel{x}}\left[2\cos w_0 t - 1 + 1\right]$

$i_c(t) = I_{DC}\cos w_0 t$

mode 2 completing when $i_c(t) = 0$

$0 = I_{DC}\cos w_0 t$

$\cancel{\cos w_0 t} = .$

$i_c(t) = I_{DC}\cos w_0 t$

$V_c(t) = \frac{1}{C/2}\int_0^t i_0\,dt$

$\Rightarrow \frac{2}{C}\int_0^t I_{DC}(2\cos w_0 t - 1)\,dt$

$\Rightarrow \frac{2I_{DC}}{C}\left[\frac{2}{w_0}\sin w_0 t\Big|_0^t - (\cancel{0}t)\right]$

$\Rightarrow \frac{2I_{DC}}{\cancel{x}}\left[w_0 2\sin w_0 t - t\right]$

$\Rightarrow 2\cdot\sqrt{\frac{L}{C}}\, I_{dc}\sin w_0 t$

$\Rightarrow V_{c0}\sin w_0 t$

$V_{c0} = 2\sqrt{\frac{L}{C}}\, I_{dc}$

mode 2 ends when $i_c = 0$

$w_0 t = \pi/2$

$i_0 = -I_{DC}$

Duration of mode 2 $\quad (w_0 t = \pi/2)$

$t_2 = \pi/2w_0$

Current commutation interval $t_c = t_1 + t_2$

$t_c = \frac{CV_{c0}}{2I_{DC}} + \frac{\pi}{2w_0}$

- As $i_c = i_{diode} = 0$, D_1 & D_2 become off (bcz $i_c = 0$) (same current flowing)

Mode 3 current path is source, S_3, D_3 load D_4 & S_4

$i_c = 0,\quad i_0 = -I_{dc},\quad V_c = V_{c0} = 2\sqrt{\frac{L}{C}}\, I_{dc}$

→ this mode continues till S_1 & S_2 are turned ON at $T/2$

$t_3 = T/2 - (t_1 + t_2)$

$\Rightarrow T/2 - \left[\frac{CV_{c0}}{2I_{DC}} + \frac{\pi}{2w_0}\right]$

$\Rightarrow \frac{T}{2} - \left[\frac{C\cdot\cancel{2}\sqrt{\frac{L}{C}}\, I_{dc}}{\cancel{2}I_{DC}} + \frac{\pi}{2w_0}\right]$

$\Rightarrow \frac{T}{2} - \left[\sqrt{LC} + \pi/2w_0\right]$

$\Rightarrow \frac{T}{2} - \left[\sqrt{LC} + \frac{\pi\sqrt{LC}}{2}\right]$

$\Rightarrow \frac{T}{2} - (1 + \pi/2)/w_0$

Mode IV :-

During mode 4 S_1 & S_2 are turned ON & S_3 & S_4 are turned off due to $V_c = +V_{c0}$

the load current remains in the same direction

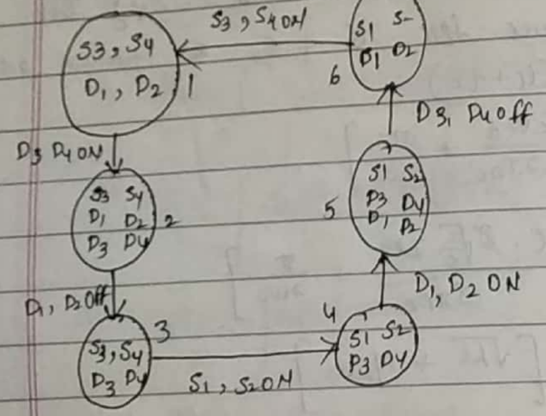
path is S_1, $C/2$, D_3, load, D_4, $C/2$, & S_2.

→ V_{C0} reduces linearly to zero

→ $I_0 = -I_{DC}$

Translation Diagram of 1φ CSI in No-overlap region of freq.

→ for No over range of frequency, sequence of operating modes is 1, 2, 3, 4, 5, 6.



→ commutation interval $t_c = \frac{1}{\omega_0}\left[1 + \pi/2\right] = \frac{2.57}{\omega_0}$

→ Duration of mode 3 $t_3 = \frac{T}{2} - \frac{2.57}{\omega_0}$

→ for higher frequency T_3 will effect (this)

→ when Inverter frequency is increased, T is decreased and t_3 is also decreased.

→ At the limiting values of no overlap range of frequency, t_3 becomes zero

$$\frac{T_{NL}}{2} - \frac{2.57}{\omega_0} = 0$$

T_{NL} → No overlap period.

→ T_{NL} is the minimum period for no overlap condition

$$\frac{T_{NL}}{2} = \frac{2.57}{\omega_0}$$

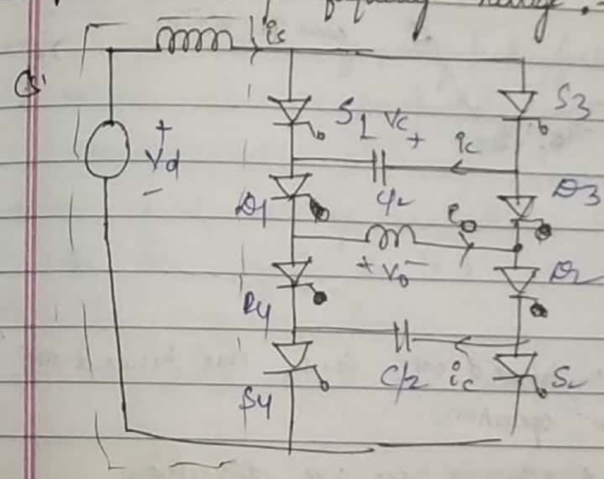
→ maximum frequency limit for no overlap condition

