सपन्दविस्तारपरिवर्तन - शक्तिपरिवर्तकानि अनुप्रयोगाश्च

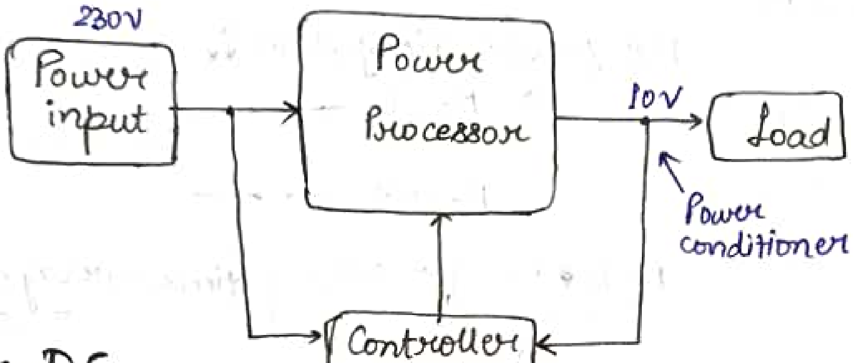
PWM POWER CONVERTERS AND APPLICATIONS

09-08-2024

Power Electronics

↳ Processing of electrical power using electronic components.
↓
Control or conversion

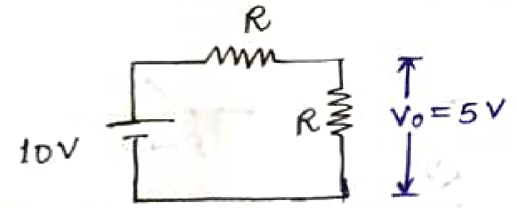
→ Power Electronic convertors:
1. AC to DC (Rectifiers)
2. DC to DC
3. DC to AC (Invertors) [DC to AC con. normally also converts AC to DC
4. AC to AC. (matrix convertor) [converts voltage & frequency



↳eg. µC, µP (digital processor)

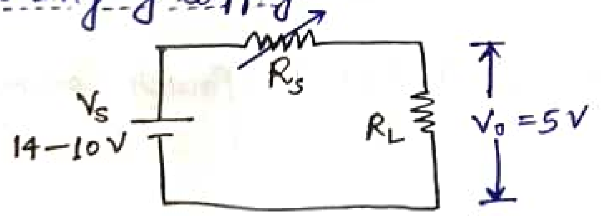
DC to DC Converter

Eg. Resistor-divider Network



Power loss $= I^2 R_s$

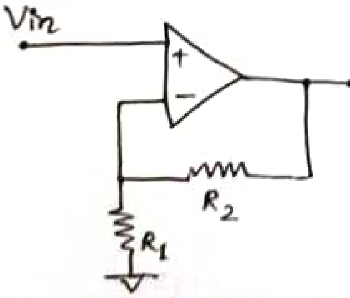
Changing supply:



$$V_o = \frac{V_S}{(R_S+R_L)} \times R_L$$

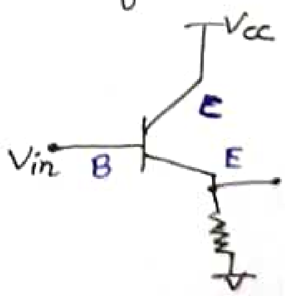
Automatic R_s control:

Non-inverting amplifier:

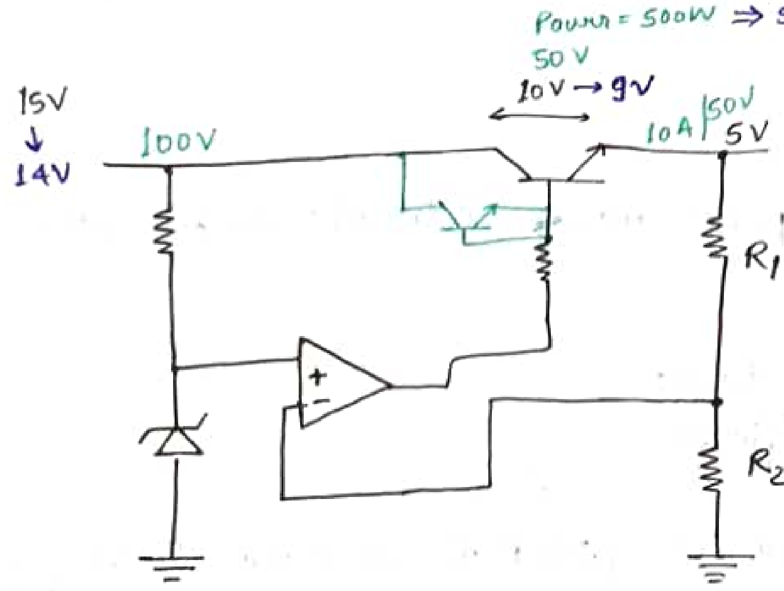


$V_o = V_{in}(1+R_2/R_1)$

Emitter follower:



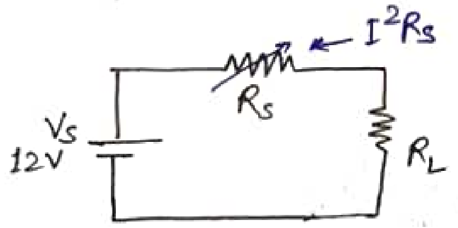
$V_o = V_{in} - V_{BE}$



→ Efficiency is very low for high voltages.

→ Not suitable for high power application

→



For power dissipation ⇓⇓,

⇒ $R_s = 0$ or $R_s \to \infty$ } SPST switch

$R_s = 10\,\Omega$ for 0.5 s, $= 0\,\Omega$ for 0.5 s } time average for 1 s $= 5\,\Omega$

⇓

Switch to any average value b/w 0 and ∞ by controlling the time.

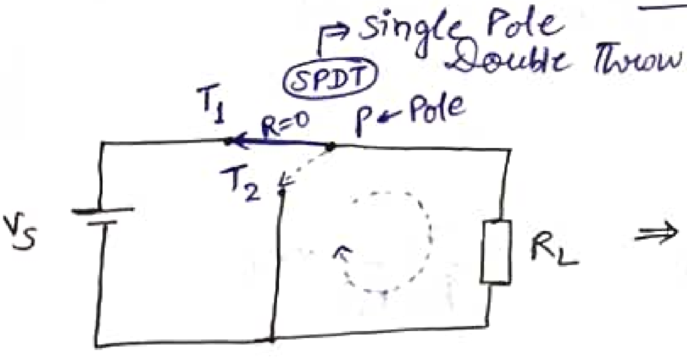
⇓

<u>SPST</u>:

0 Ω $R \to \infty$

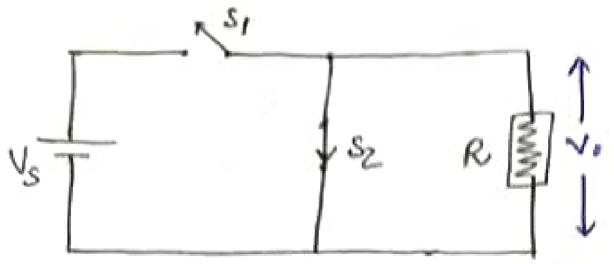
⇓

100% efficiency

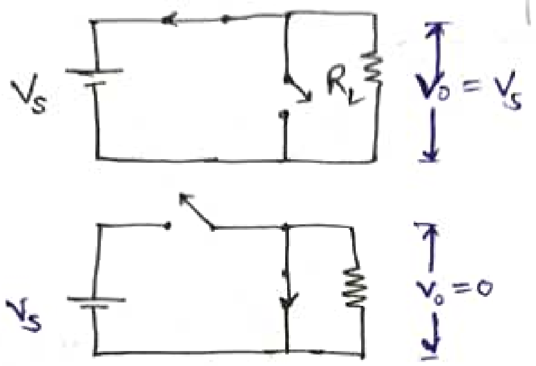


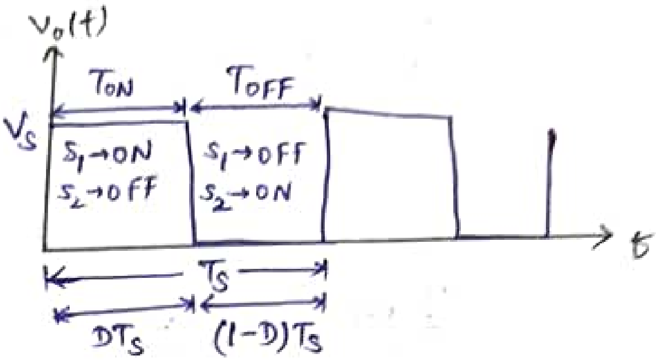
⇒ Switched Mode Power Conversion (SMPC)

12-08-2024



→ S_2 & S_2 will work as SPDT provided, they work in complementary operator, i.e., when one is open, the other is closed.





$$\text{Duty ratio} = \frac{\text{Period during which } S_1 \text{ is ON}}{\text{Total switching period}}$$

$$D = \frac{T_{ON}}{T_{ON} + T_{OFF}} = \frac{T_{ON}}{T_s}$$

$$T_{ON} = DT_s$$

↳ DC but changing ⇒ Pulsating DC

$$V_o\,(av.) = \frac{1}{T_s}\int_0^{T_s} V_o(t)\,dt$$

$$= \frac{1}{T_s}\left[\int_0^{DT_s} V_s\,dt + \int_{DT_s}^{T_s} 0\,dt\right]$$

$$\therefore \boxed{V_{o\,(av.)} = DV_s}$$ → can be changed by changing D.

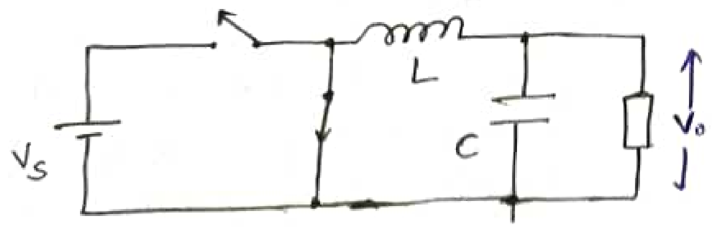
Max. D = 1, Min. D = 0

D → 0 to 1

↳ But fluctuating V_o is not acceptable.

⇓

Introduce energy-storing elements, i.e., capacitor or inductor.

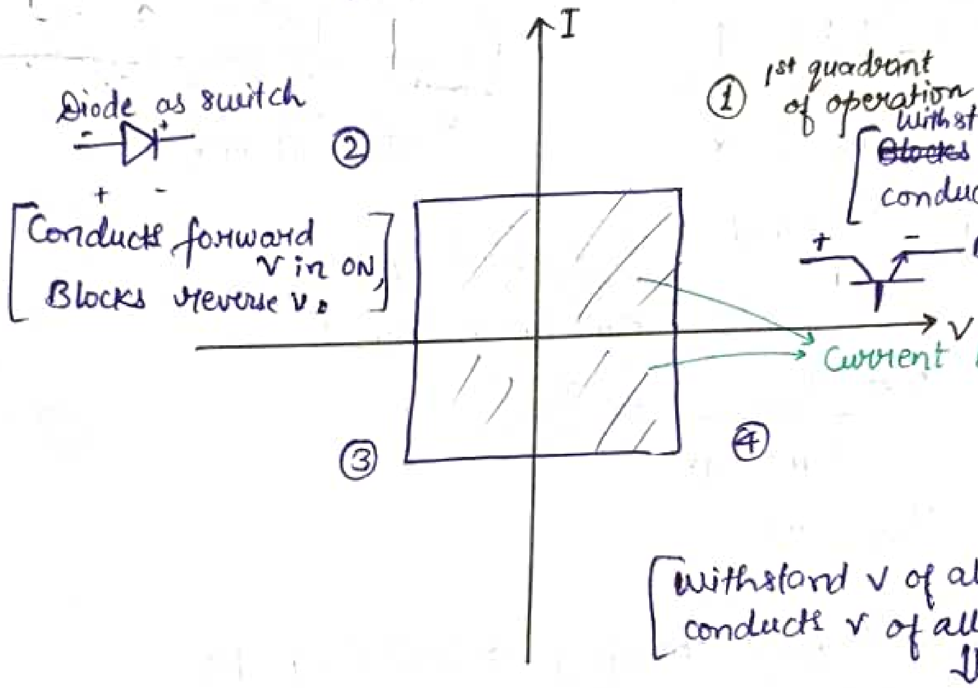


V_o ⇝ very minor fluctuation ⇒ DC to DC Buck Converter

↳ Polarity of voltage

$V_T = 0$ ↳ Direction of current

Diode as switch



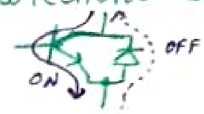
① 1st quadrant of operation

[withstand ~~Blocks~~ +ve V in OFF, conduct +ve (forward) V in ON]

BJT

[Conducts forward V in ON, Blocks reverse V.]

Current Bidirectional switch



[withstand v of all polarity in OFF, conducts v of all polarity in ON]

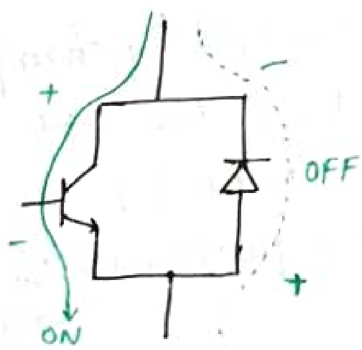
⇓

4 quadrant switch

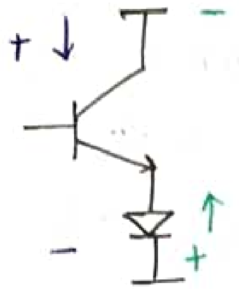
⇓

operate in all quadrants

<u>① + ④</u> : Current Bidirectional Two Quadrant Switch ⇝ For voltage source converter

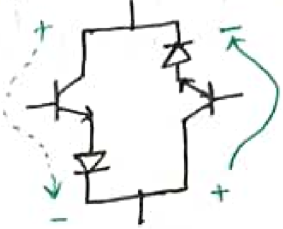


① + ②: Voltage Bidirectional Two Quadrant Switch → For current source converter

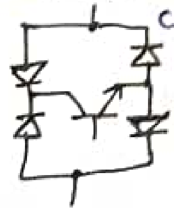


① + ② + ③ + ④ : four quadrant switch → for AC to AC matrix converter

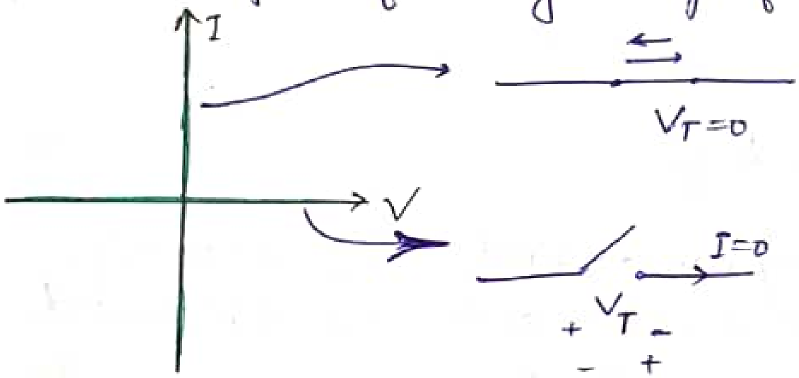
OR



OR



Ideal switch: Capable of conducting current of both dirⁿ in ON state, capable of blocking voltage of both polarity in OFF state

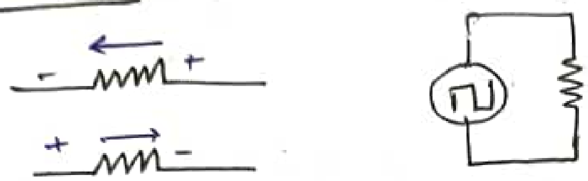


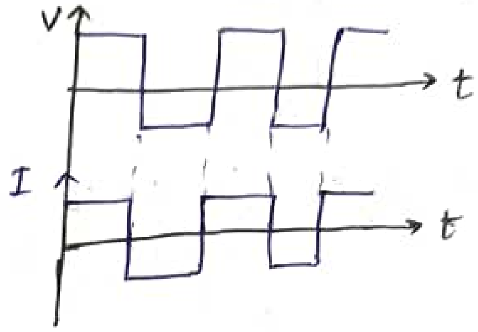
(Infinite current)

Basic Elements

Element	Basic Relationship	Voltage-Current relationship
Resistor	$V = IR$	$V = IR, \quad I = V/R$
Capacitor	$q = CV$, Energy $= \frac{1}{2}CV^2$	$i_c = C\,dV/dt, \; V_c = 1/C \int i_c\, dt$
Inductor	$\psi = Li$, energy $= \frac{1}{2}Li^2$	$V_c = L\frac{di_L}{dt}, \; i_L = \frac{1}{L}\int V_L\, dt$

Resistor





~~Energy ≤ 1/2~~

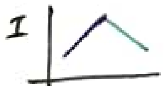
Inductor

$\psi = Li$

$$V = \frac{d\psi}{dt} = \frac{dLi}{dt} = L\frac{di}{dt}$$

→ Flux in a system does not change suddenly.

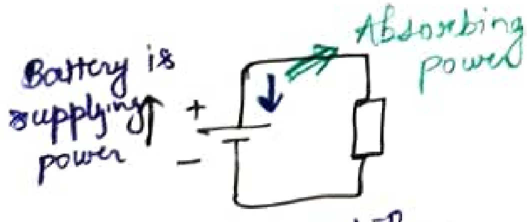
→ current in an inductor shall not be interrupted.

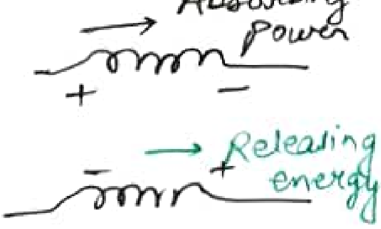


$V = L\frac{di}{dt}$ ⇒ current → not changing ⇒ $V = 0$

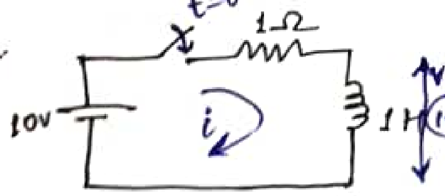
→ Inductor makes its presence felt in the circuit only if the current changes.

Energy $= \frac{1}{2}Li^2$





Eg



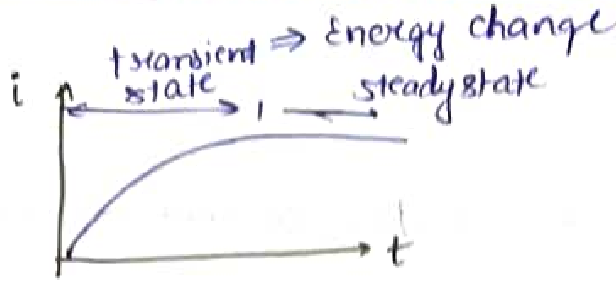
$V = \left[\begin{array}{l} t = 0^- \Rightarrow i = 0 \\ t = 0^+ \Rightarrow i = 0 \end{array}\right] \Rightarrow \frac{di}{dt} \neq 0$ (10V)

$V = L\frac{di}{dt} = 10V$

⇒ Cannot be opened ~~change~~ thereafter

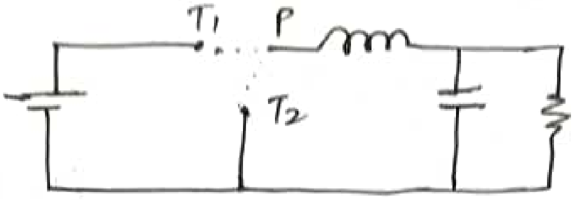
$V = 1 \times \frac{(10-0)}{10\times10^{-6}}$ (say)

$= 1MV$ ⇒ smoke



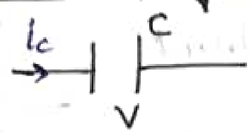
→ A switch shall not be connected in series with an inductor.