$$f_{NL} = \frac{\omega_0}{5.14} = \frac{0.19}{\sqrt{LC}}$$

→ beyond f_{NL} we get partial overlap condition

29/3/22

Partial overlap frequency range :-



→ Inverter frequency is greater than $f_{NL} = \frac{0.19}{\sqrt{LC}}$

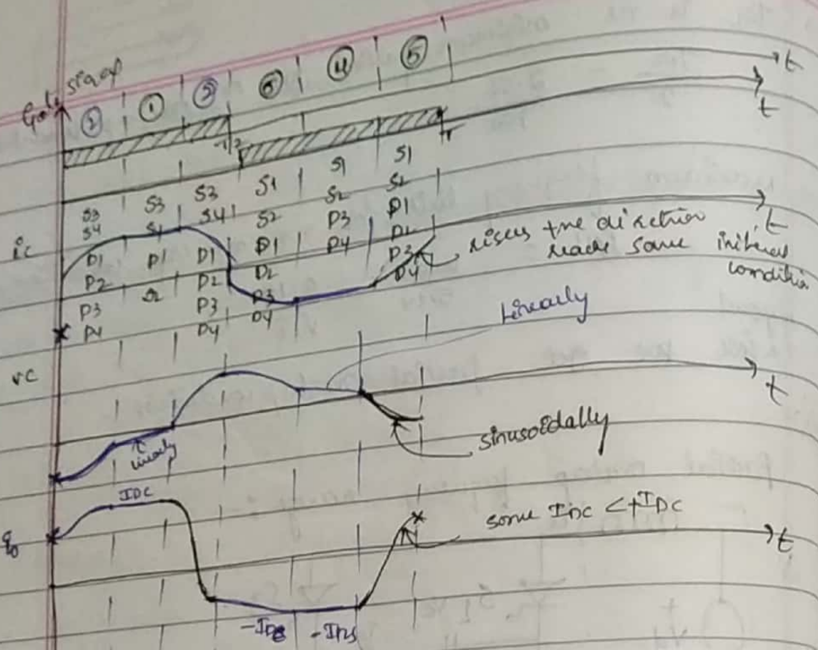
→ mode 3 & 6 are absent

→ for $t < 0$, the Inverter was in mode 5, $S_1 S_2 D_1$, D_2, D_3, D_4, were conducting

load current was oscillatory

i_c & V_c were −ve, i_0 is +ve

(Thyristorised power controller by ... pubey for CSI)



→ At t=0, S_3, S_4 are turned ON S_1, S_2 are turned off
this results in mode 2 operation.

→ i_c becomes +ve and rises in the +ve direction

→ i_o which is +ve rises to a constant value I_{dc}

→ v_c rises with a +ve slope

→ drop across the load becomes zero due to constant current of I_{dc}. D_3, D_4 are turned off

→ this results in mode 1 operation.

→ current path: source, S_3, C, D_1, load, D_2, C, S_4

→ mode 1 ends when $V_c = 0$, D_3 & D_4 are brought into conduction resulting mode 2 condition.

→ i_c rises in the +ve direction, i_o reverses to a value less than I_{DC}.

→ In partial overlap condition, sequence of modes in one cycle is 2, 2, 5, 4, 5

→ maximum frequency limit for partial overlap condition is $f_{PL} = \frac{0.24}{\sqrt{LC}}$.

Fully overlap condition :-

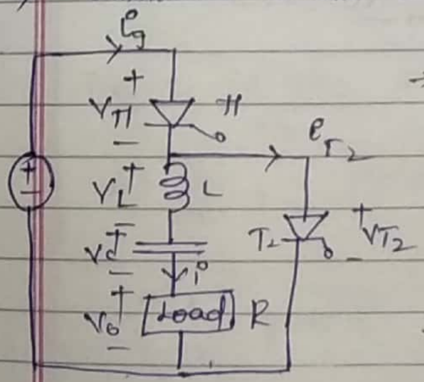
→ If the inverter frequency is further increased, all the diodes conduct continuously resulting in sine wave load current.

→ In fully overlap condition, sequence of modes in one cycle is 2, 2, 5

1/4/22

Series Inverter :-

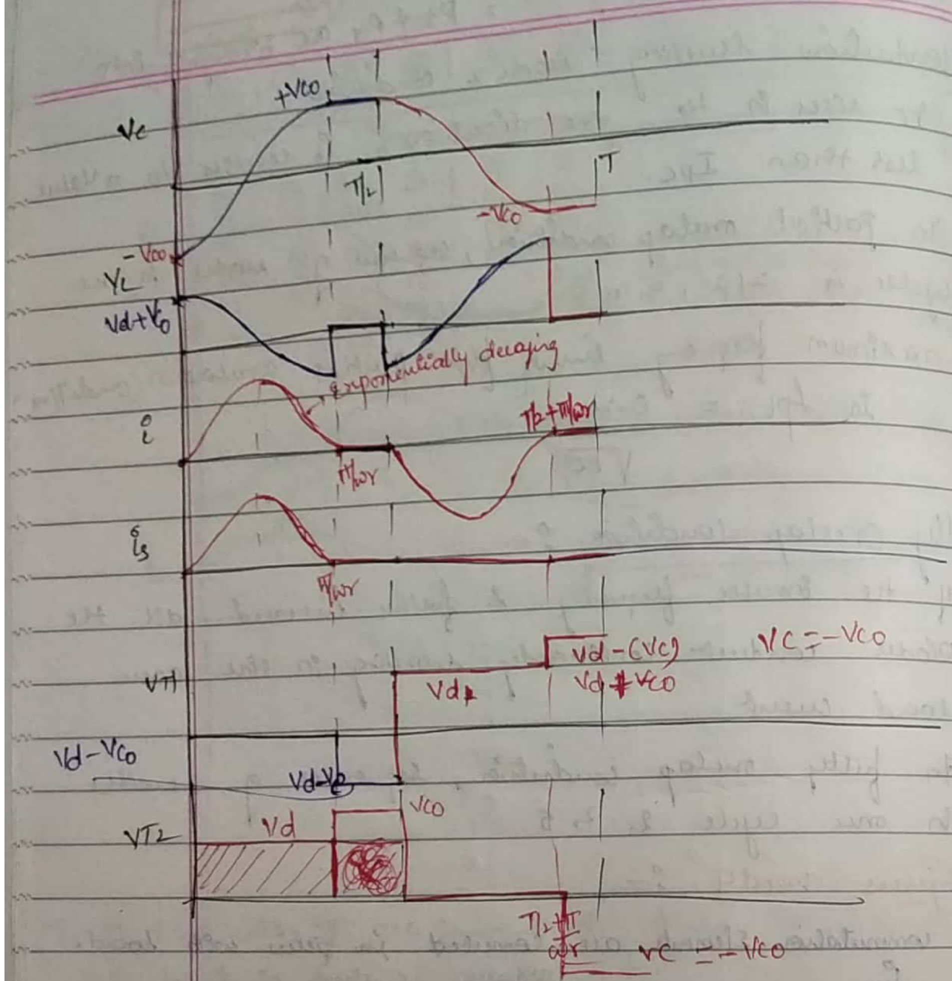
→ commutation elements are connected in series with load.



→ commutating elements L & C are connected in series with load.

→ load current flows continuously through L & C

→ hence this ckt is used in high frequency application



→ L & C are selected such that the combination RLC is underdamped.

At $t=0$, T_1 is turned ON, T_2 is in the off state

$$V_d = R\,i(t) + L\frac{di(t)}{dt} + \frac{1}{C}\int i(t)\,dt + V_c(0), \quad 0<t<T/2$$

At $t=0$

$i(0) = 0$, $V_c(0) = -V_{co}$

$$L\frac{di(t)}{dt}\Big|_{t=0} = V_d + V_{co}$$

$$\frac{dV_d}{dt} = R\,i(t)\cdot\frac{d}{dt} + L\frac{d^2 i(t)}{dt^2} + \frac{1}{C}\cdot i(t) + \frac{d(V_c(0)-V_{co})}{dt}$$

$$\frac{V_d}{s} = Rs\cdot I(s) + L s^2 I(s) + \frac{1}{Cs} I(s) + \frac{V_{co}}{s}$$

$$\frac{V_d}{s} = I(s)\left[Rs + s^2 L + \frac{1}{Cs}\right]$$

$$I(s) = \frac{V_d}{s\left[Rs + s^2 L + 1/Cs\right]}$$

$$\boxed{i(t) = \frac{V_d + V_{co}}{\omega_r L} e^{-\delta t}\sin\omega_r t}$$

$$\delta = \frac{R}{2L}, \quad \omega_r = \sqrt{\left(\frac{1}{LC}\right) - \left(\frac{R}{2L}\right)^2}, \quad \omega_0 = \frac{1}{\sqrt{LC}}$$

$$\omega_r = \sqrt{\omega_0^2 - \delta^2}$$

$$0 = R\frac{di(t)}{dt} + L\frac{d^2i(t)}{dt^2} + \frac{1}{C}i(t) + 0$$

$$R\,I(s)s + Ls^2I(s) + \frac{1}{Cs}I(s) = 0$$

$$R\frac{di(t)}{dt} + L\frac{d}{dt}\frac{di(t)}{dt} + \frac{1}{C}I(s)$$

$$R\,I(s)s + (Vd+Vco)\frac{d}{dt} + \frac{1}{C}I(s) = 0$$

$$I(s)\left[Rs + \frac{1}{Cs}\right] = -L\frac{(Vd+Vco)}{s}$$

$$I(s)\cdot\left[\frac{Rcs^2+1}{cs}\right] = -\frac{(Vd+V_{Co})}{s}$$

$$I(s) = \frac{-(Vd+V_{Co})}{Rcs^2+1}$$

$$i(t) = \frac{Vd+V_{Co}}{\omega_r L}e^{-\delta t}\sin\omega_r t$$

$$V_L(t) = L\frac{di(t)}{dt} \Rightarrow \frac{Vd+V_{Co}}{\omega_r L}\left[e^{-\delta t}\cdot\cos(\omega_r t)\omega_r + \sin\omega_r t\,(-\delta)\cdot e^{-\delta t}\right]$$

$$= \frac{Vd+V_{Co}}{\omega_r L}\left[e^{-\delta t}\cdot\omega_r\cdot\cos(\omega_r t) - \delta\sin\omega_r t\cdot e^{-\delta t}\right]$$

$$= \frac{Vd+V_{Co}}{\omega_r L}e^{-\delta t}\omega_r\cdot\cos\omega_r t - \frac{Vd+V_{Co}}{\omega_r L}\delta\sin\omega_r t\, e^{-\delta t}$$

$$\boxed{V_L(t) = (Vd+V_{Co})\,e^{-\delta t}\cos(\omega_r t+\phi)\cdot\frac{\omega_0}{\omega_r} \qquad \phi = \tan^{-1}\left[\frac{\delta}{\omega_r}\right]}$$ *

$V_C(t) = Vd - V_L - iR$; $V_{T_1} = 0$, $V_{T_2} = Vd$, $V_0 = i(t)R$

At $\omega_r t = \pi$, $i(t) = 0$, T_1 is turned off

→ $\pi/\omega_r < t < T/2$

Both switches are off

$i(t) = 0$, $i_s(t) = 0$, $V_L(t) = 0$, $V_C = V_{Cmax}$

19/04/22

→ $T/2 < t < T/2 + \pi/\omega_r$

$t' = t - T/2$

at $t' = 0$, T_2 is turned ON

→ $0 < t' < T/2$

$$0 = Ri(t') + L\frac{di(t')}{dt} + \frac{1}{C}\int i(t')\,dt + V_{Cmax}$$

at $t' = 0$

$i(0) = 0$, $V_C(0) = -V_{Cmax}$

$$\frac{di(t')}{dt}\Big|_{t'=0} = \frac{-V_{cmax}}{L}$$

at $t' = 0$

$V_c(0) = V_{cmax}$, $i(0) = 0$,

$$L\frac{d^2 i(t')}{dt^2} + \frac{1}{C} i(t') + R\frac{di(t')}{dt} + V_{cmax} = 0$$

$$L s^2 i(s) + \frac{1}{C} i(s) + sR\, i(s) + V_{cmax} = 0$$

$$\left(s^2 L + \frac{1}{C} + sR\right) i(s) = -V_{cmax}$$

$$i(s) = \frac{V_{cmax}}{s^2 L + 1/C + sR}$$

$$* \quad i(t) = \frac{V_{cmax}}{\omega_r L} e^{-\delta t} \sin \omega_r t'$$

$$i(t') = \frac{V_{cmax}}{\omega_r L} e^{-\delta t'} \sin(\omega_r t')$$

$$\delta = \frac{R}{2L}, \quad \omega_r = \sqrt{\left(\frac{1}{LC}\right) - \left(\frac{R}{2L}\right)^2}, \quad \omega_0 = \frac{1}{\sqrt{LC}}$$

$$\omega_r = \sqrt{\omega_0^2 - \delta^2}$$

$$v_L(t) = L\frac{di(t)}{dt} = \frac{-\omega_0}{\omega_r} V_{cmax} e^{-\delta t'} \cos(\omega_r t' + \phi)$$

$$v_c(t') = -V_L - iR$$

$V_{T_1} = +V_d \qquad V_{T_2} = 0, \qquad V_0 = -i(t')R$

at $\omega t = \pi$, $i(t') = 0$, T_2 is turned off

Drawbacks of Series Inverter

1) maximum Inverter frequency is limited to value less than the circuit ringing frequency (ω_r)
2) for very low values of inverter frequencies load voltage is highly distorted.

Design of 'L' :-

→ 'L' is chosen on the basis of attenuation factor.

$$i(t) = \frac{V_d + V_{co}}{\omega_r L} e^{-R/2L\, t} \sin \omega_r t$$

peak value of $i(t)$ is $\frac{V_d + V_{co}}{\omega_r L} e^{-R/2L \cdot \pi/2\omega_r}$. $\quad (\omega_r t = \pi/2)$

→ If there is no attenuation, then $i(t)$ would be

$\frac{V_d + V_{co}}{\omega_r L} \sin \omega_r t$ & peak value $= \frac{V_d + V_{co}}{\omega_r L}$

→ attenuation factor (AF) $= \dfrac{\frac{V_d + V_{co}}{\omega_r L} e^{-\frac{R}{2L}\frac{\pi}{2\omega_r}}}{\frac{V_d + V_{co}}{\omega_r L}} = e^{-\frac{R}{2L}\frac{\pi}{2\omega_r}}$

$$\ln(AF) = \frac{-R}{8 f_r L}$$

$$L = \frac{-R}{8 f_r \ln(AF)}$$

L selected such that $AF = 0.5$

R - given load Resistance.