Eg.



⇒ The inductor can only be connected in pole of the SPDT switch.

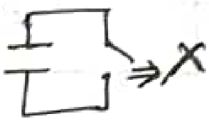
~~Inductor:~~ Capacitor:



$i_C = C\frac{dv_c}{dt}$ ⇒ No change in voltage ⇒ No current

→ ~~An~~ ~~~~ ~~inductor~~ capacitor makes its presence felt in the circuit if there is a change in voltage.

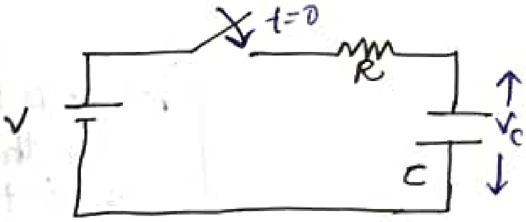
$$i = \frac{dq}{dt} = \frac{d(cv)}{dt} = C\frac{dv}{dt}$$



→ charge in a system cannot change suddenly.

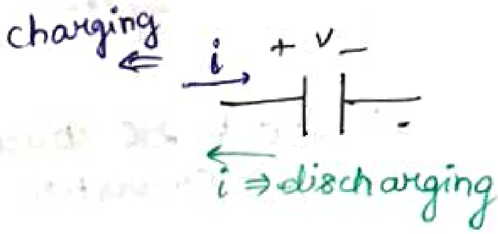
→ Switch should not be connected across a capacitor

Eg

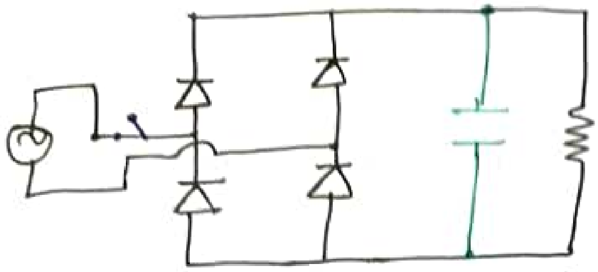


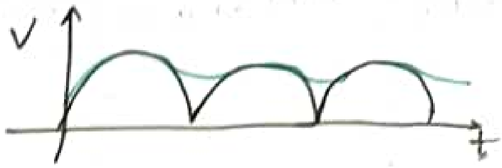
$t=0^- \Rightarrow i=0 \Rightarrow V_c=0$

$t=0^+ \Rightarrow V_c=0$, i ✓ ⇒ short circuit



Eg Diode-bridge rectifier

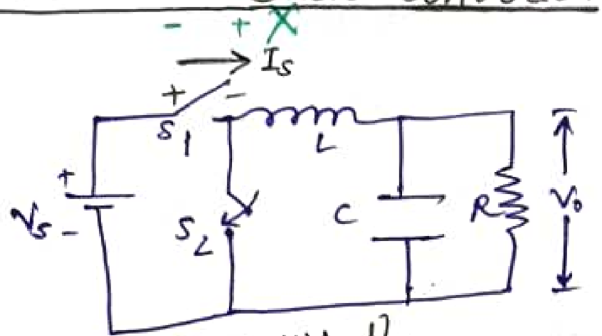




↳ Pre-charge capacitor & then switch

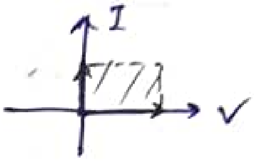
DC to DC Buck Converter

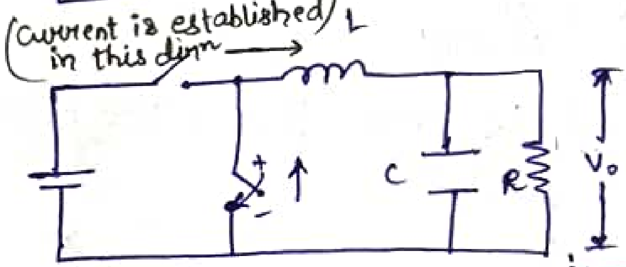
16-08-2024



⇒ 1st Quadrant

⇒ BJT

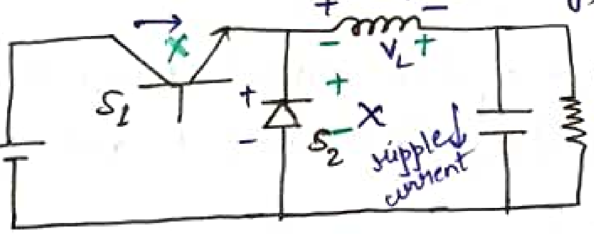




⇒ 2nd Quadrant

⇒ BJT

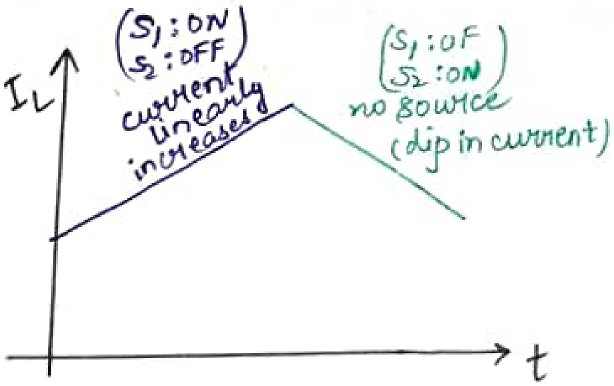
i_L (increasing) ⇒ S_1 : ON, S_2 : OFF



$I_0 = \frac{V_0}{R}$ (dc current)

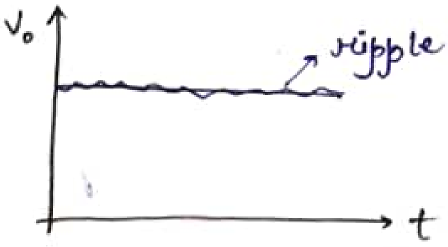
⇒ S_1 : OFF, S_2 : ON

$$\left[V_L = L \underbrace{\frac{di_L}{dt}}_{\substack{+ve \\ -ve}} \right]$$



[Diode is turned OFF by the inductor & is turned ON by the source]

⇒ DC to DC Buck converter



$V_0 = V + \Delta V$

$i_0 = \frac{V_0}{R} = \frac{V_0}{R} + \frac{\Delta V_0}{R}$

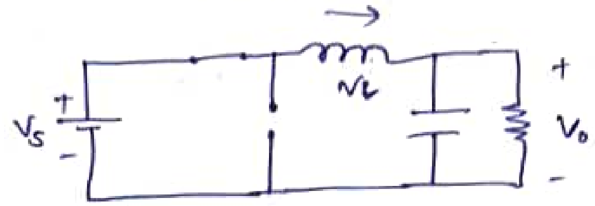
$\approx \frac{V_0}{R}$

Equivalent Circuit when S_1 is ON :

$$D = \frac{T_{ON}(S_1)}{T_{ON}(S_1) + T_{OFF}(S_1)} = \frac{T_{ON}}{T_S} \quad , \quad 0 \le t \le DT_s$$

active switch

$(T_{ON} = DT_s)$



$$V_s - V_L - V_o = 0$$

$$\Rightarrow V_L = V_s - V_o$$

$$V_L = L\frac{di_L}{dt}$$

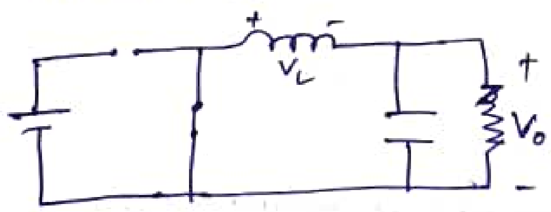
$$i_L = \frac{1}{L}\int V_L\, dt = \frac{1}{L}\int_0^{t=DT_s} (V_s - V_o)\, dt = \frac{1}{L}(V_s - V_o)t$$

$$\text{slope} = \frac{V_s - V_o}{L}$$

Equivalent Circuit when S_1 is OFF:

$$T_{OFF} = T_s - T_{ON}$$
$$= T_s - DT_s$$
$$= (1-D)T_s$$

$$DT_s \le t \le T_s$$



19-08-2024

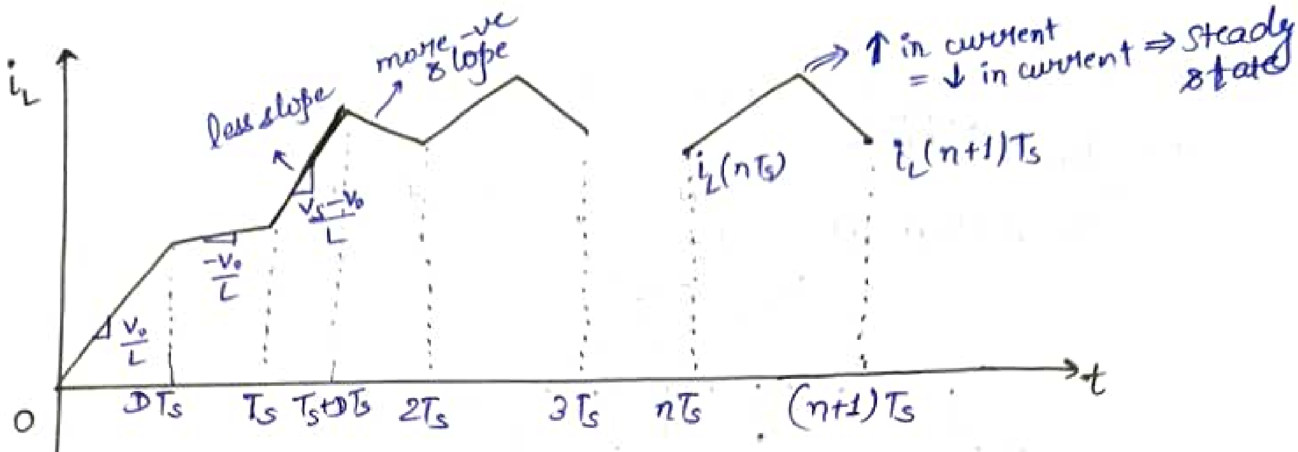
$$-V_L - V_o = 0$$

$$\Rightarrow V_L = -V_o$$

$$V_L = L\frac{di_L}{dt} = -V_o$$

$$\frac{di_L}{dt} = \frac{-V_o}{L}$$

$$V_o \approx 0 \Rightarrow \text{slope} \approx 0$$



At steady state,

$$i_L(n+1)T_s = i_L(nT_s)$$

$$V_L = L\frac{di_L}{dt}$$

$$\Rightarrow \frac{di_L}{dt} = \frac{V_L}{L}$$

$$\Rightarrow \int_0^{T_s} di_L = \int_0^{T_s} \frac{V_L}{L}\,dt$$

$$\Rightarrow i_L(T_s) - i_L(0) = \frac{1}{L}\int_0^{T_s} V_L\,dt$$

At steady state,

$$i_L(T_s) - i_L(0) = 0$$

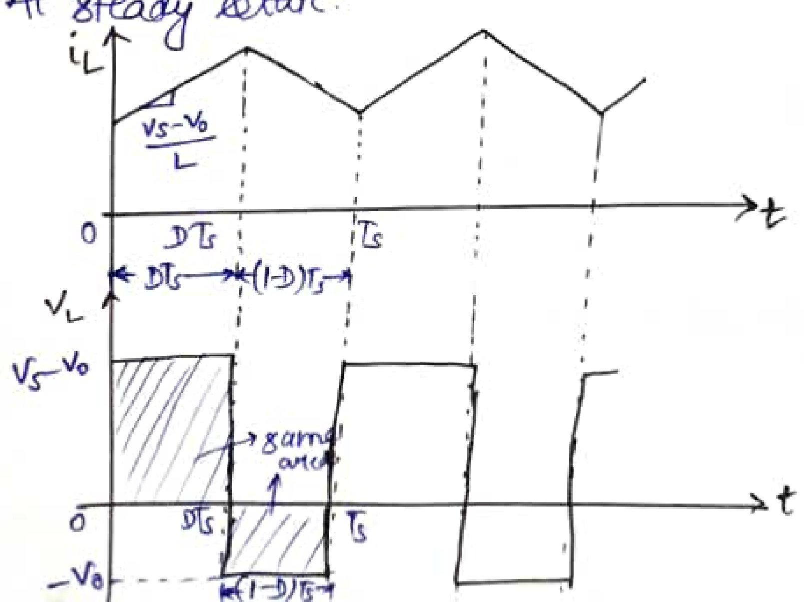
$$\Rightarrow \frac{1}{L}\int_0^{T_s} V_L\,dt = 0$$

$$\Rightarrow \int_0^{T_s} V_L\,dt = 0$$

$$\Rightarrow \frac{1}{T}\int_0^{T_s} V_L\,dt = 0$$

Average value (DC component) of inductor voltage must be zero.

At steady state.



$(V_s - V_o) DT_s + (-V_o)(1-D)T_s = 0$

↳ Principle of Volt-second Balance

(Principle of flux balance) $\Rightarrow V = N\frac{d\phi}{dt}$ (Faraday's law) $\Rightarrow V\,dt = \text{flux}$

$$\Rightarrow V_s D T_s - V_o D T_s + (-V_o)(1 - D T_s) = 0$$

$$\Rightarrow \boxed{V_o = D V_s}$$

For capacitor:

Charge accumulates ⇒ voltage ~~bus~~ keeps building up
⇒ converter fail.

$$i_c = C\frac{dV_c}{dt}$$

$$\Rightarrow dV_c = \frac{1}{C}\int i_c\,dt$$

$$\Rightarrow \int_0^{T_s} dV_c = \frac{1}{C}\int_0^{T_s} i_c\,dt$$

$$\Rightarrow V_c(T_s) - V_c(0) = \frac{1}{C}\int_0^{T_s} i_c\,dt$$

At steady state,

$$V_c(T_s) - V_c(0) = 0$$

$$\Rightarrow \frac{1}{C}\int_0^{T_s} i_c\,dt = 0$$

$$\Rightarrow \frac{1}{T_s}\int_0^{T_s} i_c\,dt = 0$$

⇒ Average value (dc component) of capacitor current must be zero.

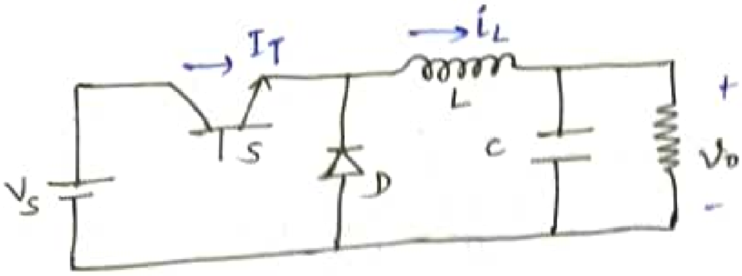
⇒ Principle of Ampere-second Balance.

→ dc current through inductor = load current $\left[I_o = \frac{V_o}{R}\right]$

→ Ripple current flows through the capacitor.

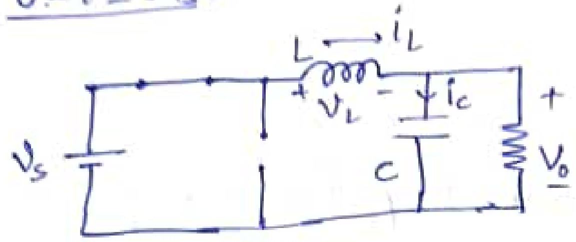
→ We cannot allow dc current to flow through the capacitor and dc voltage to appear across inductor.

20-08-2024



$V_o = DV_s$

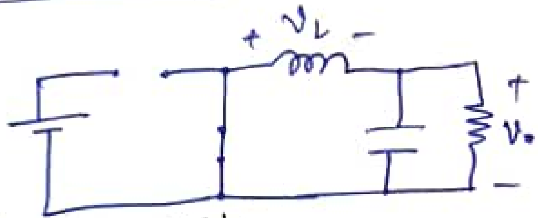
<u>$0 < t \le DT_s$:</u>



$$V_L = L\frac{di_L}{dt} = V_s - V_o$$

$$\Rightarrow \frac{di_L}{dt} = \frac{V_s - V_o}{L}$$

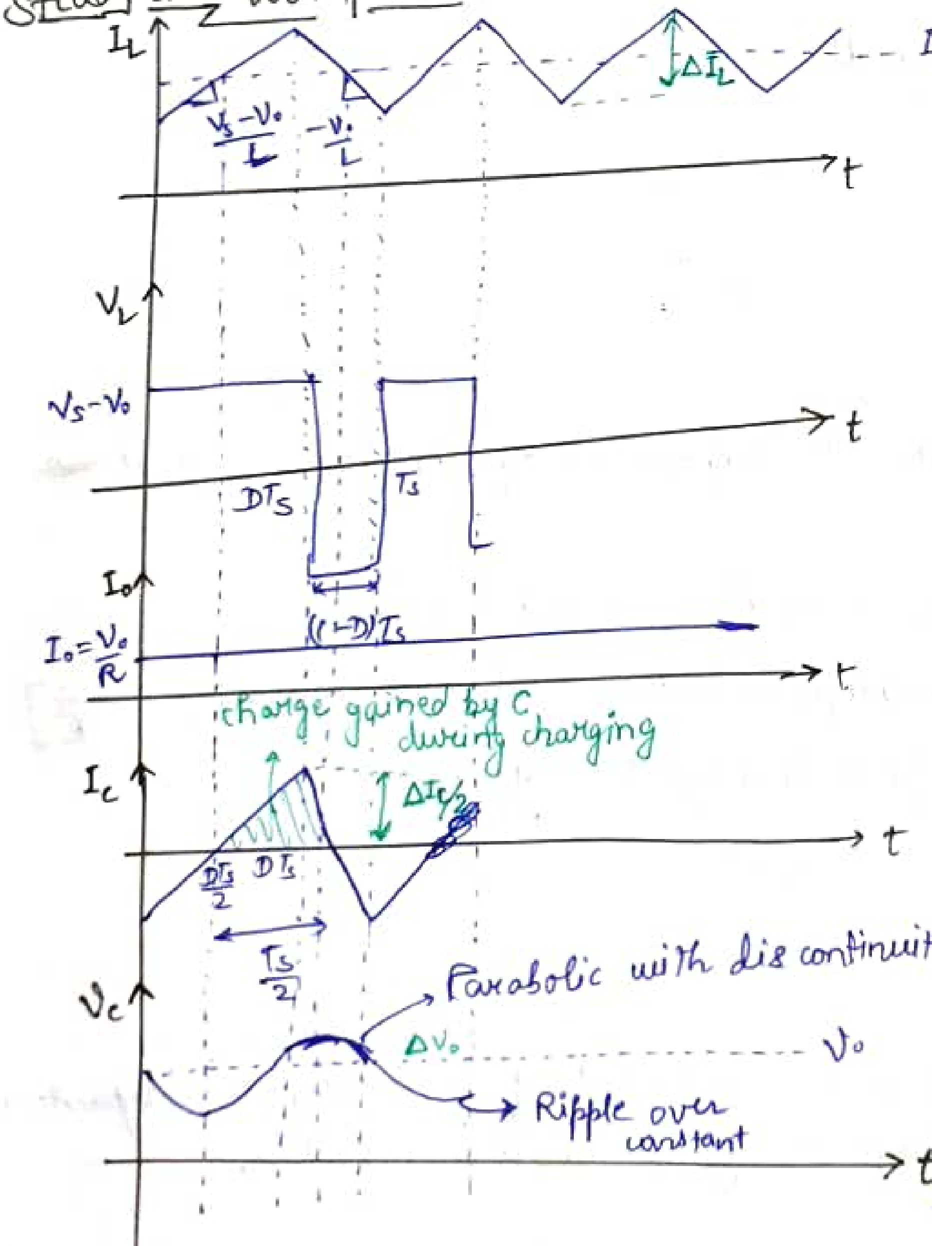
<u>$DT_s < t \le T_s$:</u>



$$V_L = L\frac{di_L}{dt} = V_o$$

$$\Rightarrow \frac{di_L}{dt} = \frac{V_o}{L}$$

<u>Steady state waveforms:</u>



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

$$I_C = C\frac{dv_c}{dt}$$

$$\Rightarrow V_c = \frac{1}{C}\int I_c \, dt$$

$$q = CV \Rightarrow \Delta q = C\Delta V$$

$$\Delta V = \Delta q / C$$

$$\Delta q = \frac{1}{2}\frac{\Delta i_L}{2} \times \frac{T_s}{2} \quad \left[\begin{matrix}\text{Area} \\ \text{of } \Delta\end{matrix}\right]$$

$$\Rightarrow C = \frac{\Delta q}{\Delta V} = \frac{1/2 \, \Delta i_L/2 \times T_s/2}{\Delta V}$$