Design 'C' :-

→ 'C' is selected from the value of ω_r

$$\omega_r = \sqrt{\left[\frac{1}{LC} - \left(\frac{R}{2L}\right)^2\right]}$$

$$C = \frac{1}{L}\left[\frac{1}{\omega_r^2 + \left(\frac{R}{2L}\right)^2}\right]$$

→ If the load is variable, then C is selected for the maximum possible value of R so that the circuit is under damped.

→ Voltage rating of 'C' is ~~Vd + Vco~~ V_{comax}

Selection of thyristor :-

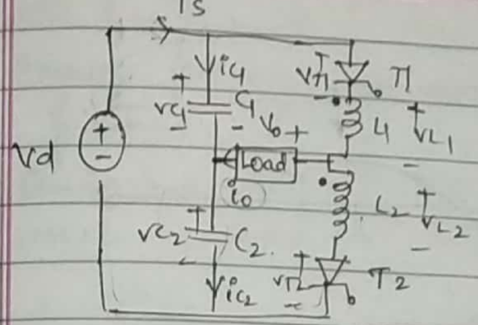
→ Forward blocking voltage rating must be greater than V_{cmax}

→ peak current rating must be greater than peak load current for minimum load resistance

$$\frac{V_d + V_{C0}}{\omega_r L} e^{-\frac{R_{min}}{2L} \cdot \frac{\pi}{2\omega_r}}$$

→ t_q must be less than $t_c = \frac{T}{2} - \pi/\omega_r$

Modified Series Inverter



$L_1 = L_2$

$C_1 = C_2$

L_1 & L_2 are tightly coupled

→ for $t = 0$ T_2 - ON

$V_{C1} = V_{cmax}$

$V_{C2} = -V_{cmin}$

i_0 is Negative.

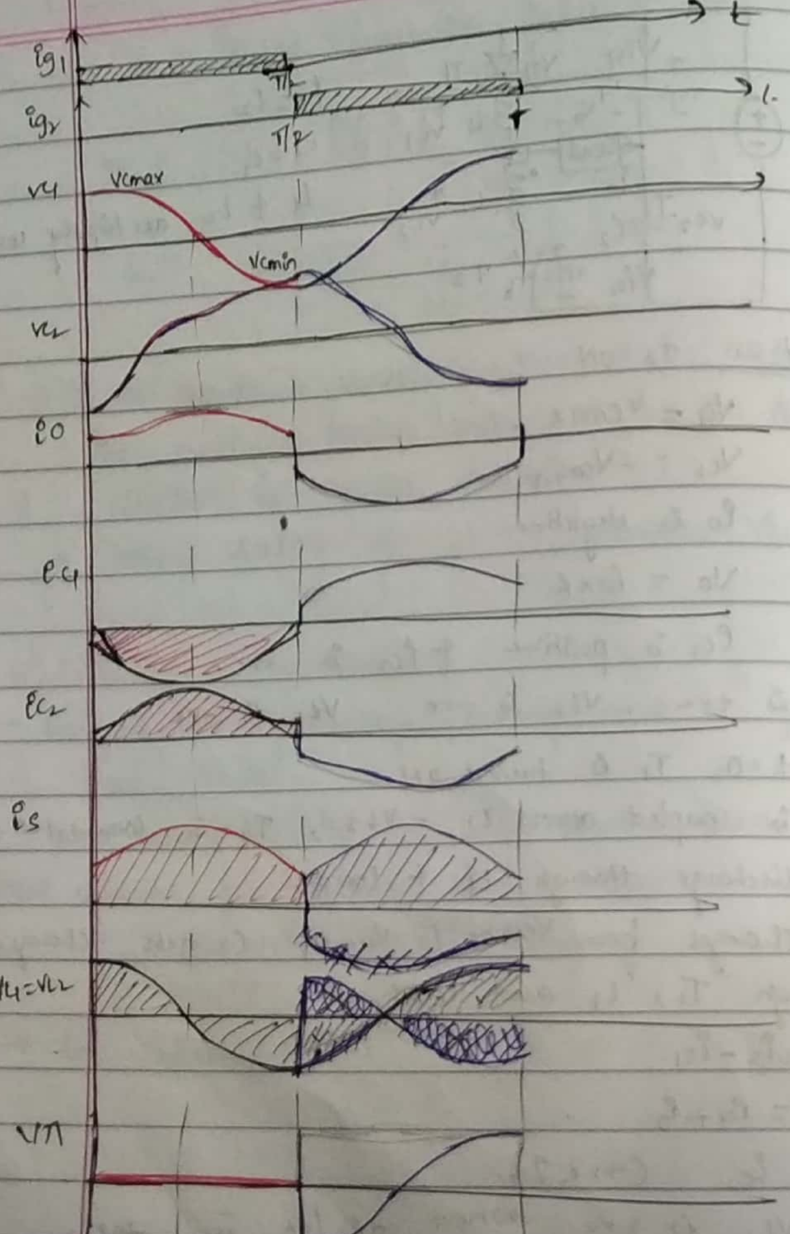
$V_0 = i_0 \times R$

i_{C1} is positive & i_{C2} is -ve.

i_s is +ve, V_{L2} is -ve, V_{L1} is -ve

- At $t = 0$, T_1 is turned ON
  V_{C1} is coupled across $L_1 = V_{L2}$, T_2 is commutated off
- C_1 discharge through L_1 & load.
- V_{C1} changes from V_{C1max} to V_{C1min}, C_2 gets charged through T_1, L_1 and load.
- $i_0 = i_s - i_{C1}$
- $i_{C2} = i_{C1} + i_0$
- $i_s = i_{C2}$ (+ve)
- $V_{L1} = V_{L2}$ is +ve when di_0/dt is +ve

Date........
Page........

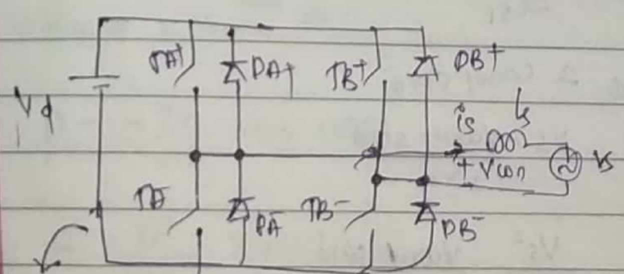


- At $t = T/2$, T_2 is turned ON
- Inverter frequency can be less than the ringing frequency
- During -ve half cycle also source supplies power
  lesser distortion in source current

22/4/22

→ Rectifier mode of operation occurs during regenerative braking of an induction motor load connected to a DC source through an inverter.

→ Kinetic energy associated with motor and load is recovered and fedback to the DC source.



→ A single phase induction motor is connected DC source through inverter

L_s → winding inductance

V_s → back emf (sinusoidal with fundamental frequency)

→ $V_{con} = V_{Ls} + V_s$

$V_{Ls} = L_s \, di_s/dt$

fundamental

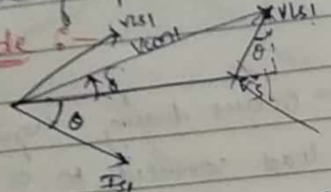
$V_{con1} = V_{Ls1} + V_s$

$V_s = V_{con1} - V_{Ls1}$

$= V_{con1} - j\omega L_s I_{s1}$

→ Direction of I_{s1} decides the inverter and rectifier mode of operation.

Inversion mode :-



• V_{con1} leads V_s by an angle 'δ'

• Real power at the AC side

$p = V_s I_{s1} \cos\theta$

$= V_s \times \frac{V_{Ls1}}{\omega L_{s1}} \cos\theta$

$V_{Ls1} \cos\theta = V_{con1} \sin\delta$

$p = \frac{V_s \cdot V_{con1} \sin\delta}{\omega L_{s1}}$

$p = \frac{V_s^2}{\omega L_{s1}} \frac{V_{con1} \sin\delta}{V_s}$

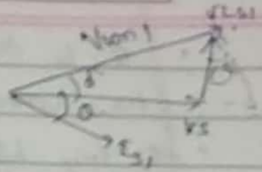
→ V_{con1} leads V_s and active components of I_{s1} is inphase with V_s.

Power flows from DC side to AC side ← Inversion mode

Reactive power at the AC side

$Q = V_s I_{s1} \sin\theta$.

$= V_s \frac{V_{Ls1}}{\omega L_{s1}} \sin\theta$



$V_{Ls1} \sin\theta = V_{con1} \cos\delta - V_s$

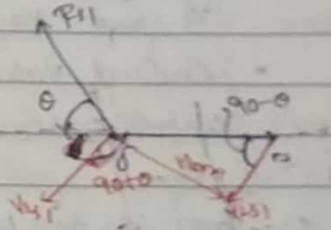
$Q = \frac{V_s}{\omega L_{s1}} [V_{con1} \cos\delta - V_s]$

$= \frac{V_s^2}{\omega L_{s1}} \left[\frac{V_{con1}}{V_s} \cos\delta - 1 \right]$

Rectifier mode :-

• V_{con1} lags the V_s by an angle 'δ'

• Real power at the AC side is



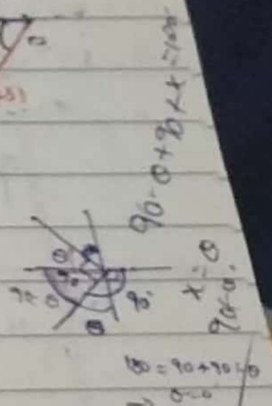
$p = V_s I_{s1} \cos(180 + \theta)$

$= -V_s \frac{V_{Ls1}}{\omega L_s} \cos\theta$

$V_{Ls1} \cos\theta = V_{con1} \sin\delta$

$p = -\frac{V_s}{\omega L_s} V_{con1} \sin\delta$

$= -\frac{V_s^2}{\omega L_s} \frac{V_{con1}}{V_s} \sin\delta$



Reactive power at the AC side :-

$Q = V_s I_{s1} \sin(180 + \theta)$

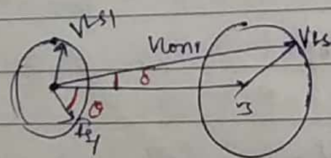
$= -V_s \frac{V_{Ls1}}{\omega L_{s1}} \sin\theta$

$Q = -\frac{V_s}{\omega L_{s1}} [V_s - V_{con1} \cos\delta]$

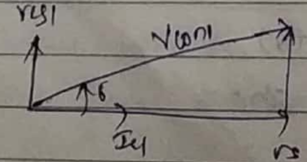
$Q = \frac{V_s^2}{\ } \left[\frac{V_{con1}}{V_s} \cos\delta - 1 \right]$

Refer (Ned Mohan chapter - 8 & 18)

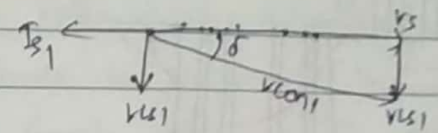
- Q is the sum of reactive power absorbed by the converter and inductance L_s.
- At very high switching frequencies L_s can be made very small
- then Q is the reactive power absorbed by the converter.
- For given value of AC side potential (back emf) V_s and the chosen value of inductance L_s,
- Desired values of P & Q can be obtained by controlling the magnitude and phase angle δ of V_{con1}.
- V_{con1} can be varied by keeping the magnitude of I_{s1} and V_s constant



Inversion at UPF !-



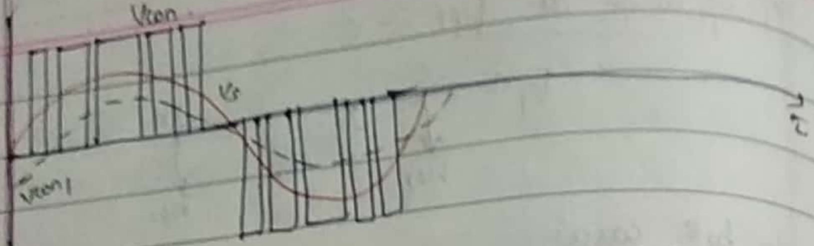
Rectification at UPF !-

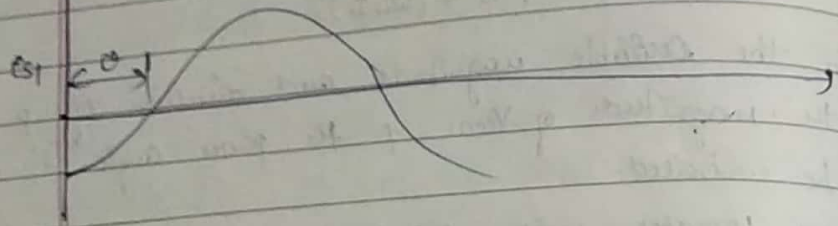


- In both cases

$$V_{con1} = \sqrt{V_s^2 + (\omega L_s I_s)^2}$$

- For the desirable magnitude and direction of P & Q, the magnitude of V_{con1} & the phase angle 'δ' must be controlled.
- PWM converter works in the linear ranges ($m_a \le 1$)
- Vd must be of sufficiently large magnitude $V_d > \sqrt{2} V_s$
- Reactive power flow can be controlled by introducing a phase shift between e_s & V_s
- PWM VSI based static VAr compensation
- PWM VSI based SVCs are viable solution to problems associated with passive shunt compensators, thyristor controlled reactors.
- They are capable of delivering controlled amount of lagging and leading VArs to a load on a bus system rapidly.