Peak-to-peak ripple in the inductor current $(I_L) = \left(\frac{V_s - V_o}{L}\right) DT_s$

or, $\Delta I_L = -\frac{V_o}{L}(1-D)T_s$

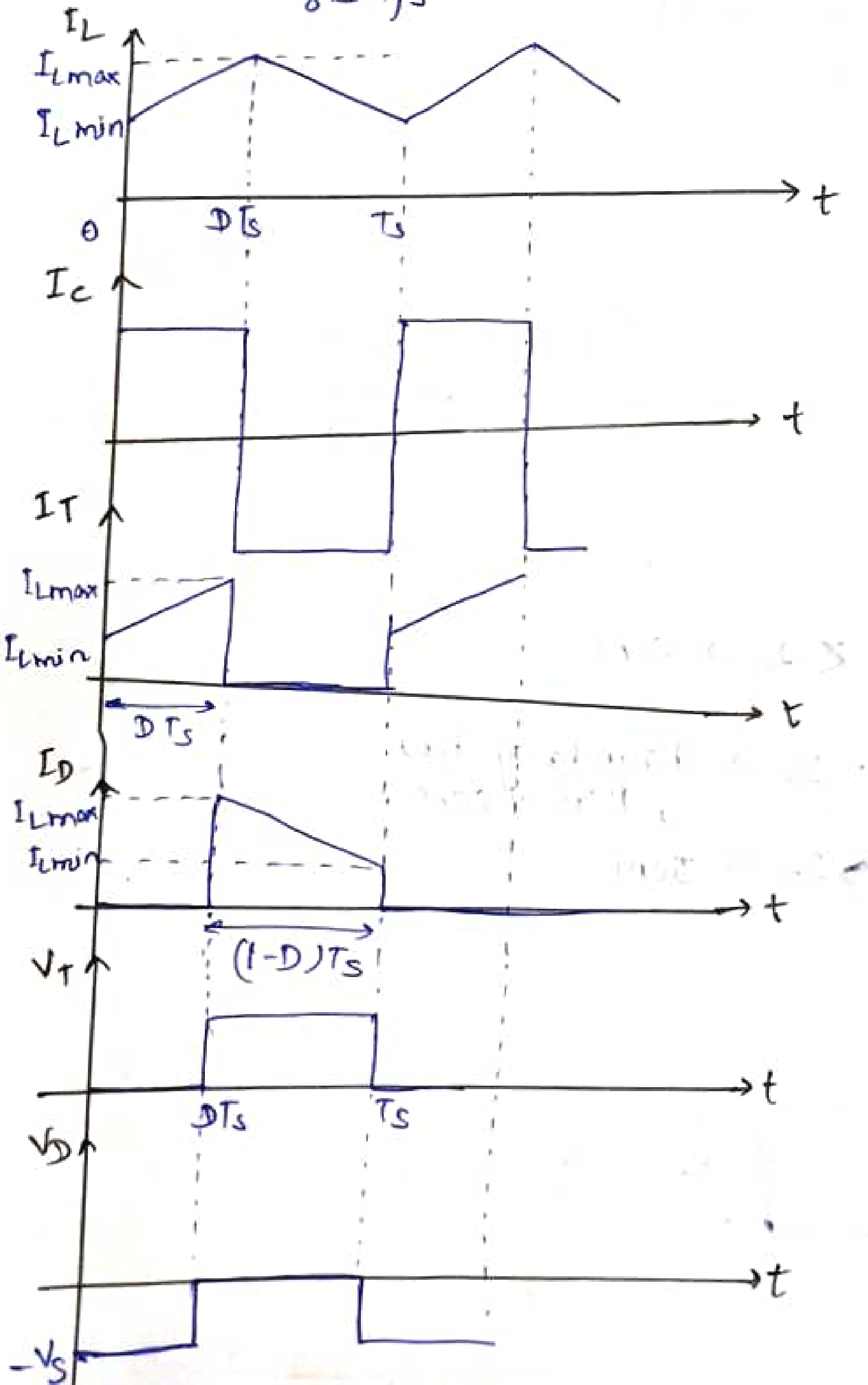
$$\Delta I_L = \left(\frac{V_S - V_o}{L}\right) DT_S$$

$$\Rightarrow L = \frac{V_S - V_o}{\Delta I_L} DT_S$$

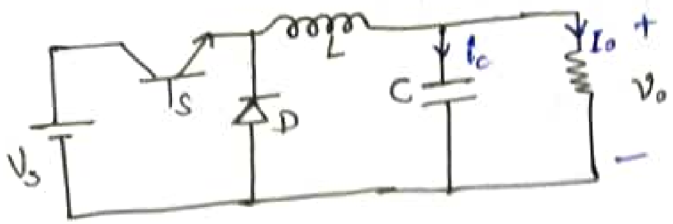
$$= \frac{V_S - V_o}{\Delta I_L f_s} \quad \left(\because T_S = \frac{1}{f_S}\right)$$

$$C = \frac{\Delta I_L \times T_S/8}{\Delta V}$$

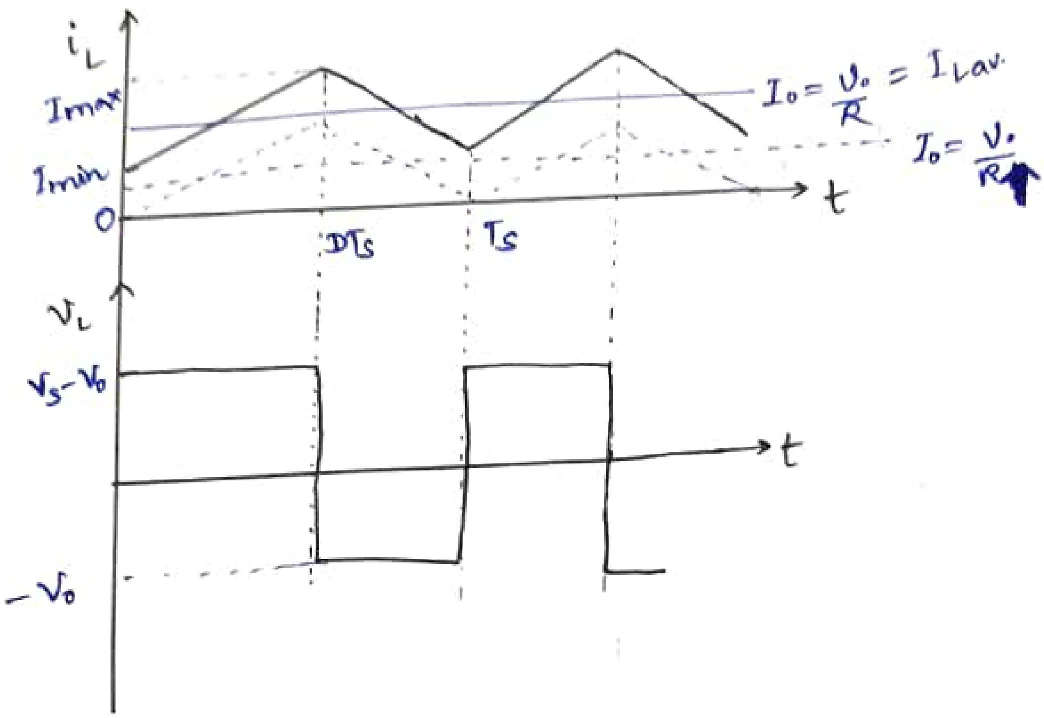
$$= \frac{\Delta I_L}{8 \Delta V f_s}$$



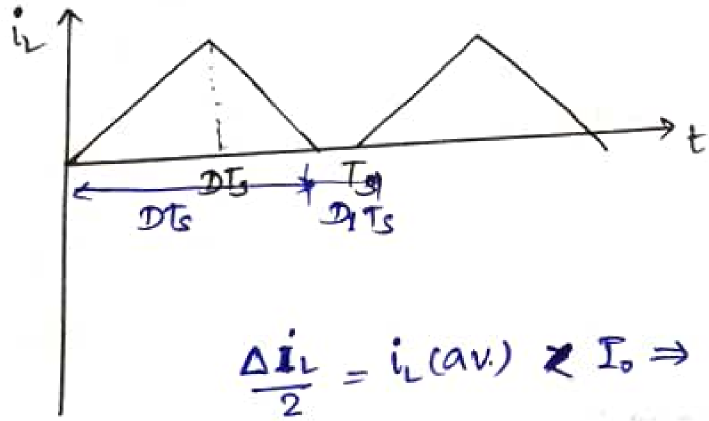
23-08-2024



$\boxed{V_o = D V_s} \Rightarrow$ for CCM



$\Rightarrow$ Continuous Conduction Mode (CCM)



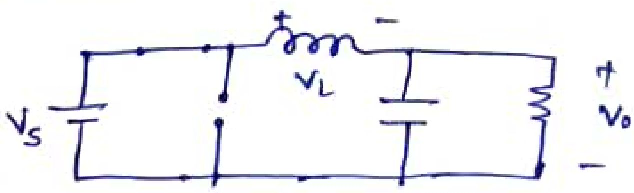
$\Rightarrow$ Discontinuous Conduction Mode (DCM)

$\frac{\Delta i_L}{2} = i_L(av.) < I_o \Rightarrow$ CCM

$\frac{\Delta i_L}{2} = i_L(av.) = I_o \Rightarrow$ Boundary b/w DCM & CCM

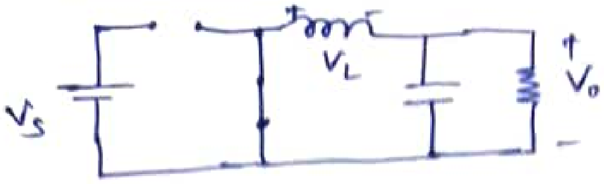
$\frac{\Delta i_L}{2} = i_L(av.) > I_o \Rightarrow$ DCM

$\underline{0 < t \leq DT_s}$:

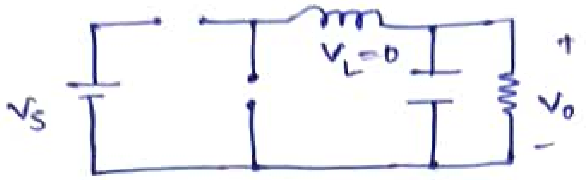


$V_L = V_s - V_o$

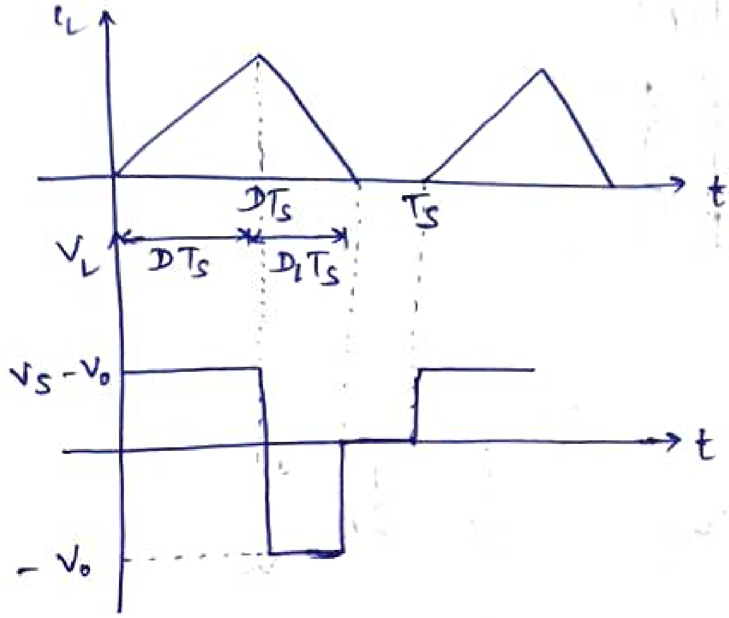
$DT_s < t < (D+D_1)T_s$:



$(D+D_1)T_s < t \le T_s$:



$V_L = 0$



$$(V_s - V_o)DT_s + (-V_o)D_1T_s + (0)(1-(D+D_1))T_s = 0$$

$$\Rightarrow (V_s - V_o)DT_s - V_o D_1 T_s = 0$$

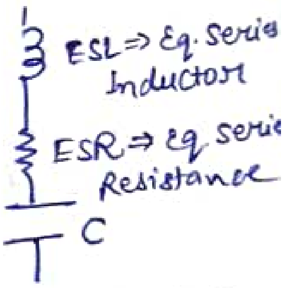
$$\Rightarrow V_s DT_s - V_o DT_s - V_o D_1 T_s = 0$$

$$\Rightarrow DV_s - V_o(D+D_1) = 0$$

$$\Rightarrow \boxed{V_o = \frac{V_s D}{D+D_1}} > \boxed{V_o = DV_s}$$

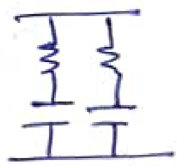
↳ Capacitor provides voltage to the load
⇓
Ripple increases.

Non-ideal capacitor:



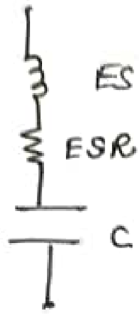
ESR↑ ⇒ Ripple↑

To decrease ESR:



Non-idealities

Non-ideal Capacitor :

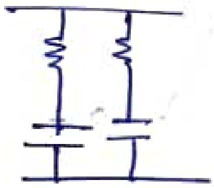


ESL ⇒ Equivalent Series Inductance

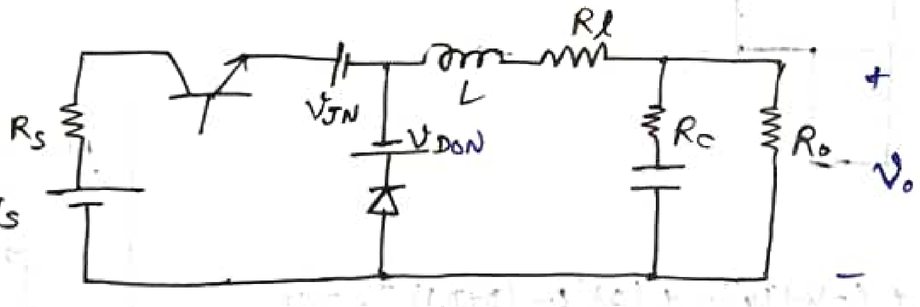
ESR ⇒ Equivalent Series Resistance

ESR ↑ ⇒ Ripple ↑

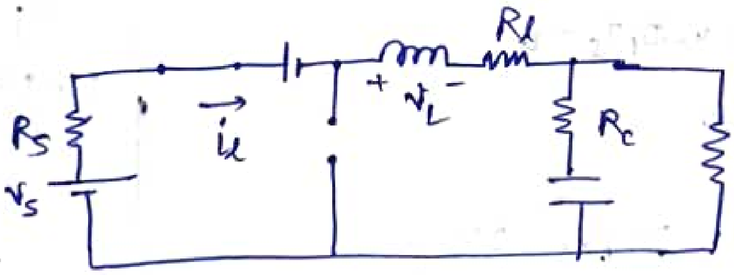
To decrease ESR:



Other non-idealities :



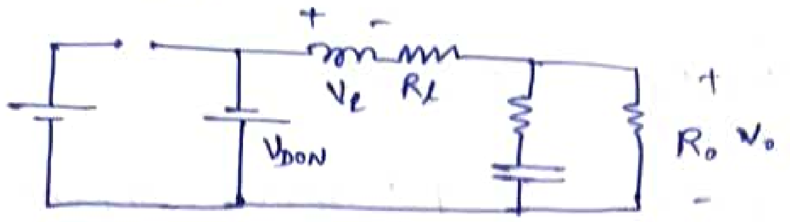
$0 < t \leq DT_s$:



$$V_s - i_L R_s - V_{JN} - V_l - i_L R_L - v_o = 0$$

$$\Rightarrow V_l = V_s - i_L(R_s + R_L) - V_{JN} - V_o$$

$DT_s < t \le T_s$:



$$-V_{DON} - V_L - i_L R_L - V_o = 0$$

$$\Rightarrow V_L = (V_o + V_{DON} + i_L R_L)$$

$$(V_S - i_L(R_S + R_L) - V_{TON} - V_o)\, DT_s - (V_o + V_{DON} + i_L R_L)(1-D)T_s = 0$$

$$i_L = i_L(av.) = I_o = V_o/R$$

$$V_S - \frac{V_o}{R}(R_S + R_L) - V_{TON} - V_S$$

DCM : (27-08-2024)

$$\frac{\Delta i_L}{2} = \frac{V_o}{2L}(1 - DT_s) = \frac{V_o}{R} = I_o$$

← operation on the boundary b/w CCM & DCM

$$\Delta i_L = \left(\frac{V_S - V_o}{L}\right) DT_s$$

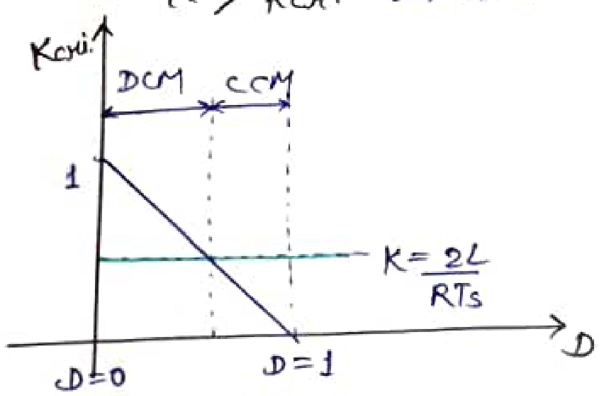
$$\Delta i_L = \frac{V_o}{L}(1-D)T_s$$

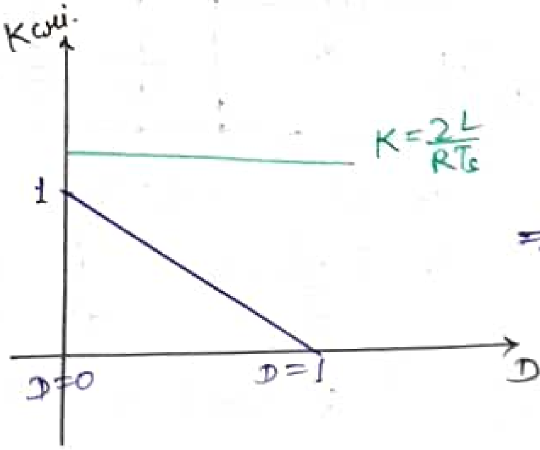
$$\frac{2L}{RT_s} = (1-D) = K \;:\; \text{Conduction parameter}$$

$$K_{critical} = (1-D)$$

$K < K_{critical} \Rightarrow$ DCM

$K > K_{cr.} \Rightarrow$ CCM





⇒ Always in CCM mode

$$\frac{2L}{RT_s} = (1-D)$$

$$R_{cri.} = \frac{2L}{(1-D)T_s}$$

$R < R_{cri.} \rightarrow$ CCM

$R > R_{cri.} \rightarrow$ DCM

$$R = \frac{2L}{T_s}$$

For Buck Converter:

$V_o = D V_s$

$V_o I_o = V_s I_s$ (Input power = Output Power)

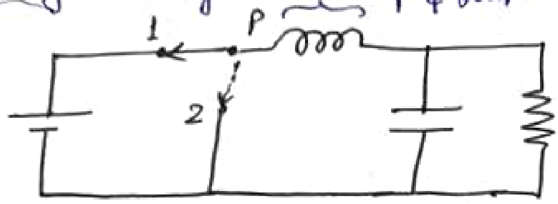
$D \cancel{V_s} I_o = \cancel{V_s} I_s \Rightarrow D I_o = I_s$

$\Rightarrow I_o = \frac{I_s}{D}$ (Output current > Input current)

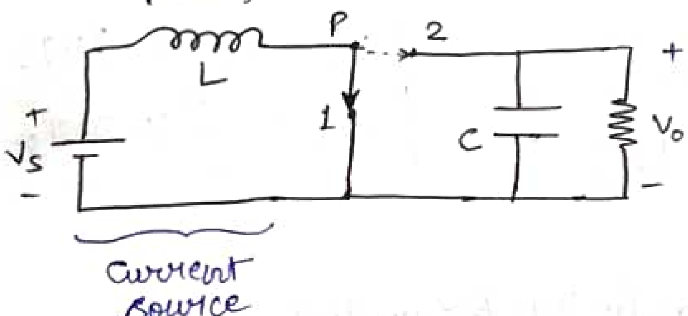
Bucking the voltage ⇒ Boost the current

For boosting the voltage ⇒ buck the current.