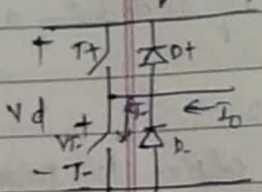


26/04/22 Resonant Converters :-

High frequency switchmode power converter :-

Advantage :- • high Efficiency

• Devices operate at the maximum Efficient points like cut off & Saturation points



• multi output is possible.

• Size and cost are much lower Especially at high power levels.

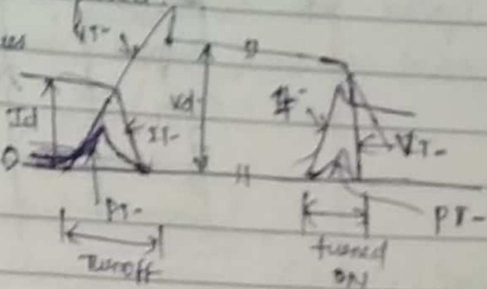
Limitations :-

• Greater circuit complexity compared to linear Converters.

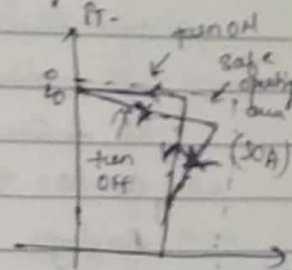
• Controllable Switches (Operated in a switch mode) are required to turn ON & turn OFF the entire load current during each switching

• Presence of large dV/dt and di/dt during switching hence high electromagnetic interference.

• High stress levels on devices that increases linearly with the switching frequency of the prom.



• higher switching losses at higher frequency

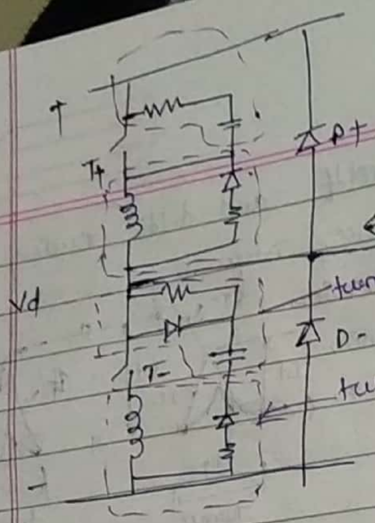


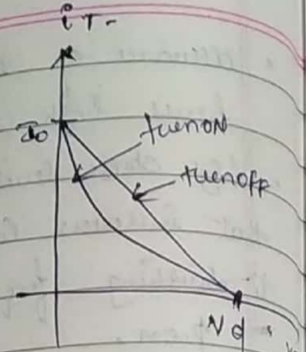
Dissipative Snubber ckts :-

• the switching stresses can be reduced by connecting simple dissipative circuits in series and parallel with the switches in the switch mode Converters.

• these Snubbers shift the switching power loss from the switch to the Snubber ckt and ∴ do not provide a reduction in the overall switching power loss.

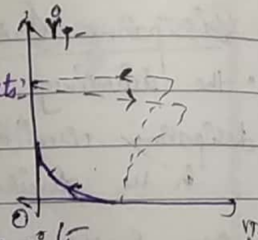
• To minimize these problems, switches are made to change the state of turn ON to turn OFF (or vice versa) when the voltage across it (or current through it) is zero at the switching instant.





• these topologies requires some form of LC resonance and hence, they are classified as resonant converters.

• the switch voltage and current are shaped so as to get zero voltage & (or) zero current during switching and are known as soft switching converters.



Advantage of soft switching resonant converters:

• Reduced power loss at high switching frequency
• less size and hence high power density
• high efficiency
• less stress on the devices.

(ned mohan)

Classification of Resonant Converters.

Resonant switch converters :-

• Additional ckt elements are added to get zero voltage/ zero current switching and are called resonant switch converters.

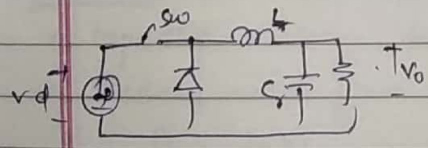
i) Zero current switching (ZCS) topology
ii) Zero voltage switching (ZVS) topology
iii) Zero voltage switching, clamped voltage. (ZVS CV) topology

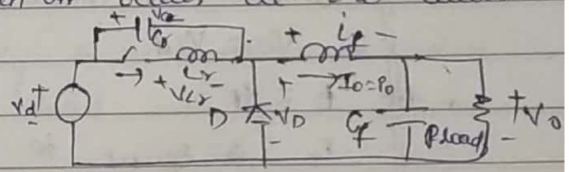
• LC resonance is utilized to shape the switch voltage and current to provide zero-voltage and/or zero current switching

• During one switching period, there are resonant as well as non-resonant operating intervals. therefore these converters are also known as quasi-resonant converters.

Zero current switching (ZCS) converters :-

• the switch turn ON and turn off occurs at zero current.





• Lr & Cr are the resonant elements used to get zero current turn ON & turn off condition.

initial conditions :-

- Let the switch is in the off condition.
- Diode is in the ON state
- $V_c = V_d$, $i_T = 0$
- At $t = t_0$ switch is turned ON.
- Due to the presence of inductance, turn ON occurs at zero current
- L_r & C_r are shorted through switch.

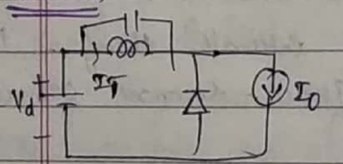
$V_{oi} = V_d - V_c = 0$

$V_c = V_d$

- Diode continuous to conduct.