Bucking voltage: Inductor b/w P & output

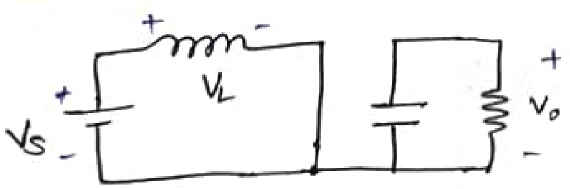


Inductor b/w P & input



[Current doesn't change across L]

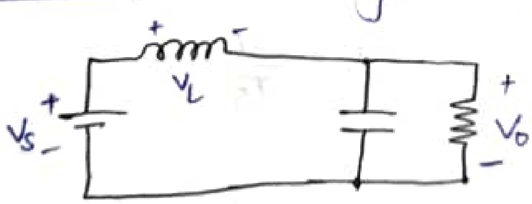
0 < t ≤ DT_s: Switch in position ①



$V_s - V_L = 0 \Rightarrow V_L = V_s$

$V_L = L\frac{di_L}{dt} = V_s$ $\quad \frac{di_L}{dt} = \frac{V_s}{L}$

$DT_s \leq t < T_s$: Switch in position ②



$$V_s - V_L - V_o = 0$$

$$\Rightarrow V_L = L\frac{di}{dt} = V_s - V_o$$

$$\frac{di_L}{dt} = \frac{V_s - V_o}{L}$$

Applying volt-sec balance,

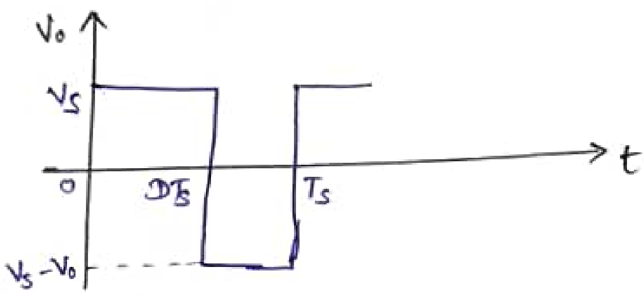
$$V_s D T_s + (V_s - V_o)(1-D)T_s = 0$$

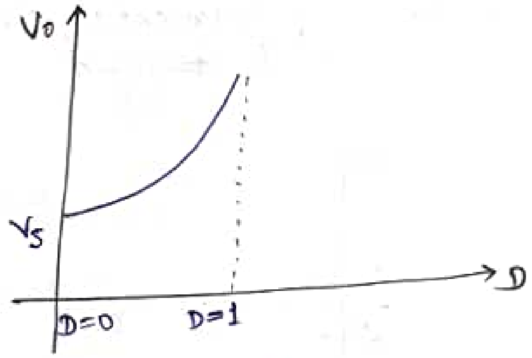
$$\Rightarrow V_s D + V_s(1-D) - V_o(1-D) = 0$$

$$\Rightarrow V_s - V_o(1-D) = 0$$

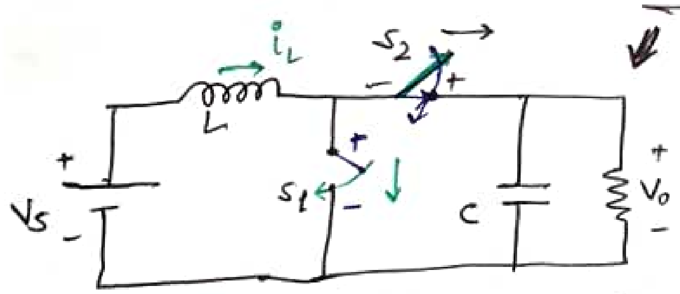
$$\Rightarrow V_o = \frac{V_s}{(1-D)}, \quad D \neq 1$$

$$D = 0 \rightarrow V_o = V_s$$

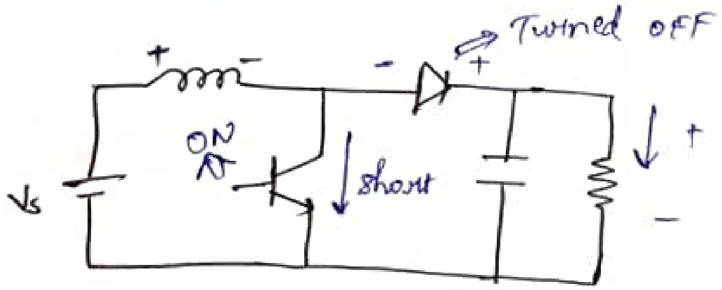




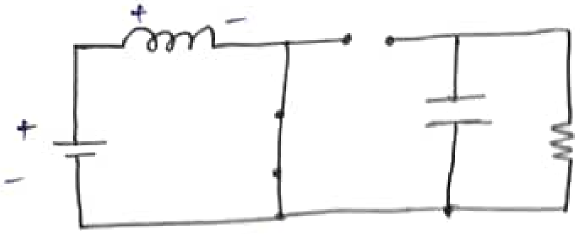
DC to DC Boost Converter



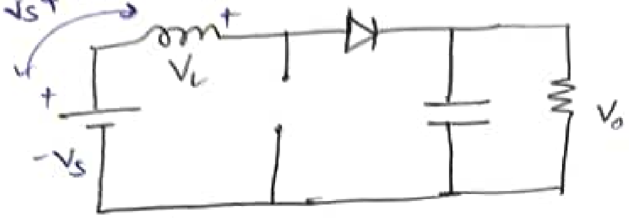
S_1 : 1st quadrant
S_2 : 2nd quadrant

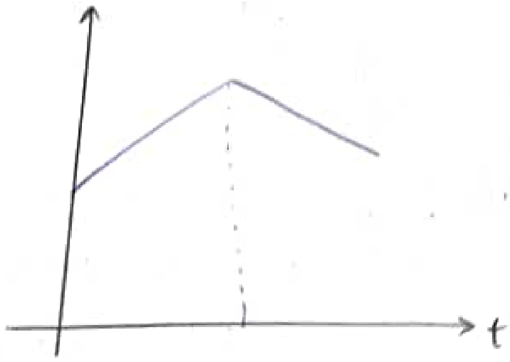


$\Rightarrow$ when S_1 is ON, S_2 turns OFF



Vs & VL adds up > Vo

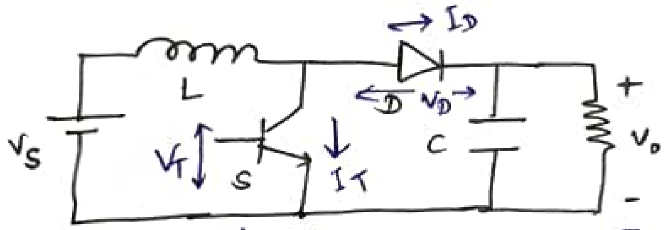




$$V_L = L\frac{di_L}{dt}$$

30-08-2024

DC-DC Boost Converter



$$V_o = \frac{V_s}{1-D}, \quad D \neq 1$$

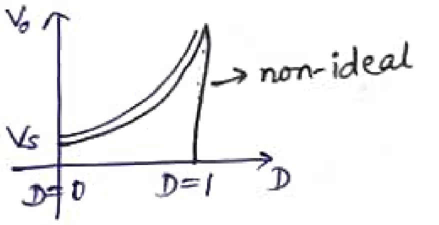
$\left[D = \frac{T_{ON}}{T_S} \Rightarrow D = 1 : \text{'s' permanentaly closed} \right.$
$\left. \hookrightarrow L \text{ ~~damaged~~ fails} \right]$

Assuming 100% efficiency,

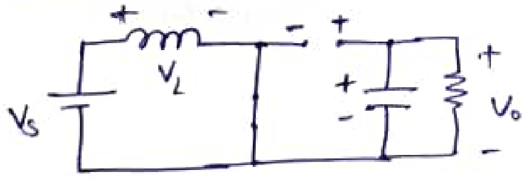
$$V_o I_o = V_s I_S$$

$$\Rightarrow I_S = \frac{V_o I_o}{V_s} = \frac{V_s I_o}{(1-D)\cancel{V_s}} = \frac{I_o}{(1-D)}$$

$$\Rightarrow I_o = I_S(1-D)$$

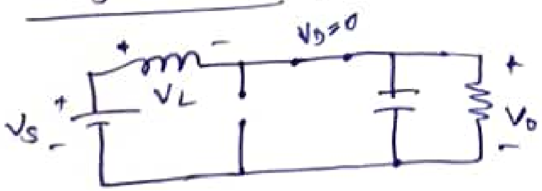


$0 < t \leq DT_s$:

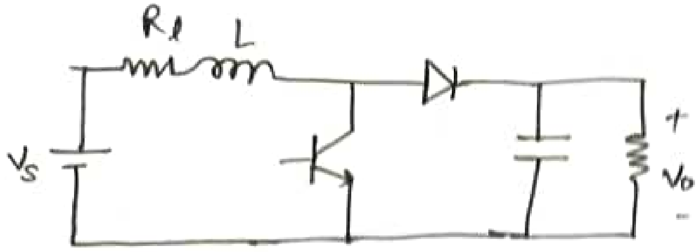


$$V_S - V_L = 0$$
$$V_L = L\frac{di_L}{dt} = V_s$$
$$\frac{di_L}{dt} = \frac{V_s}{L}$$

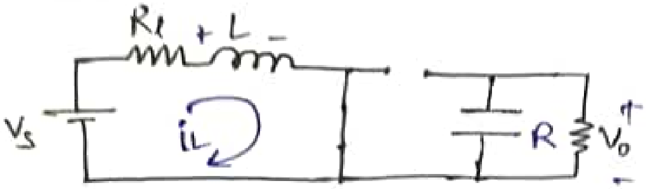
$DT_s < t \leq T_s$:



$$V_s - V_L - V_o = 0$$
$$V_L = L\frac{di_L}{dt} = V_s - V_o$$
$$\frac{di_L}{dt} = \frac{V_s - V_o}{L}$$

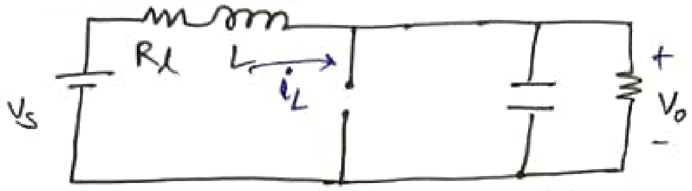


$0 < t \leq DT_s$:



$$V_s - i_L R_L - V_L = 0 \Rightarrow V_L = V_s - i_L R_L$$

$DT_s < t \leq T_s$:



$$V_s - i_L R_L - V_o - V_L = 0$$

$$\Rightarrow V_L = V_S - i_L R_L - V_o$$

Applying principle of volt-sec. Balance,

$$(V_s - i_L R_L) D T_s + (V_s - i_L R_L - V_o)(1-D) T_s = 0$$

$$\Rightarrow V_s D + V_s(1-D) - i_L R_L (D + (1-D)) - V_o(1-D) = 0$$

$$\Rightarrow V_s - i_L R_L - V_o(1-D) = 0$$

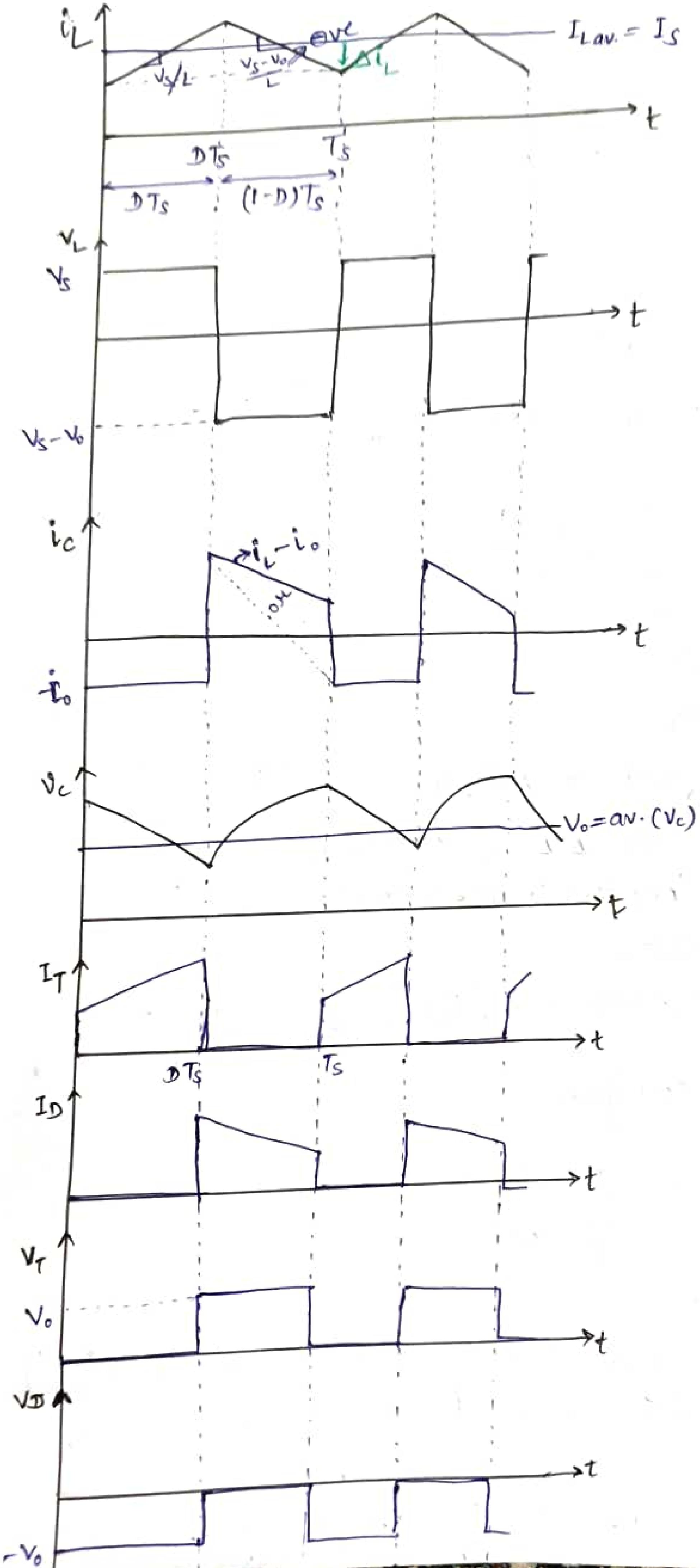
$$\Rightarrow V_S - \frac{V_o}{R(1-D)} R_L - V_o(1-D) = 0 \quad \left[I_L = I_S = \frac{I_o}{(1-D)} = \frac{V_o}{R(1-D)} \right]$$

$$\Rightarrow V_s - V_o \left[\frac{R_L}{R(1-D)} + (1-D) \right] = 0$$

$$V_o = \frac{V_s}{\frac{R_L}{R(1-D)} + (1-D)} = \frac{V_s(1-D)}{\frac{R_L}{R} + (1-D)^2}$$

As $D \to 1$, $V_o = 0$.

[Always operate the boost converter with a load, otherwise the voltage builds up and blasts.]



$$\Delta i_L = \frac{V_S}{L} D T_S$$
$$= \frac{V_S - V_0}{L}(1-D)T_S$$

$$v_c = \frac{1}{C}\int i_c \, dt$$

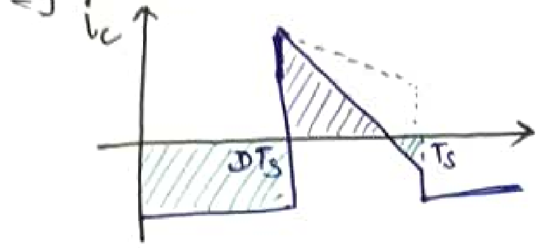
Book: Power Elec. by
↳ Daniel W Hart

02-09-2024

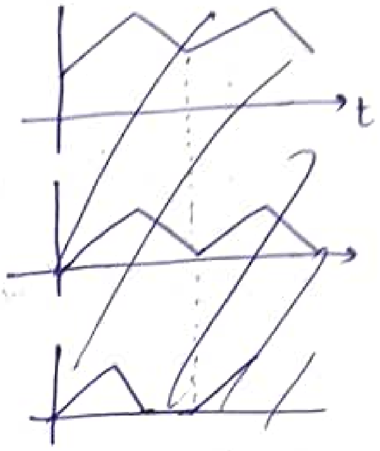
Peak-to-peak ripple in the inductor current:

$$\Delta i_L = \frac{V_s}{L} D T_s = \left(\frac{V_s - V_o}{L}\right)(1-D) T_s$$

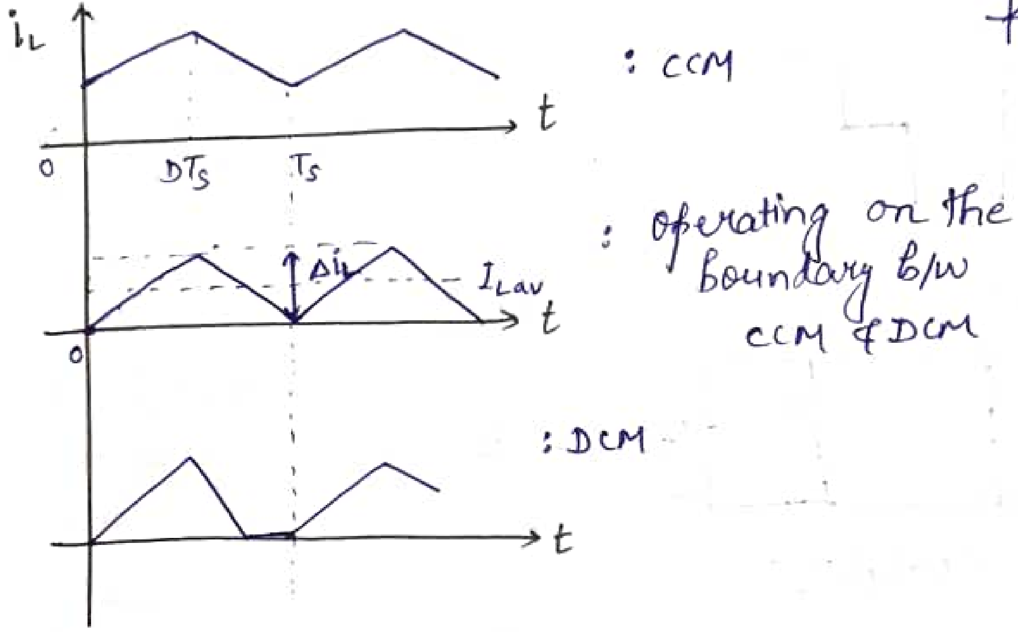
Capacitor current:



$$\Delta V = \frac{\Delta Q}{C}$$



Inductor current:



Assuming 100 % efficiency,

$$V_s I_s = V_o I_o, \quad V_o = \frac{V_s}{1-D}$$

$$I_s = \frac{V_o I_o}{V_s} = \frac{V_s I_o}{(1-D) V_s} = \frac{I_o}{1-D}$$

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

$$I_{L(av.)} = I_s = \frac{V_o}{R(1-D)} = \frac{V_s}{R(1-D)^2}$$

On the boundary b/w CCM & DCM:

$$I_{L(av.)} = \frac{\Delta i_L}{2}$$

$$\frac{V_s}{R(1-D)^2} = \frac{V_s}{2L}(D T_s)$$

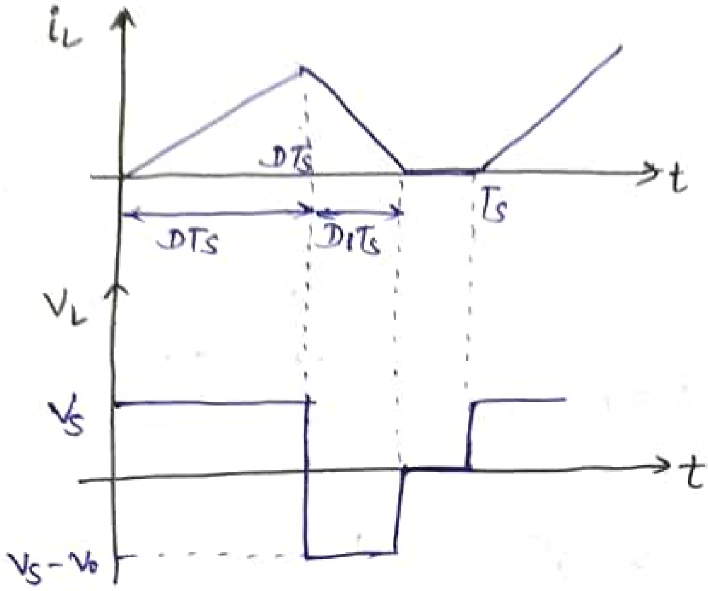
$$K_{cri.} = \frac{2L}{R T_s} = D(1-D)^2$$

| K: conduction parameter

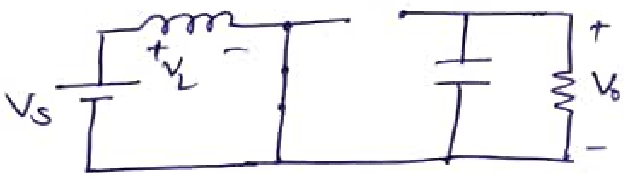
$I_{L(av.)} > \frac{\Delta i_L}{2} \longrightarrow CCM$

$I_{L(av)} < \frac{\Delta i_L}{2} \longrightarrow DCM$

DCM:

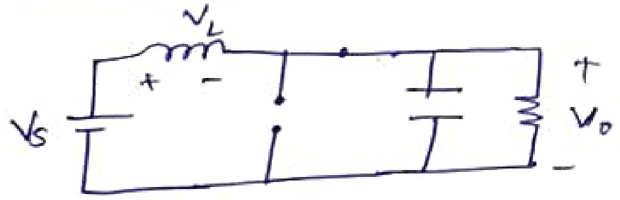


$0 < t \le DT_s$:



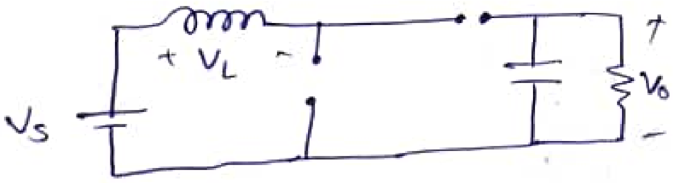
$V_L = V_S$

$DT_s < t \le (D+D_1)T_s$:



$V_L = V_S - V_o$

$(D+D_1)T_s < t \le T_s$:



$V_L = 0$

Applying volt-second Balance,

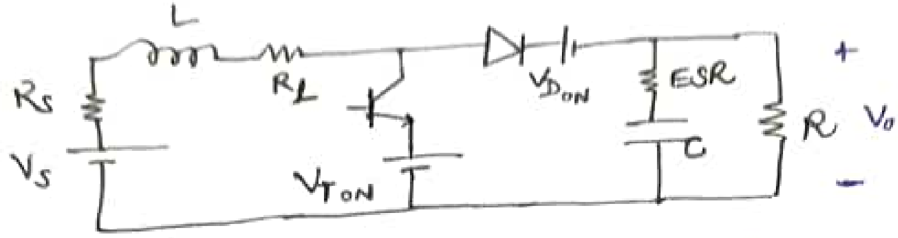
$$V_s DT_s + (V_s - V_o) D_1 T_s + 0(1-(D+D_1))T_s = 0$$

$$\Rightarrow V_s D + (V_s - V_o) D_1 = 0$$

$$\Rightarrow V_s(D+D_1) = V_o D_1$$

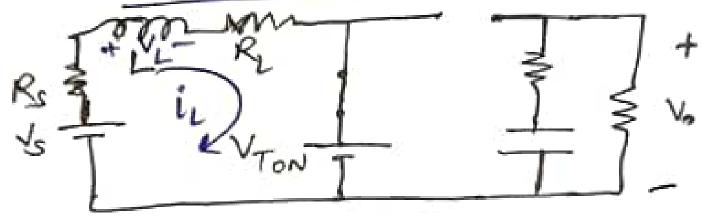
$$\Rightarrow V_o = \frac{V_s(D+D_1)}{D_1} = V_s\left(1 + \frac{D}{D_1}\right)$$

Boost Converter with non-idealities :



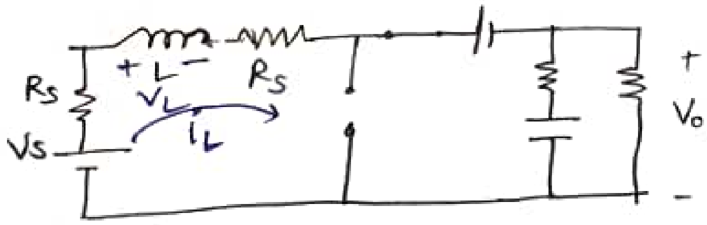
R_s : Internal resistance of the source
R_L : Parasitic resistance of the inductor
V_{TON} : ON-state voltage drop of the active switch
V_{DON} : ON-state voltage drop of the diode
ESR : Equivalent series resistance of the capacitor.

$0 < t \le DT_S$:



$$V_S - i_L R_S - V_L - i_L R_L - V_{TON} = 0$$
$$\Rightarrow V_L = V_S - i_L (R_S + R_L) - V_{TON}$$

$DT_S < t \le T_S$:



$$V_S - i_L R_S - V_L - i_L R_L - V_{DON} - V_o = 0$$
$$\Rightarrow V_L = V_S - i_L (R_S + R_L) - V_{DON} - V_o$$

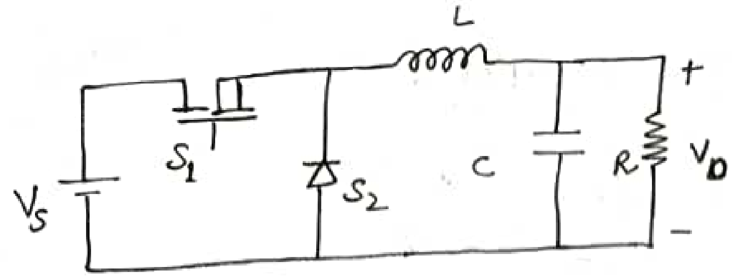
Applying volt-sec. balance,

$$(V_S - i_L (R_S + R_L) - V_{TON}) D \cancel{T_S} + (V_S - i_L (R_S + R_L) - V_{DON} - V_o)(1-D)\cancel{T_S} =$$

$$\Rightarrow i_L = i_{L(av)} = I_S = \frac{I_o}{1-D} = \frac{V_o}{R(1-D)}.$$

03-09-2024

Q)



A buck converter operating in CCM mode is shown in figure.
$V_s = 30V$, $R = 20\Omega$, $L = 0.4\ mH$.
The inductor has a parasitic resistance of 0.02Ω and the input source has an internal resistance of $0.01\ \Omega$. The ON-state voltage drop of the switches S_1 and S_2 are 0.8V and 0.6V, respectively. The switching frequency is 25KHz and the operating duty ratio (D) is 0.8.

(a) Evaluate the output voltage (V_0).

(b) Evaluate the efficiency of the converter.

(c) Evaluate the peak-to-peak ripple in inductor current.

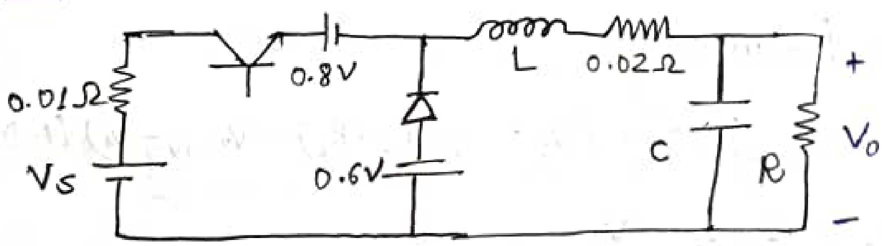
(d) Sketch the waveform of inductor current and mark all salient points.

(e) Sketch the waveform of the capacitor current and mark all salient points.

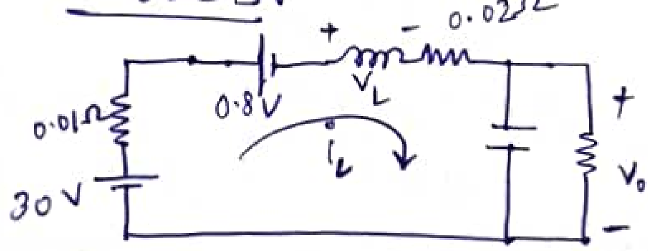
(f) Evaluate the capacitance (C) required to keep the ripple in the output voltage less than 1% of the average output voltage.

(g) Estimate the conduction loss in the switches S_1 and S_2.

Soln: Buck converter with non-idealities:

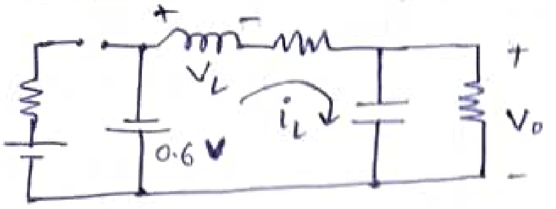


$0 < t \leq DT_s$:



$V_L = (30 - 0.8 - 0.01 i_L - 0.02 i_L - V_0)$

$DT_s < t \le T_s$:



$$V_L = -(0.6 + 0.02\, i_L + V_o)$$

ⓐ Applying volt-second balance,

$$(30 - i_L(0.01 + 0.02) - 0.8 - V_o)\, DT_s + -(V_o + 0.6 + 0.02 I_L)(1-D)\, T_s = 0$$

$$\left[i_L = I_o = \frac{V_o}{R}, \quad R = 20\,\Omega, \; D = 0.8 \right]$$

$$\Rightarrow \left(30 - \frac{V_o}{20}(0.01 + 0.02) - 0.8 - V_o\right) 0.8 - \left(V_o + 0.6 + 0.02\frac{V_o}{20}\right) 0.2 = 0$$

$$\Rightarrow V_o = \frac{23.24}{1.0014} = 23.2075\ \text{V}$$

Output current, $I_o = \dfrac{V_o}{R} = \dfrac{23.2075}{20} = 1.1604\ A$

Input source current, $I_s = D I_o = 0.8 \times 1.1604$
$= 0.928\ A$

$$\left[\begin{array}{l} V_o I_o = V_s I_s \\ D \cancel{V_s} I_o = \cancel{V_s} I_s \\ I_s = D I_o \end{array}\right]$$

[current conversion ratio is not affected by series non-idealities.]

ⓑ Efficiency of the converter $= \dfrac{\text{Output power}}{\text{Input power}}$

$$= \frac{V_o I_o}{V_s I_s} = \frac{23.2075 \times 1.1604}{30 \times 0.928} = 0.9669$$

ⓒ Peak-to-peak ripple in the inductor current,

$$\Delta i_L = \frac{V_L}{L}(1-D)\, T_s$$

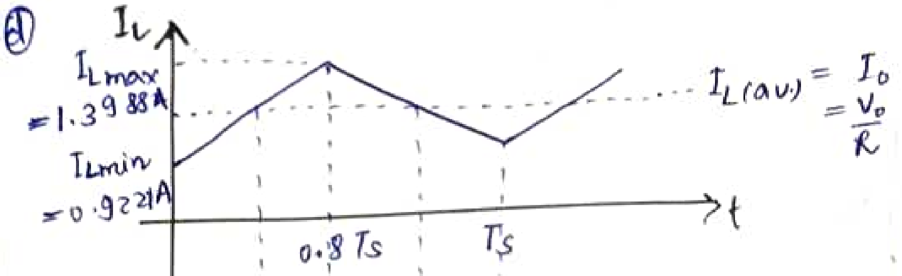
For $DT_s < t \le T_s$:

$$V_L = 23.2075 + 0.02 \times 1.1604 + 0.6$$
$$= 23.833\ \text{V}$$

$$T_s = \frac{1}{f_s} = \frac{1}{25 \times 10^3} = 40 \times 10^{-6}\ s$$

$$\therefore \Delta i_L = \frac{23.833 \times 0.2 \times 40 \times 10^{-6}}{0.4 \times 10^{-3}} = 0.4767\ A.$$

(d)

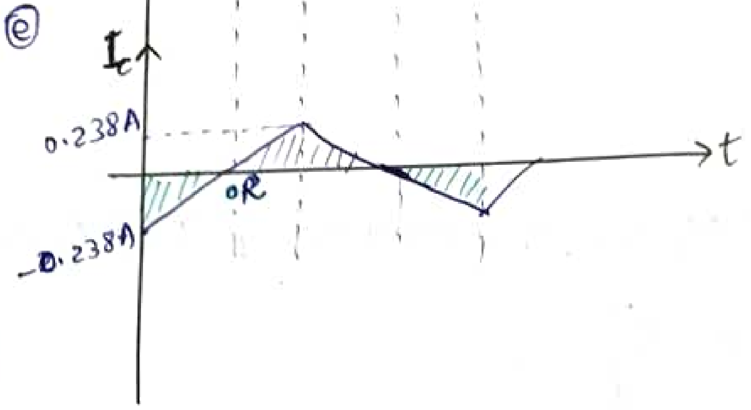


$$I_{Lmin} = I_{L(av)} - \frac{\Delta i_L}{2}$$
$$= 1.1604 - \frac{0.4767}{2}$$
$$= 0.9221A$$

$$I_{Lmax} = I_{L(av)} + \frac{\Delta i_L}{2}$$
$$= 1.1604 + \frac{0.4767}{2}$$
$$= 1.3988 A$$

$$I_c = I_L - I_o$$
$$I_{cmax} = I_{Lmax} - I_o$$
$$I_{cmin} = I_{Lmin} - I_o$$

(e)

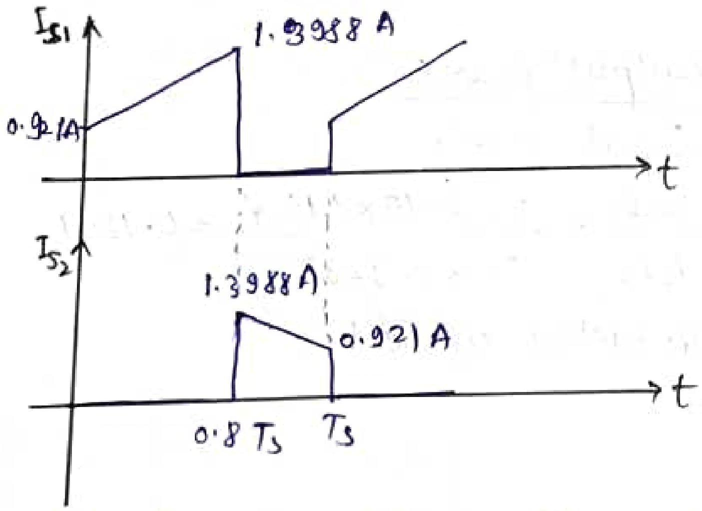


(f) $C = \frac{\Delta Q}{\Delta V}$

$$\Delta V = 1\% \text{ of } 23.275$$
$$= 0.23275$$

$$\Delta Q = \frac{1}{2} \times 0.238 \times \frac{40\times10^{-6}}{2}$$

$$\text{Capacitance, } c = \frac{\frac{1}{2} \times \frac{0.238 \times 40\times10^{-6}}{2}}{0.23275}$$
$$= 10.24 \times 10^{-6} F$$



(g) Average conduction loss $= \frac{1}{T}\int_0^T V_T \times I_T\, dt = \frac{1}{T}\int_0^T V_{TON}\, I_T\, dt$

$$= V_{TON} \times \frac{1}{T}\int_0^T I_T\, dt$$

$V_T = V_{TON} = 0.8V$ for S_1

$$= \boxed{V_{TON} \times I_{T(av.)}}$$

Average conduction loss in switch S_1

$= $ Average current through S_1 × ON-state voltage drop

$$= \frac{\left(\frac{1.3988+0.9221}{2}\right) DT_s}{T_s} \times 0.8 = 0.7427\ W$$

Av. conduction loss in diode $= \frac{\left(\frac{1.3988+0.9221}{2}\right)(1-D)\,T_s}{T_s} \times 0.6$

$= 0.25208 \times 0.6$

$= 1.392\ W$

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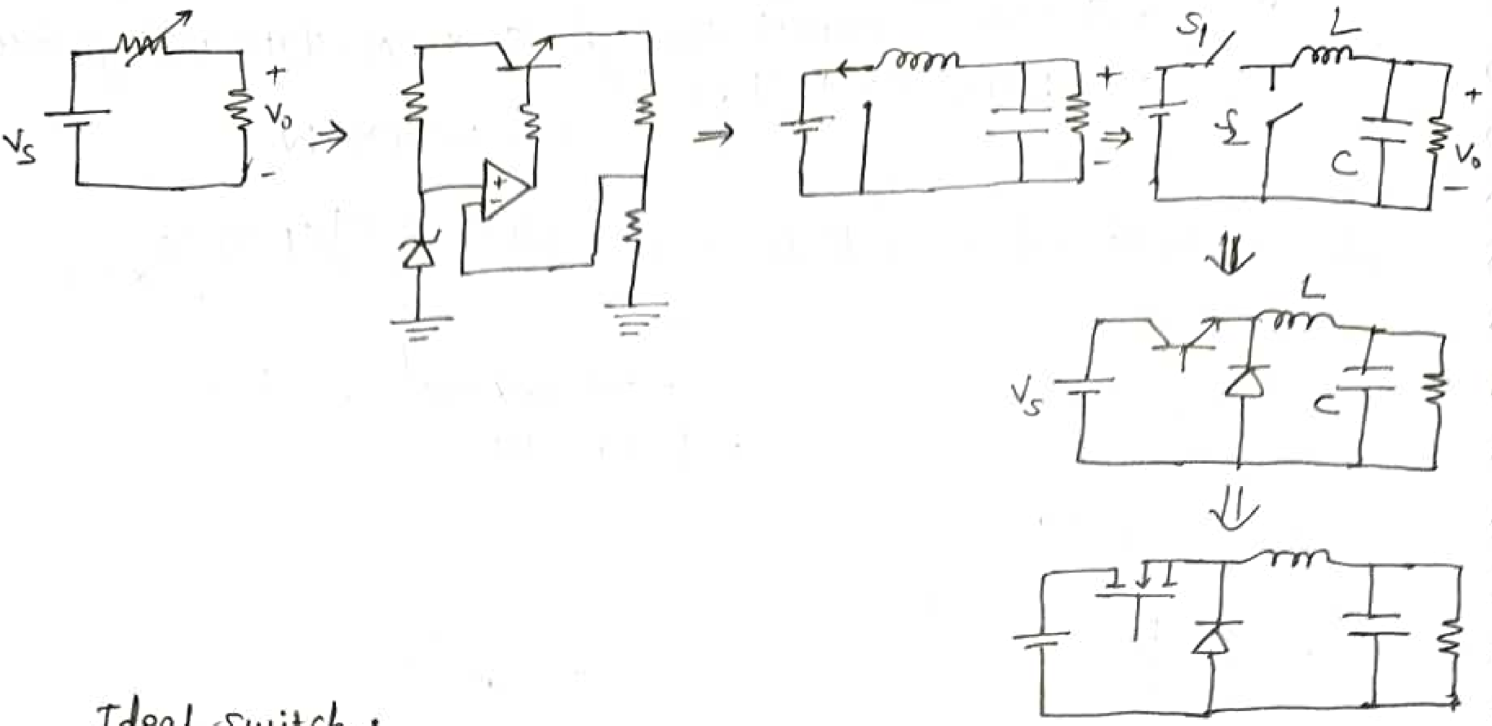
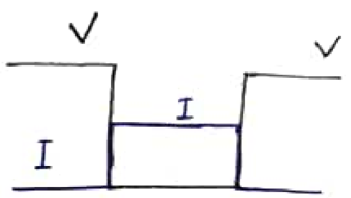
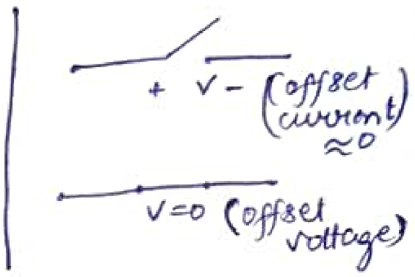


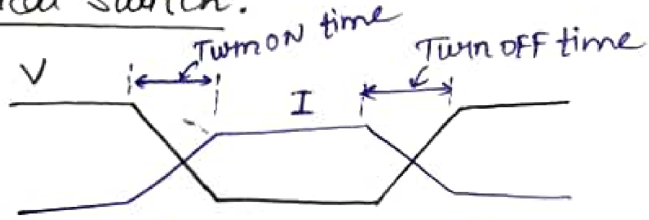
Ideal Switch :



Power: dissipated by the switch

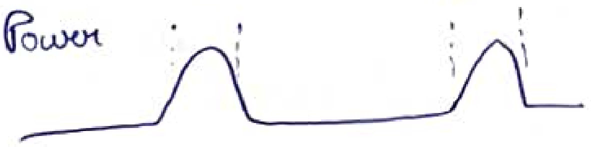


Practical Switch :



OFF to ON Transition Turn ON

ON to OFF transition Turn OFF



[Switching Loss] ⟸ Hard switching

Soft switching: Lossless switching where either V or I is maintained zero.