$V_D = V_c = V_d$

- **$t_0 \to t_1$**



- $V_{Lr} = V_d$
- i_T rises linearly
- i_T is less than i_{Lf}
- $i_D = I_0 - i_T$

- D continuous to conduct untill $i_T = I_0$

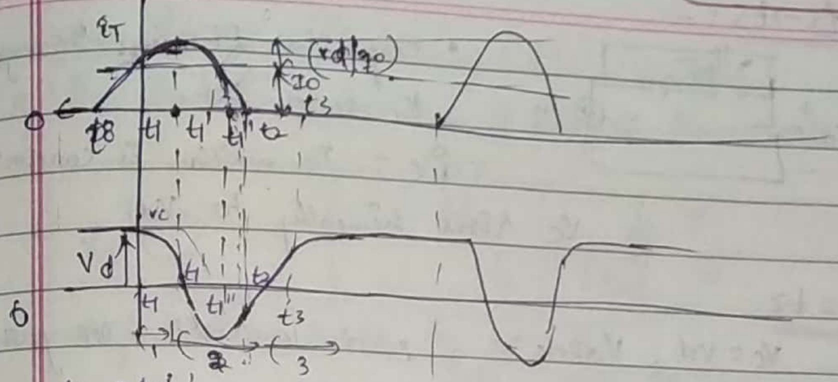
$V_c = V_d$

- At $t = t_1$

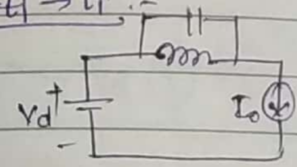
i_T is equal to i_{Lf}

- D stops conducting
- L_r & C_r form a parallel resonant ckt.

Date........ Page........



$t_1 \to t_1'$:-



- C_r discharges from V_d to zero through switch & L_r

$i_c = V_d \sqrt{\frac{L_r}{C_r}} \sin \omega_0 t$

$\omega_0 = \frac{1}{\sqrt{L_r C_r}}$

$i_T = I_0 + i_c$

- At t_1' i_T & i_c are the their peak value V_c reach zero.
- **$t_1' \to t_1''$**
- i_c decreases sinusoidally to zero
- At t_1'', $i_c = 0$, $i_T = I_0$, V_c reaches $-V_d$

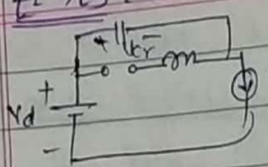
$t_1'' \to t_2$

- capacitor discharges sinusoidaly in the Negative direction.
- Discharge current flows towards load ckt

$i_T = I_0 - i_c$

- i_T reduces to zero sinusoidally.
- Switch is turned off Naturally
- turn off occurs at zero current.

$t_2 \rightarrow t_3$:-



• capacitor Discharges through the load ckt.

$i_c = I_o$ which is constant

V_c rises linearly to V_d.

at $t = t_3$

$V_c = V_d$, $V_{diode} = 0$, Diode conducts, off period of the buck converter begins.

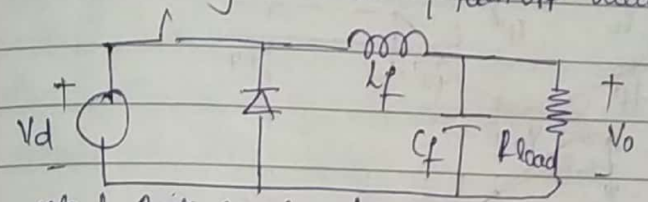
$t_3 \rightarrow t_4$

- Switch is off
- load current freewheels through Diode
  $V_c = V_d$
- $i_T = 0$
- at $t = t_4$ gate pulse given to switch.

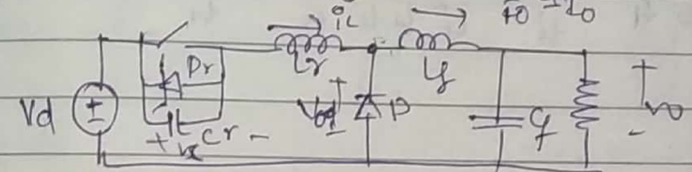
4/5/22

Zero Voltage Switching (ZVS) Converters :-

- The switching turn ON & turn off occurs at Zero Voltage



modified Buck converter to get ZVS



Initial condition :-

- The Switch is in ON state. D is off
- $V_c = 0$
- $i_L = I_o$
- $V_{oi} = V_d$
- At $t = t_o$ Switch is turned off (at ZV condition by C_r)
- Due to the presence of capacitance turn off occurs at ZV

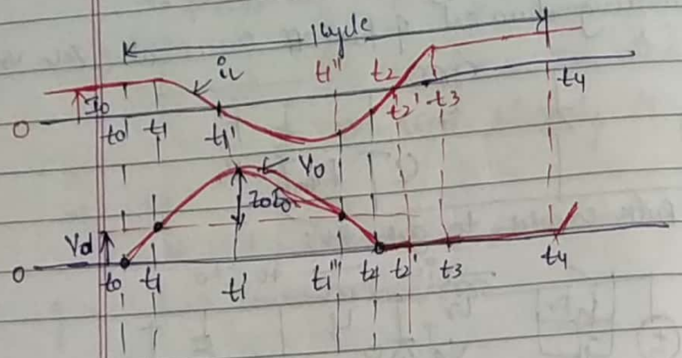
t_o to t_1 :-

- i_L which is constant load current flows through the capacitor
- V_c rises linearly from zero to V_d.
- at $t = t_1$, $V_c = V_d$, $V_{oi} = V_d - V_c = 0$, Diode starts conducting.

t_1 to t_1' :-

- Switch is off and D is ON
- C_r & L_r resonates

- 'C' gets charged to a potential greater than V_d
- Due to $-V_c$ voltage a/c L_r.
- $V_c > V_d$
- at t_1', i_L is zero V_c is maximum $= V_d + V_{Lr}$

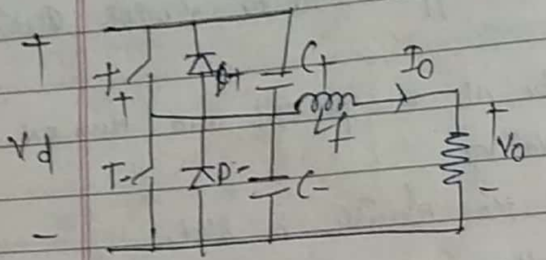


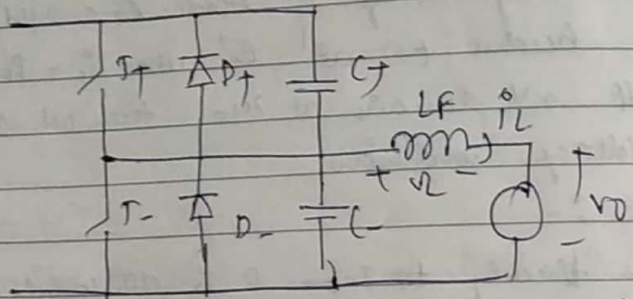
- t_1' to t_1'' :-
- capacitor discharges through dc source, D & L_r
- i_L reverses sinusoidally due to $L_r - C_r$ resonance.
- $i_D = I_o - I_L$, At t'' $V_c = V_d$.
- $i_L = -I_o$, at t_2 $V_c = 0$.
- $V_{Dr} = 0$, D_r start conducting
- V_c continues to be at zero
- $t_2 \rightarrow t_2'$
- D & D_r conduct, $V_{cr} = 0$, $V_{Lr} = V_d$
- i_L rises linearly to zero through D_r.
  Switch is reverse biased while D_r is conducting.
- at t_2', $i_L = i_{Dr} = 0$, D_r become off & switch goes to the ON state if gating signal is provided to achieve on state of the Buck