↳ High switching frequency.

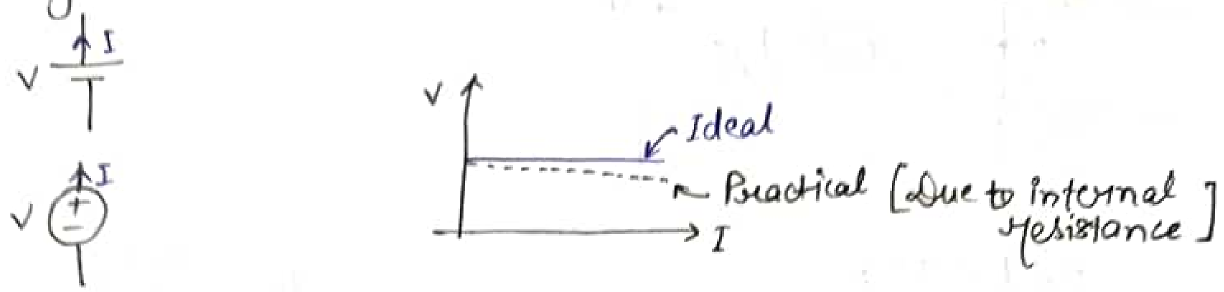
→ Zero voltage switching (ZVS) : Maintain V=0 while switching

→ Zero Current switching (ZCS) : Maintain I=0.

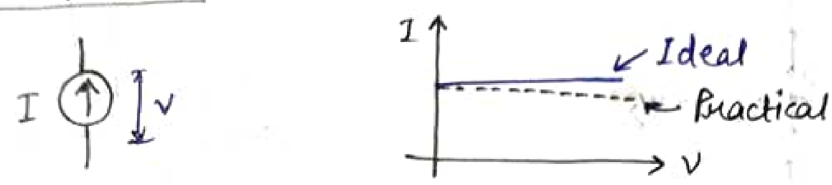
DC to AC Converters

DC Sources:

Voltage Source:



Current source:



DC to AC Converters (Inverters):

- Voltage Source converter (Inverter) [VSI]
  - ⇓ Most commonly used
- Current Source Converters (Inverter) [CSI]

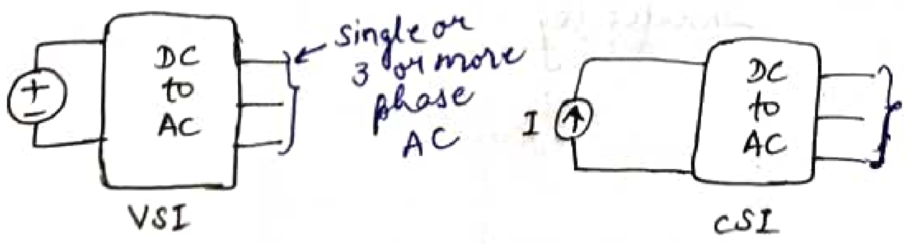
Sinusoid waves: Give high efficiency

↳ Mathematical advantages: Differentiation or Integration gives sine waves.

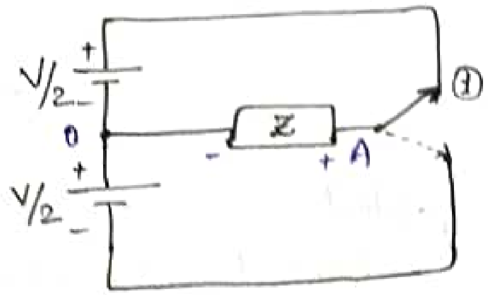
↳ Any periodic wave can be represented as the sum of infinite sine waves.

[Ensure that average value of o/p V is zero]

09-09-2024

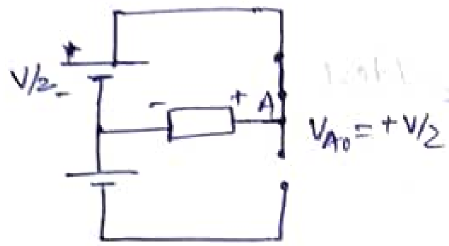


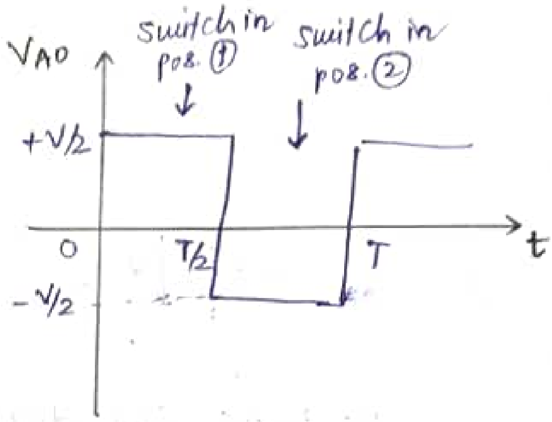
Voltage Source Inverters (VSI): Half-Bridge Inverter



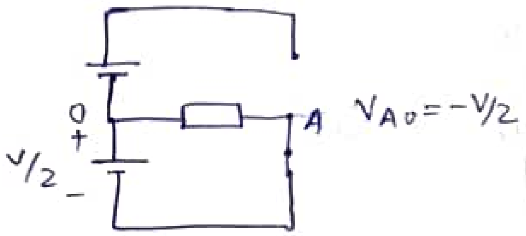
$0 < t \le T/2$:

Switch in position ①:





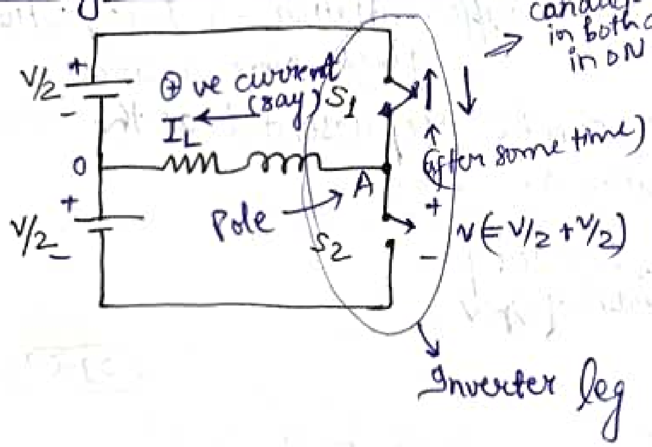
$T/2 \le t < T$:

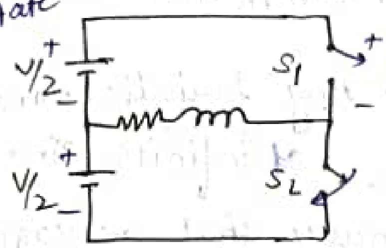


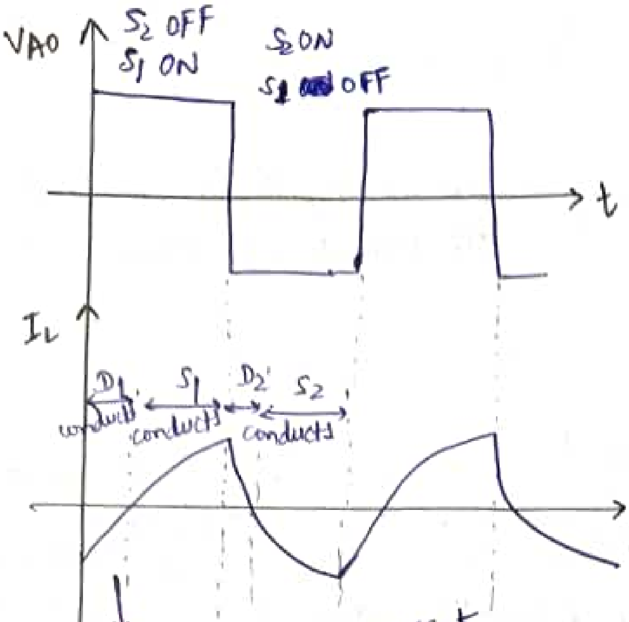
AC Loads: R-L (or R-L-E) (in general)

Using 2 SPST switches: [Complementary Operation] ⟹ IGBT (Current-bidirectional 2 quadrant switch)

⟹ conducts current in both dirn in ON state

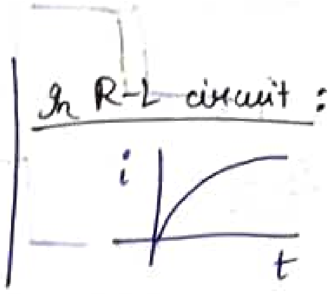




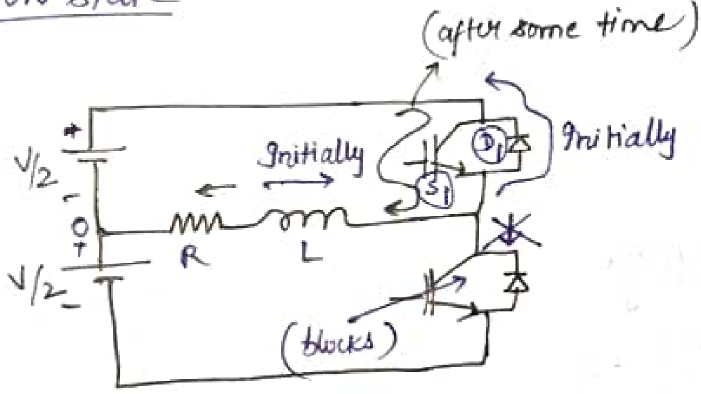


[In steady state]
⇓
(After some switchings)

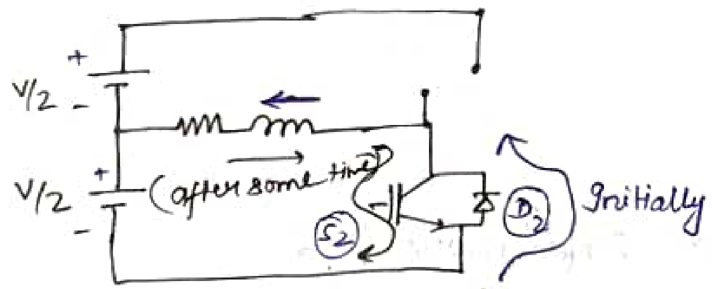
Initially -ve current even in ON state



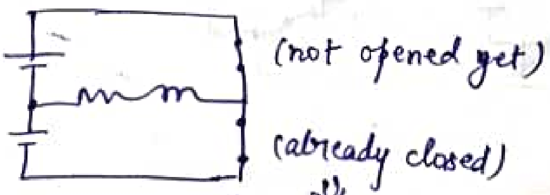
In ON state :



In OFF state :



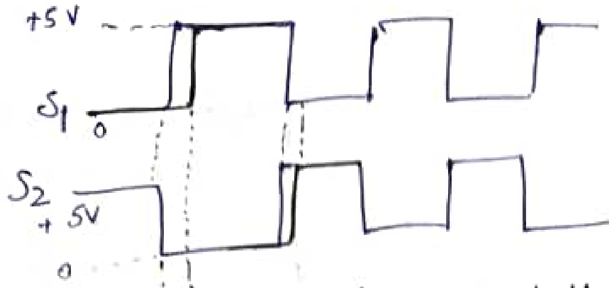
→ Switching time is decided by R-L.
→ without reverse diodes, it will blast.
→ There is a finite switching ON and switching OFF time.
→ Ensure that when one switch is ON, other is OFF.



⇓
(Due to unequal switching time of switches)

⇒ short-circuit current
⇓
Damages the inverter

Gate pulses of S_1 and S_2 :



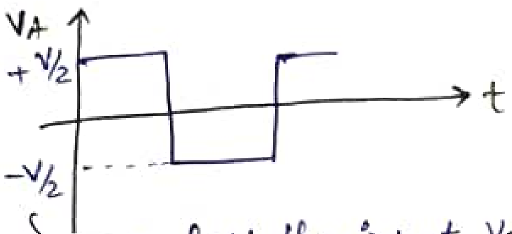
→ Ensure T_{ON} (turn ON) & T_{OFF} (turn off time) are same for S_1 & S_2.

→ Ensure that S_2 is fully opened Before closing S_1 ⇒ Give some time delay to S_1 ⇒ Ensure to give certain dead time to the pulses, before turning ON the inverter.

[Only delay the rising edges of pulses]

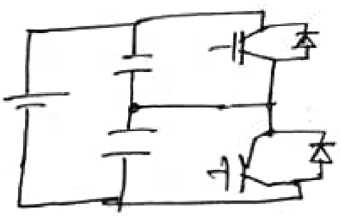
dead time/ dead band

10-09-2024

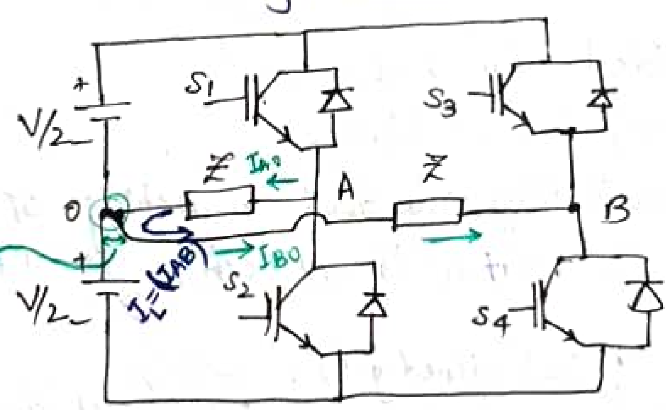


→ only half the input voltage

Using only one ~~input~~ voltage source :



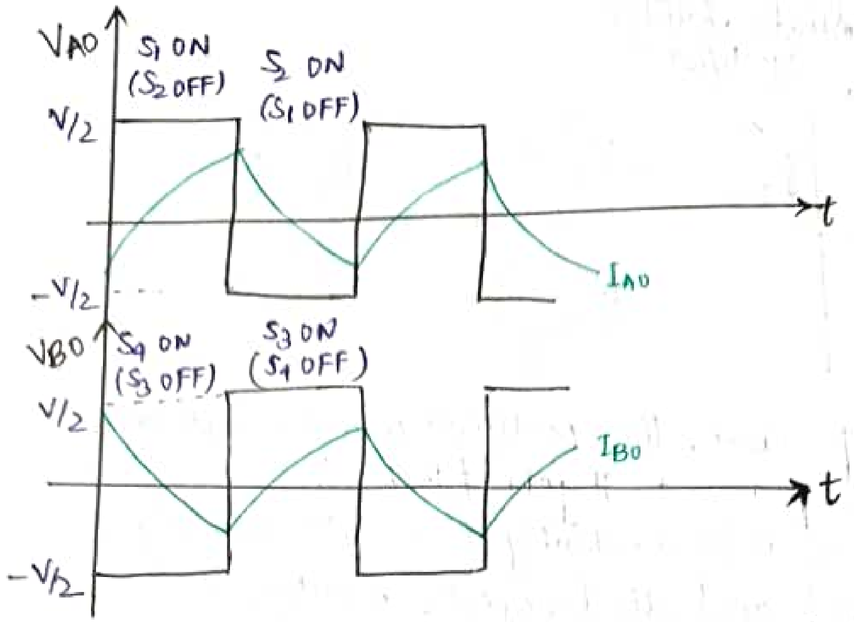
To increase V_A amplitude : Add more legs



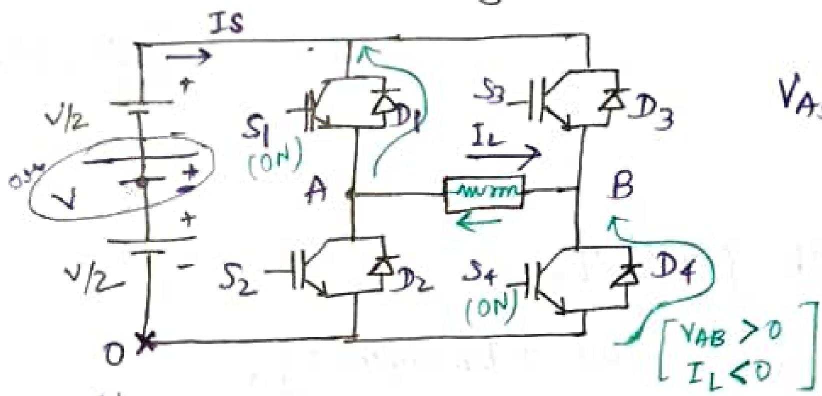
Current cancels

this link can be removed

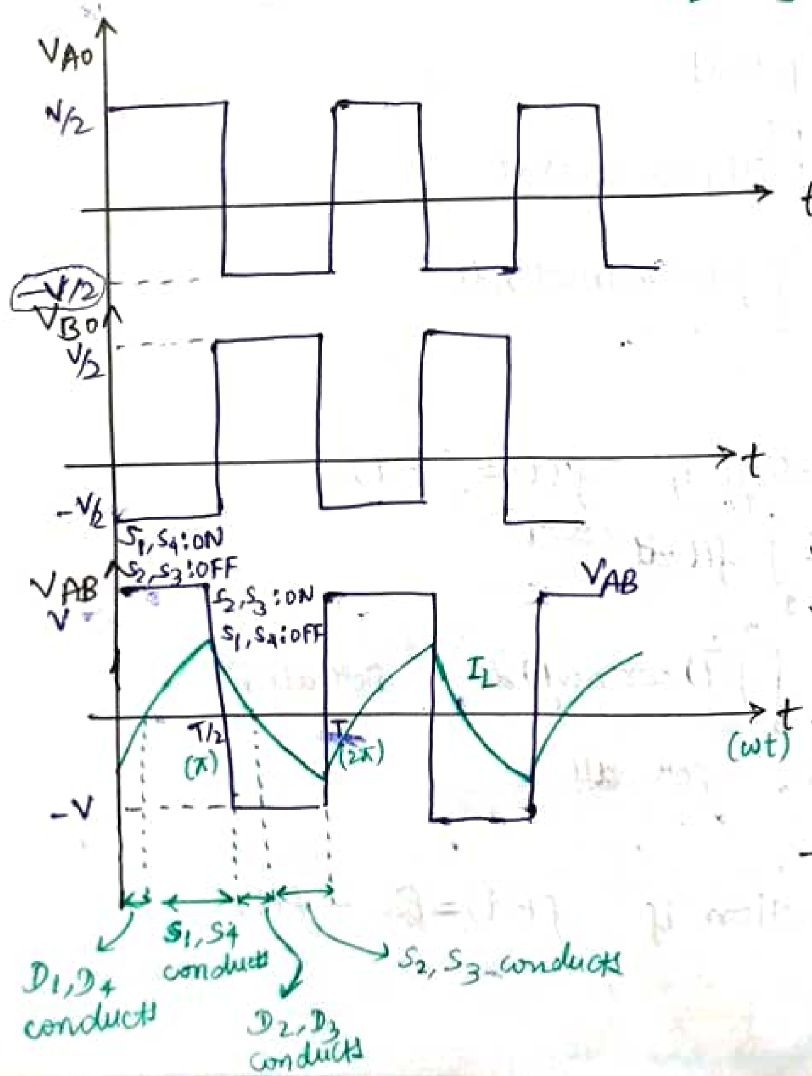
V_{AO}, V_{BO} : Pole voltages

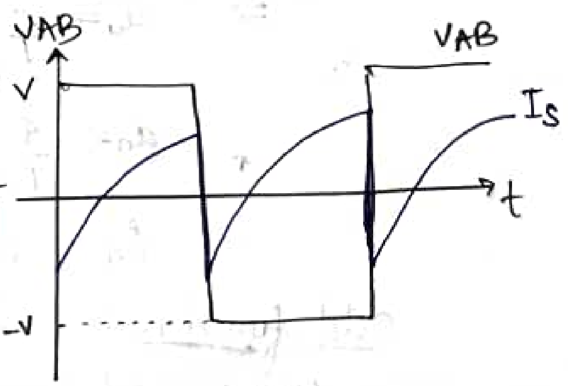


⇓ Full Bridge Inverter (H-Bridge Inverter)

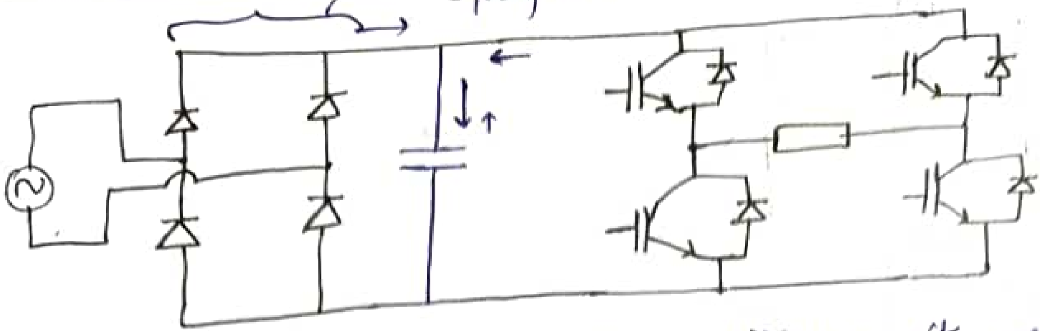


$$V_{AB} = V_{AO} + V_{OB}$$
$$= V_{AO} - V_{BO}$$





With AC source: $\rightarrow$ Diode-bridge rectifier



without the capacitor, the rectifier won't work as in reverse current, it gets blocked.
with capacitor, it is constantly & simultaneously getting charged and discharged, resulting in ripple which has to be considered.

17-09-2024

Fourier Series

If $f(t)$ is periodic with period T.

$$f(t) = a_0 + \sum_{n=1}^{\infty} [a_n \cos n\omega t + b_n \sin n\omega t],$$

$$a_0 = \frac{1}{T}\int_0^T f(t)\,dt$$

$$a_n = \frac{2}{T}\int_0^T f(t)\cos(n\omega t)\,dt$$

$$b_n = \frac{2}{T}\int_0^T f(t)\sin(n\omega t)\,dt$$

Even function:

$f(t)$ is even function if $f(t) = f(-t)$.

$$\Rightarrow \quad a_0 = \frac{2}{T}\int_0^{T/2} f(t)\,dt$$

$$a_n = \frac{4}{T}\int_0^{T/2} f(t)\cos(n\omega t)\,dt, \quad \text{for all } n$$

$$b_n = 0, \quad \text{for all } n$$

Odd function:

$f(t)$ is odd function if $f(-t) = -f(t)$.

$$\Rightarrow \quad a_0 = 0$$

$$a_n = 0$$

$$b_n = \frac{4}{T}\int_0^{T/2} f(t)\sin(n\omega t)\,dt, \text{ for all } n.$$

Half-wave Symmetry:

$f(t)$ has half-wave symmetry if

$$f(t) = -f(t - T/2).$$

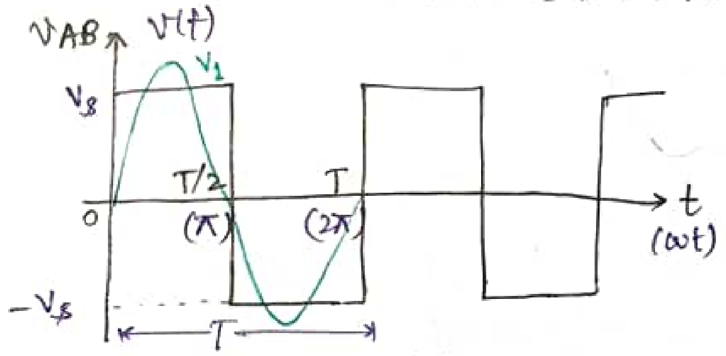
If $f(t)$ is an odd function with half-wave symmetry.

$a_0 = 0$

$a_n = 0$, for all n

and, $b_n = \frac{4}{T}\int_0^{T/2} f(t)\sin(n\omega t)\,dt$, for n = odd $(n = 1, 3, 5, \ldots)$

$= 0$, for n = even.



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

$$v(t) = \begin{cases} +V_s & \text{for } 0 < \theta < \pi \\ -V_s & \text{for } \pi < \theta < 2\pi \end{cases}$$

↳ odd function with half-wave symmetry.

$\Rightarrow a_0 = 0,\ a_n = 0$, for all n

$$b_n = \frac{4}{2\pi}\int_0^{\pi} v(\omega t)\sin(n\omega t)\,d(\omega t) \quad , \text{for } n = 1, 3, 5, \ldots$$

$$= \frac{4}{2\pi}\int_0^{\pi} V_s \sin n(\omega t)\,d(\omega t)$$

$$= \frac{4V_s}{2\pi}\left[-\frac{\cos n\omega t}{n}\right]_0^{\pi}$$

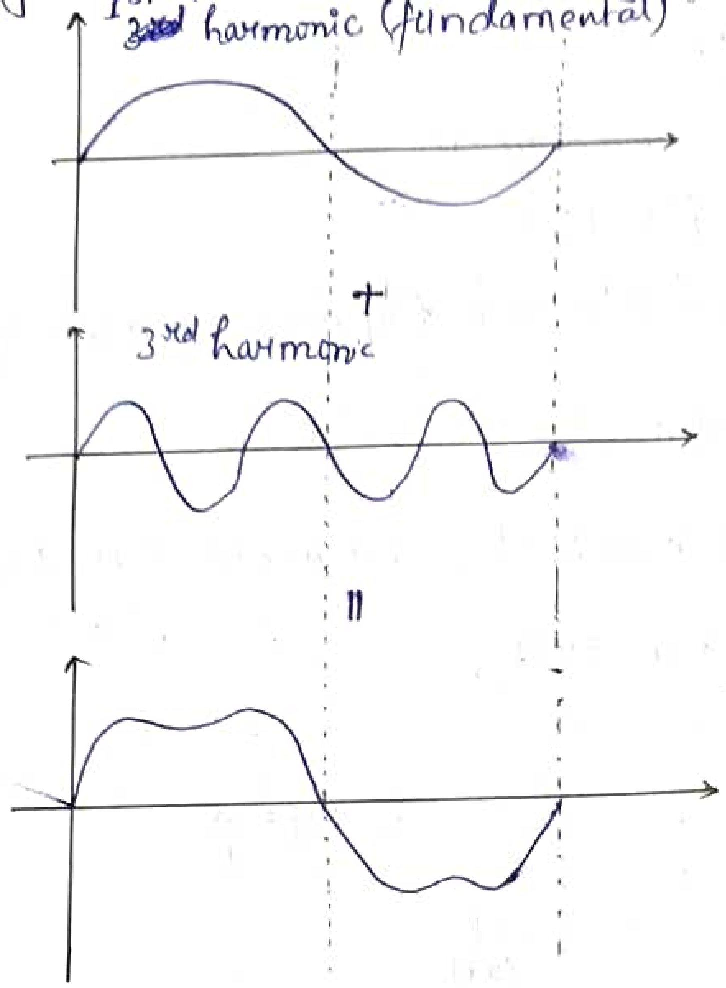
$$= -\frac{4V_s}{2\pi n}\left[-1 - 1\right] = \frac{8V_s}{2n\pi}$$

$$= \frac{4V_s}{n\pi} \quad \text{for } n = 1, 3, 5, \ldots$$

$$\therefore\ v(\omega t) = \sum_{n=1}^{\infty} b_n \sin n\omega t \underset{n=1,3,5,\ldots}{} = \frac{4V_s}{\pi}\left[\sin\omega t + \overset{\text{3rd harmonic}}{\frac{\sin 3\omega t}{3}} + \overset{\text{5th harmonic}}{\frac{\sin 5\omega t}{5}} + \ldots\right]$$

only odd harmonics

→ Magnitude of harmonics is inversely proportional to the harmonic.



Fundamental component (V_1) = $\frac{4V_s}{\pi} \sin \omega t$

Peak value of fund. component, $V_{1p} = \frac{4V_s}{\pi}$ $(> V_s)$

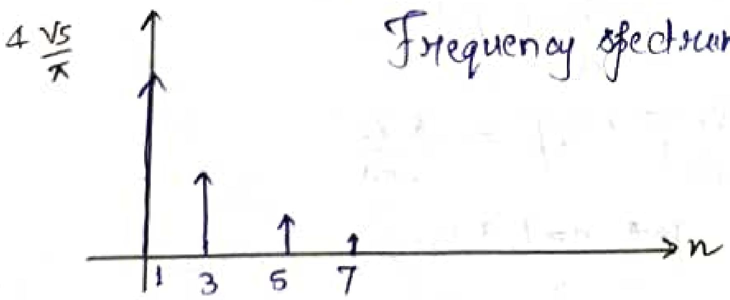
RMS value of fund. component, $V_{1rms} = \frac{4V_s}{\sqrt{2}\pi}$

To get fundamental component

↳ Low Pass Filter is not desirable as it changes its frequency.

↳ Also, it has high cost and bigger than the inverter itself.

Frequency spectrum:

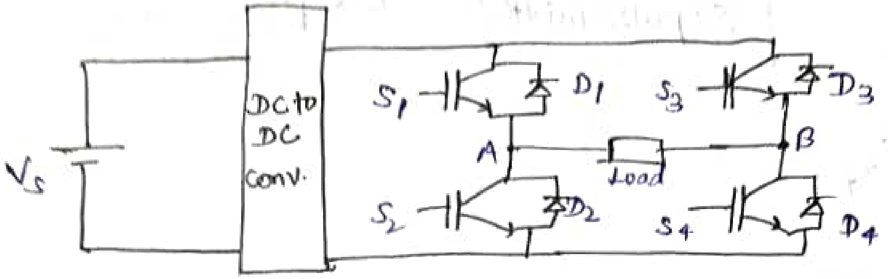


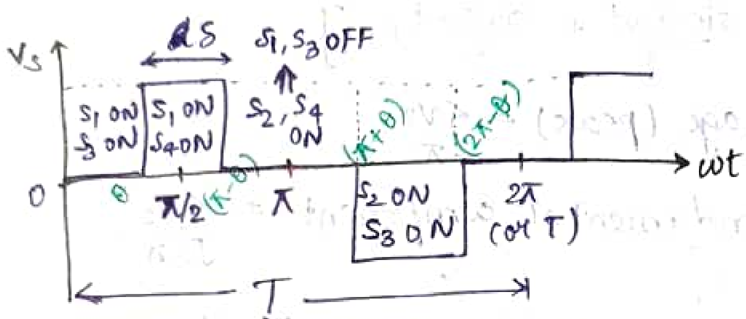
To ~~a~~ control the magnitude of fundamental component:

↳ change V_s → changing / Variable DC source is hard to design

⇓

Introduce DC to DC converter (Buck converter).





↳ same as $V_{AB}(T)$.

: Quasi-Squaree wave

→ By changing the value of δ ~~d~~, peak/RMS value of fund. comp. can be changed (by changing V_s).

→ To get $V_s = 0 \Rightarrow$ we can't just take $V_s=0 \Rightarrow$ Instead just make 2 above or 2 below switches ON.

[∵ V_s shall not be interrupted suddenly]

$\boxed{20\text{-}09\text{-}2024}$

↳ odd function

↳ Half wave, quarter wave symmetry.

⇓ sufficient to integrate in $(0, \pi/2)$.

$a_0 = 0,\ a_n = 0$, for all n.

$$b_n = \frac{8}{2\pi}\int_0^{\pi/2} v(t)\sin n\omega t\ d(\omega t) \qquad \left[\because V_1 = \frac{4V_s}{\pi}\right]$$

for n: odd

$$= \frac{8}{2\pi}\left[\int_0^{\theta} 0 \times \sin n\omega t\ d\omega t + \int_{\theta}^{\pi/2} V_s \sin(n\omega t)\, d(\omega t)\right]$$

$$= \frac{8V_s}{2\pi}\left[-\frac{\cos n\omega t}{n}\right]_{\theta}^{\pi/2} = \frac{4V_s}{n\pi}\left[-(\cos n\pi/2 - \cos n\theta)\right]$$

$$= \frac{4V_s}{n\pi}\cos n\theta$$

$$\therefore v(t) = \sum_{n=1,3,5}^{\infty} b_n \sin n\omega t$$

$$= \frac{4V_s}{\pi}\left[\cos\theta \sin\omega t + \frac{\cos 3\theta \sin 3\omega t}{3} + \frac{\cos 5\theta \sin 5\omega t}{5} + \dots\right]$$

$[\because n = 1, 3, 5, \dots,\ \cos n\pi/2 = 0]$

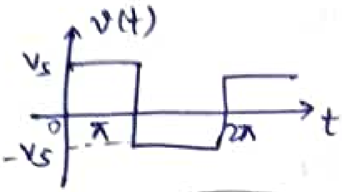
$$\therefore v(t) = \frac{4V_s}{\pi}\left[\cos\theta \sin\omega t + \frac{\cos 3\theta \sin 3\omega t}{3} + \frac{\cos 5\theta \sin 5\omega t}{5} + \frac{\cos 7\theta \sin 7\omega t}{7} + \dots\right]$$

Peak value of fundamental component

$$= \frac{4V_s}{\pi}\cos\theta = \frac{4V_s}{\pi}\left[\cos(\pi/2 - \delta/2)\right] = \frac{4V_s}{\pi}\sin\delta/2$$

[δ: pulse width] → Pulse width modulation

#



$$v(t) = \frac{4V_s}{\pi}\left[\sin\omega t + \frac{\sin 3\omega t}{3} + \frac{\sin 5\omega t}{5} + \dots\right]$$

Fundamental voltage (peak) $= \frac{4V_s}{\pi}$

RMS value of fundamental component $= \frac{4V_s}{\sqrt{2}\pi}$

Total Harmonic Distortion (THD) $= \dfrac{\text{RMS value of all harmonics}}{\text{RMS value of fundamental component}}$

For a rectangular waveform, $THD = \dfrac{\sqrt{V_s^2 - \left(\frac{4V_s}{\sqrt{2}\pi}\right)^2}}{\frac{4V_s}{\sqrt{2}\pi}} = \dfrac{\sqrt{V_s^2 - \frac{8V_s^2}{\pi^2}}}{\frac{4V_s}{\sqrt{2}\pi}} = \dfrac{\sqrt{\pi^2 - 8}}{4/\sqrt{2}}$

$= 0.483$

% THD = 48.3 %

→ (Recommended value ~ 5%)

→ Reducing/eliminating lower order harmonics significantly reduces THD.

$\theta = \pi/6 \Rightarrow$ No 3rd harmonic

$\theta = \pi/10$ or $18° \Rightarrow$ No 5th harmonic

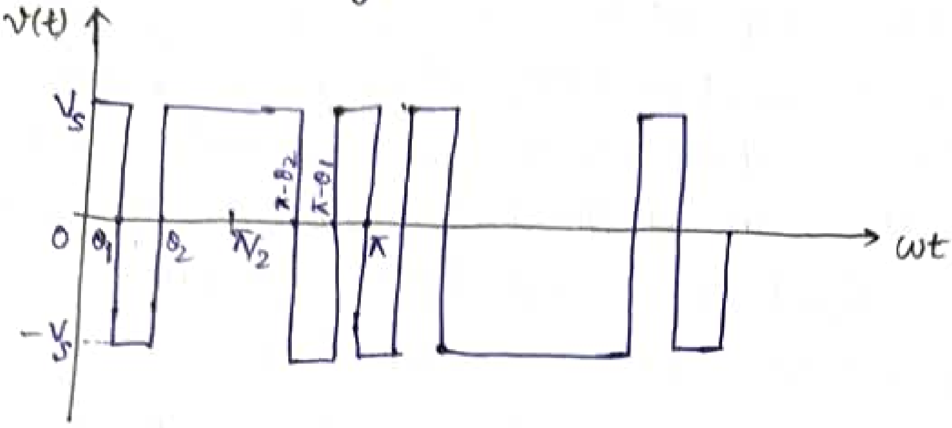
In general, for $\theta = \frac{90°}{n}$, n^{th} harmonic can be eliminated.

→ Selective Harmonic Elimination PWM (SHEPWM)

→ We can either control the magnitude of fundamental component or eliminate a harmonic, or control a harmonic magnitude.

→ If a harmonic is causing troublesome, eliminate it.

To control two parameters:



↳ odd function with half-wave and quarter-wave symmetry.