- converter ckt.
- Gating signal are applied to the switch during this interval
- V_{cr} continues to be at zero potential and turn ON occurs at zero voltage.
- peak voltage a/c the switch is $2V_d$.
- reverse recovery voltage of diode $D_r = 2V_d$.
- switch become ON at t_2' when $i_L = i_{Dr} = 0$ & D_r is off, V_c remains at zero. turn ON occurs at zero voltage condition
- $t_2' \rightarrow t_3$:-
  i_L rises linearly to I_o, D is still conducting $V_{Lr} = V_d$
- $t_3 \rightarrow t_4$:-
- $i_L = I_T = I_o$, $V_c = 0$, $V_o = V_d$,
- at t_4 switch is turned off again at zero voltage

8/5/22

Zero Voltage Switching clamped V (ZVS-CV) topology





- → Switches turn ON & OFF at zero 'V'
- → Peak 'V' across the switch is clamped to the I/p DC 'V'
- → C_f is consider as very large & hence load is replaced by a V source (the V remains constant).
- → initial conditions: T_+ is ON &, T_- is OFF

$V_L = V_d - V_0$ (constant)

i_L rises linearly

$V_{C-} = V_{01} = V_d$; $V_{T+} = 0$

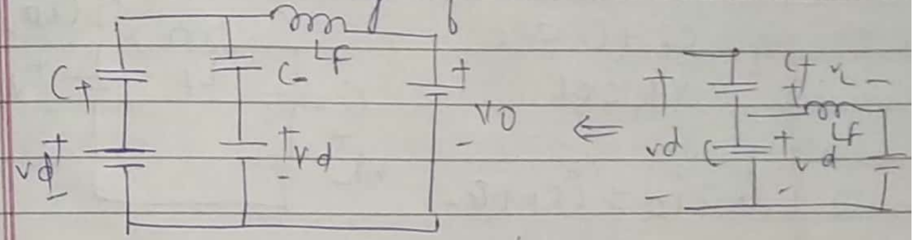
at $t = t_0$; T_- is turned off at ZV ~~and~~ value to V_{C+}

- → $C_+ = C_- = \frac{1}{2}C$ are selected as a small values
- → the resonant frequency $f_0 = \frac{1}{2\pi\sqrt{L_f C}}$ is very large compared to switching frequency
- → L_f/C is very large & variation in L_f is small
- → $i_L = i_0 = i_{C+} + i_{C-}$

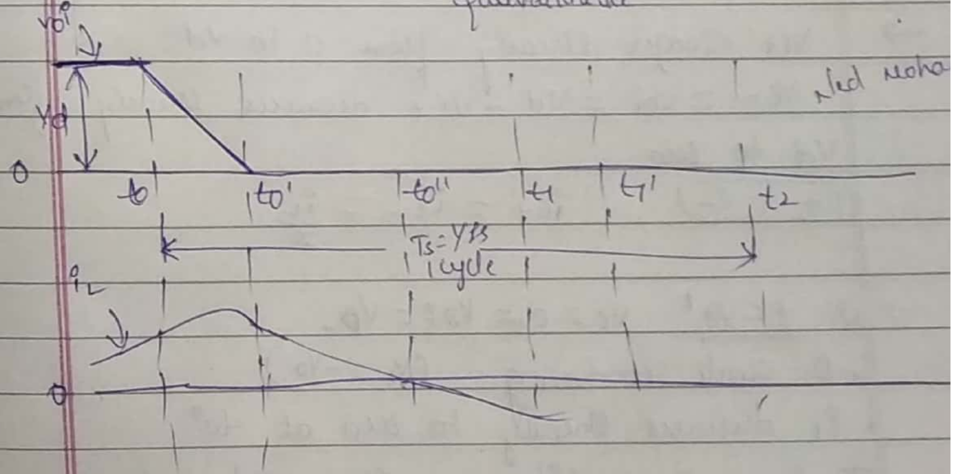
at $t_0 \to t_0'$

$T_+, T_-, D_+, \& D_-$ are in the off state

C_- has initial voltage of V_d.



Equivalent ckt

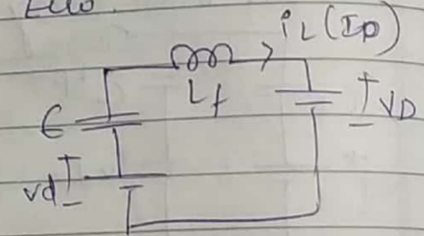


→ $t_1 \to t_1'$ T_+ & T_- are off, −ve i_L flows through 'C'
C_+ discharges from V_d to '0' through L_f & i/p source. C_- gets charged from 0 to V_d.

→ $t_1' \to t_2$ when V_{C+} is zero, Diode conducts −ve i_L
$V_L = V_d - V_o$ is +ve (as buck converter $V_o < V_d$)
$\frac{di_L}{dt}$ = +ve (I rises)
$V_{C-} = V_{oi} = V_d$

T_+ is gated while D_+ is conducting.
T_+ starts conducting when D_+ becomes off when i_L is reduced to zero.

$C_{eq} = C_+ + C_- = C$
$V_{th} = V_d$



$i_L = i_o = i_{C+} + i_{C-}$

→ V_{C+} changes linearly from 0 to V_d.
$V_{C-} = V_{oi} = V_d - V_{C+}$ decreases linearly from V_d to zero.
$(C_+ = C_-)$ $\quad i_{C+} = i_{C-} = \frac{i_L}{2}$

→ at $t = t_o'$ $V_C = 0$, $V_{oi} = V_{D-}$
• D_- starts conducting $(V_L = -V_o)$
• i_L decreases linearly to zero at t_o''
T_- is gated while D_- is conducting

T_- starts conducting when D_- becomes off due to zero i_L at t_o''

at t_o'' D_- goes to the off state and T_- is gated at some instant between t_o' & t_o''

at t_o'' D_- becomes off, T_- starts conducting i_L reverses (−ve) direction

at $t_o'' \to t_1$ i_L flows through T
$V_L = -V_o$

Mean V comes a/c T_+ is V_d

at t_1 T_- is turned off i_L → +ve value