$a_0 = 0, \quad a_n = 0$ for all 'n'.

$$b_n = \frac{8}{2\pi}\int_0^{\pi/2} V_s(\omega t)\, d(\omega t)\, \sin(n\omega t)$$

$$= \frac{4}{\pi}\left[\int_0^{\theta_1} V_s \sin(n\omega t)\, d(\omega t) + \int_{\theta_1}^{\theta_2} (-V_s)\sin(n\omega t)\, d\omega t + \int_{\theta_2}^{\pi/2} (V_s)\sin(n\omega t)\, d\omega t\right]$$

$$= \frac{4V_s}{\pi}\left[-\frac{\cos n\omega t}{n}\Big|_0^{\theta_1} + \frac{\cos n\omega t}{n}\Big|_{\theta_1}^{\theta_2} - \frac{\cos n\omega t}{n}\Big|_{\theta_2}^{\pi/2}\right], \quad n = 1,3,5,\ldots$$

$$= \frac{4V_s}{n\pi}\left[-\cos n\theta_1 + \cos 0 + \cos n\theta_2 - \cos n\theta_1 - \cos n\frac{\pi}{2} + \cos n\theta_2\right]$$

$$\Rightarrow b_n = \frac{4V_s}{n\pi}\left[1 - 2\cos n\theta_1 + 2\cos n\theta_2\right]$$

$$b_1 = \frac{4V_s}{\pi}\left[1 - 2\cos\theta_1 + 2\cos\theta_2\right] = x \quad \text{[To control magnitude of fundamental component]}$$

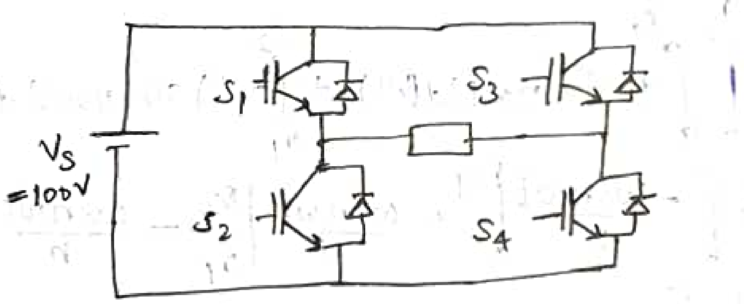
$$b_3 = \frac{4V_s}{3\pi}\left[1 - 2\cos 3\theta_1 + 2\cos 3\theta_2\right] = 0 \quad \text{[To eliminate 3rd harmonic]}$$

Ensure that there is no DC component, otherwise there will be a DC offset.

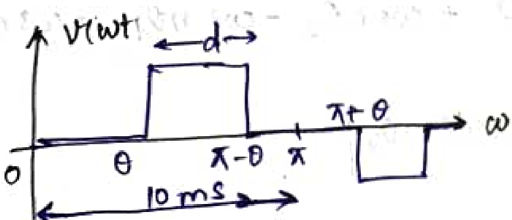
Eg. A pulse width modulated H-bridge inverter is shown in figure. The frequency of the fundamental component of the voltage across the load is 50 Hz. It has to be ensured that even harmonics are absent in the inverter output voltage.

(a) Evaluate the RMS value of the fundamental voltage realizable if 3rd harmonic has to be eliminated from the output voltage by employing selective harmonic elimination PWM.

(b) If the required RMS value of the fundamental voltage is 85V, evaluate the pulse width required in a half cycle of the inverter output voltage (quasi square wave) without focusing on elimination of any odd harmonics.



Soln:



$$v(\omega t) = \frac{4V_s}{\pi}\left[\cos\theta \sin\omega t + \cos 3\theta \frac{\sin 3\omega t}{3} + \cos 5\theta \frac{\sin 5\omega t}{5} + \dots\right]$$

(a) If 3rd harmonic has to be eliminated,

$$3\theta = 90^\circ \Rightarrow \theta = \frac{90^\circ}{3} = 30^\circ$$

Fundamental component (peak value) $= \frac{4V_s}{\pi}\cos 30^\circ = \frac{4\times 100}{\pi}\cos 30^\circ$

$= 110.26\,V$

RMS value of the fundamental component realizable

$= \frac{110.26}{\sqrt{2}} = 77.97\,V$

(b) RMS value of fundamental voltage $= 85\,V$

Peak " " $= 85\sqrt{2} = 120.21\,V$

$$\frac{4V_s}{\pi}\cos\theta = \frac{4\times 100}{\pi}\cos\theta = 120.21\,V$$

$$\Rightarrow \cos\theta = 0.944$$

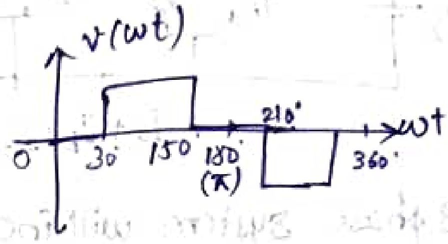
$$\Rightarrow \theta = 19.25^\circ$$

Pulse width $= 141.25^\circ$

$$= \frac{141.25}{180}\times 10\times 10^{-3} = 7.86\,ms.$$

Total harmonic distortion of voltage $= \dfrac{\text{RMS value of all harmonic}}{\text{RMS value of fundamental harmonic}}$

For elimination of 3rd harmonic, $\theta = 30^\circ$



$$\text{RMS value} = \sqrt{\frac{1}{T}\int_0^T f(t)^2\,dt}$$

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

$$= \sqrt{\frac{1}{2\pi}\left(\int_{\pi/6}^{5\pi/6} V_s^2\,d(\omega t) + \int_{7\pi/6}^{11\pi/6} (-V_s)^2\,d(\omega t)\right)}$$

$$= \sqrt{\frac{V_s^2}{2\pi}\left(\frac{4\pi}{6} + \frac{4\pi}{6}\right)}$$

$$= V_s\sqrt{\left(\frac{1}{3}+\frac{1}{3}\right)}$$

$$= \sqrt{\frac{2}{3}}\,V_s$$

$$THD = \frac{\sqrt{\left(\sqrt{\frac{2}{3}}\times 100\right)^2 - (77.97)^2}}{77.97} = 0.31 \rightarrow 31\%$$

→ Current across load also changes with harmonic

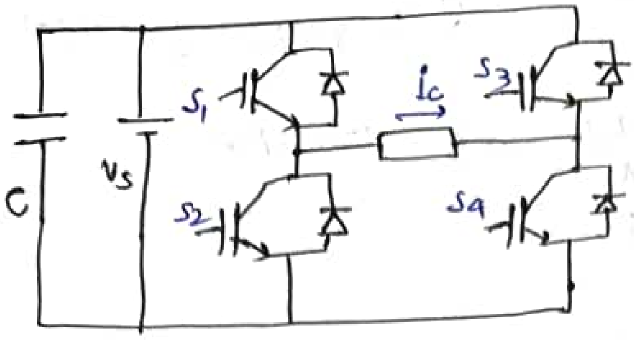
$Z_1 = R + j\omega L \Rightarrow |Z_1| = \sqrt{R^2 + (\omega L)^2}$

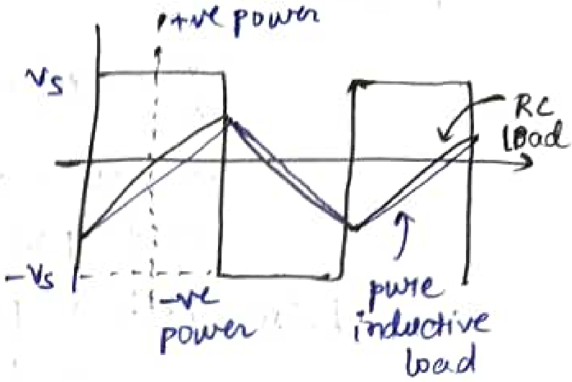
$Z_3 = R + j3\omega L \quad |Z_3| = \sqrt{R^2 + (3\omega L)^2}$

[As $n\uparrow \Rightarrow V_n\downarrow, Z_n\uparrow \Rightarrow I_n\downarrow$]

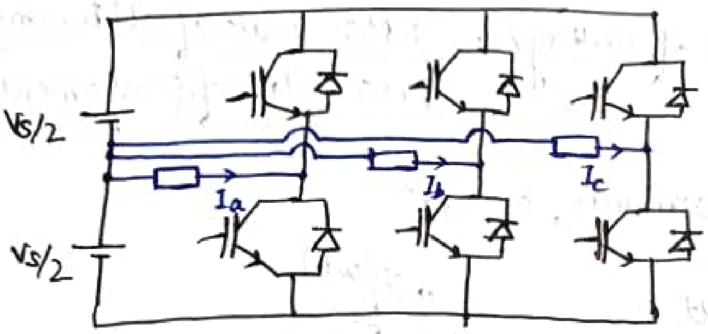
$I_3 = \dfrac{V_3}{Z_3}$, $I_5 = \dfrac{V_5}{Z_5}$ | $I_{rms} = \sqrt{I_1^2 + I_3^2 + I_5^2 + \cdots}$

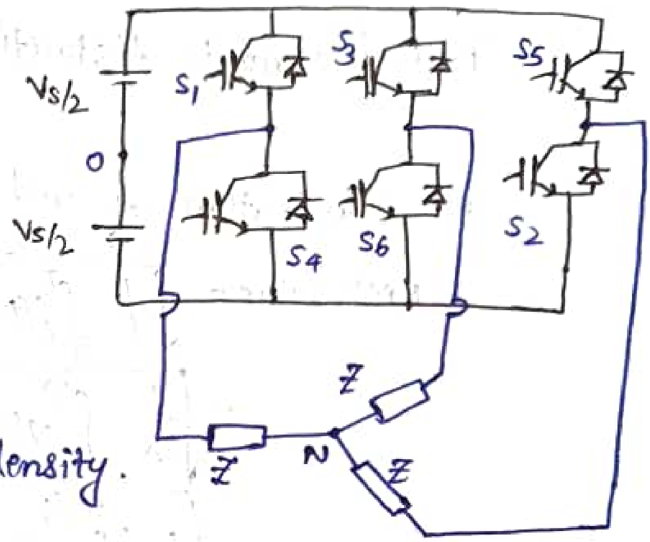
01-10-2024





Three Phase Voltage Source Inverter

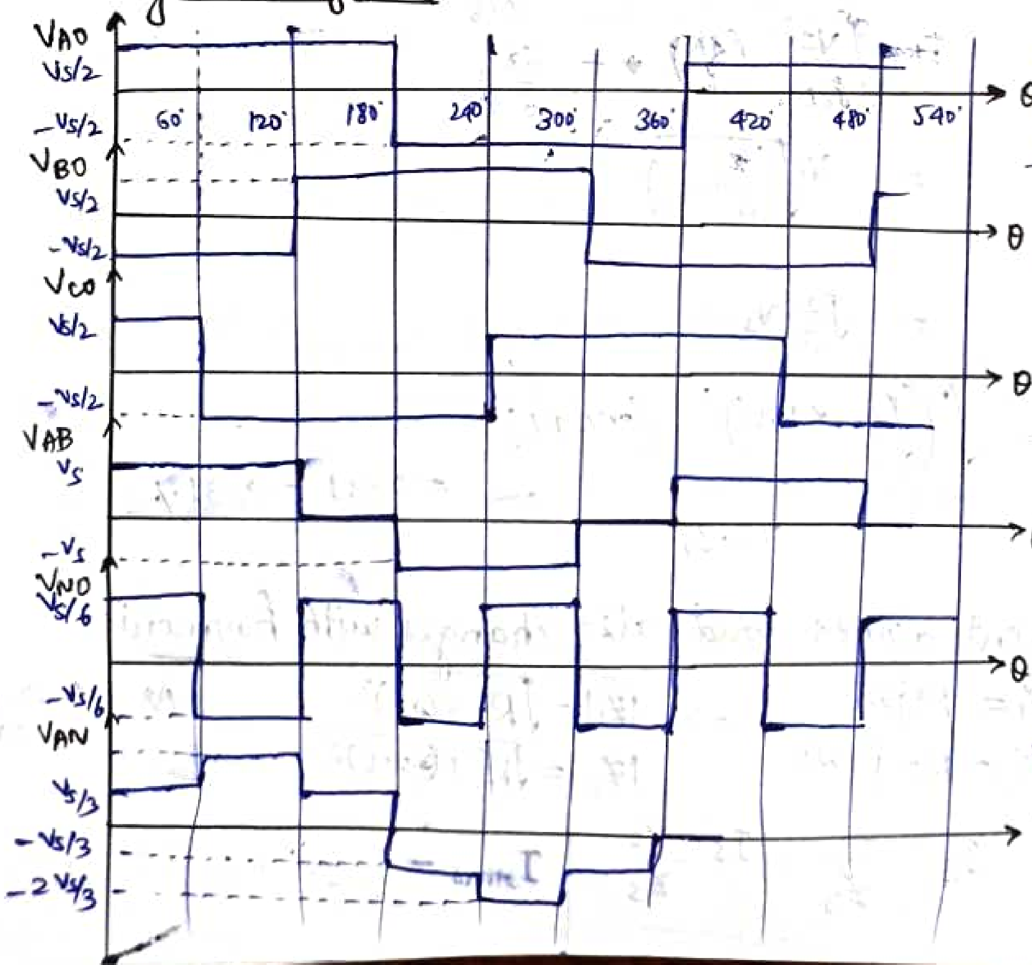




$I_a + I_b + I_c = 0$

→ 3-phase system will increase power density.
↳ Higher efficiency
↳ Constant DC voltage.

Pole Voltage Waveform:



V_{AO}, V_{BO}, V_{CO} } Pole voltage

V_{AB}, V_{BC}, V_{CA} } Line voltage

V_{AN}, V_{BN}, V_{CN} } Phase voltage

$V_{AB} = V_{AO} + V_{OB}$
$= V_{AO} - V_{BO}$

$V_{AN} = V_{AO} + V_{ON}$
$= V_{AO} - V_{NO}$

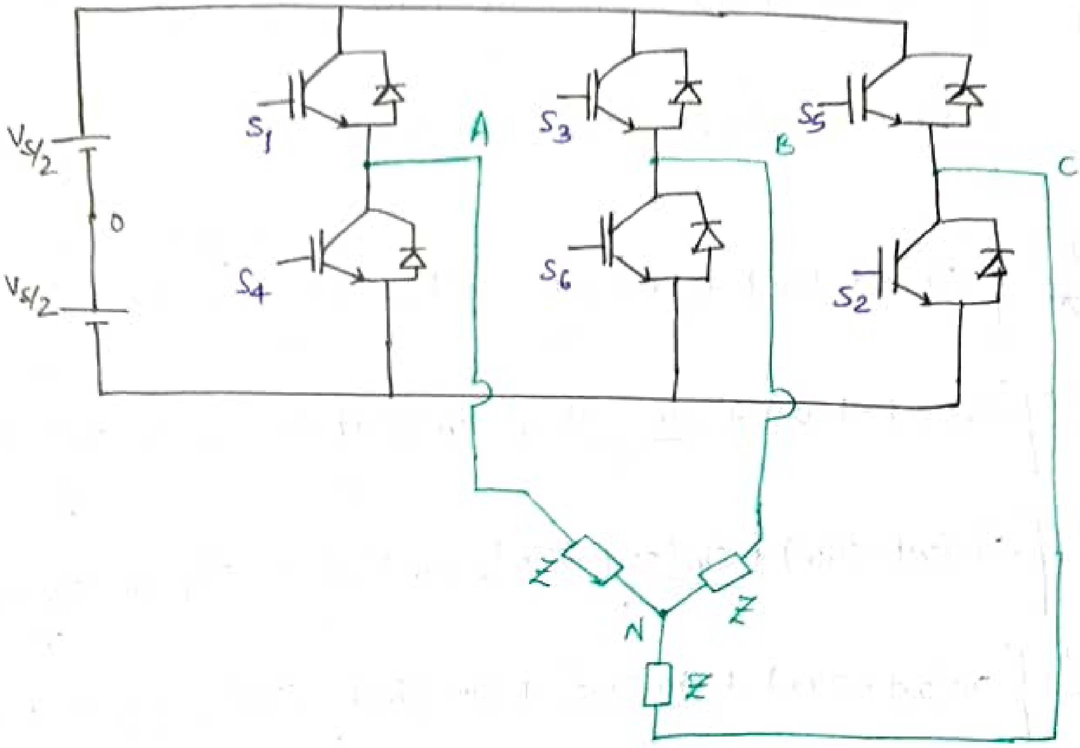
$V_{AN} = V_{AO} - V_{NO}$
$V_{BN} = V_{BO} - V_{NO}$
$V_{CN} = V_{CO} - V_{NO}$

$V_{AN} + V_{BN} + V_{CN} =$
$V_{AO} + V_{BO} + V_{CO} - 3V_{NO}$

$\Rightarrow \boxed{V_{NO} = \frac{V_{AO} + V_{BO} + V_{CO}}{3}}$

07-10-2024

Three Phase Voltage Source Inverters



Pole voltages: V_{AO}, V_{BO}, V_{CO}

Line voltages: V_{AB}, V_{BC}, V_{CA}

Phase voltages: V_{AN}, B_{BN}, V_{CN}

$$V_{AN} = V_{AO} - V_{NO}$$
$$V_{BN} = V_{BO} - V_{NO}$$
$$V_{CN} = V_{CO} - V_{NO}$$

Common mode voltage, $V_{NO} = \dfrac{V_{AO} + V_{BO} + V_{CO}}{3}$ → No phase shift in c.m.v.

⇓

It cannot circulate current

[Will circulate if N is connected to 0]

⇓ huge current

[Shall not be connected (Useless current; only adds to loss)]

[Fundamental component (3 sine waves, phase shifted by 120°) won't flow through NO]

In 3-phase circuit, 3rd harmonic won't be present.

$$V_{AO} = \frac{4V_s/2}{\pi}\left[\sin\omega t + \frac{\sin 3\omega t}{3} + \frac{\sin 5\omega t}{5} + \frac{\sin 7\omega t}{7} + \dots\right]$$

$$V_{BO} = \frac{4V_s/2}{\pi}\left[\sin(\omega t - 120^\circ) + \frac{\sin 3(\omega t - 120^\circ)}{3} + \frac{\sin 5(\omega t - 120^\circ)}{5} + \dots\right]$$

$$V_{CO} = \frac{4V_o/2}{\pi}\left[\sin(\omega t - 240^\circ) + \frac{\sin 3(\omega t - 240^\circ)}{3} + \frac{\sin 5(\omega t - 240^\circ)}{5} + \dots\right]$$

$$\Rightarrow V_{BO} = \frac{4V_s/2}{\pi}\left[\sin(\omega t - 120^\circ) + \frac{\sin(3\omega t - 360^\circ)}{3} + \frac{\sin(5\omega t - \overset{(360^\circ + 240^\circ)}{600^\circ})}{5} + \frac{\sin(7\omega t - \overset{(2\times 360^\circ + 120^\circ)}{840^\circ})}{7} + \dots\right]$$

$$= \frac{4V_s/2}{\pi}\left[\sin(\omega t - 120^\circ) + \frac{\sin 3\omega t}{3} + \frac{\sin(5\omega t - 240^\circ)}{5} + \frac{\sin(7\omega t - 120^\circ)}{7} \dots\right]$$

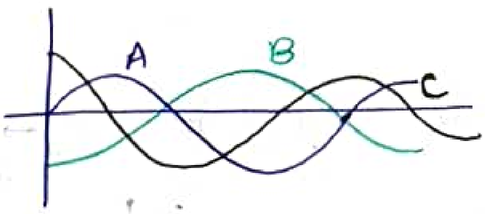
$$V_{CO} = \frac{4V_s/2}{\pi}\left[\sin(\omega t - 240^\circ) + \frac{\sin(3\omega t - 720^\circ)}{3} + \frac{\sin(5\omega t - 1200^\circ)}{5} + \frac{\sin(7\omega t - 1680^\circ)}{7} + \dots\right]$$

$$= \frac{4V_s/2}{\pi}\left[\sin(\omega t - 240^\circ) + \frac{\sin 3\omega t}{3} + \frac{\sin(5\omega t - 120^\circ)}{5} + \frac{\sin(7\omega t - 240^\circ)}{7} + \dots\right]$$

08-10-2024

Line voltage, $V_{AB} = V_{AO} - V_{BO}$ ⇝ no 3rd or any odd harmonics

Phase voltage, $V_{AN} = V_{AO} - \underbrace{V_{NO}}_{\text{3rd harmonic}}$



Possible phase sequences:

A B C

A C B

Fundamental phase sequence : ABC → $\left\{\begin{array}{l}\sin\omega t \\ \sin(\omega t - 120^\circ) \\ \sin(\omega t - 240^\circ)\end{array}\right\}$ +ve phase sequence

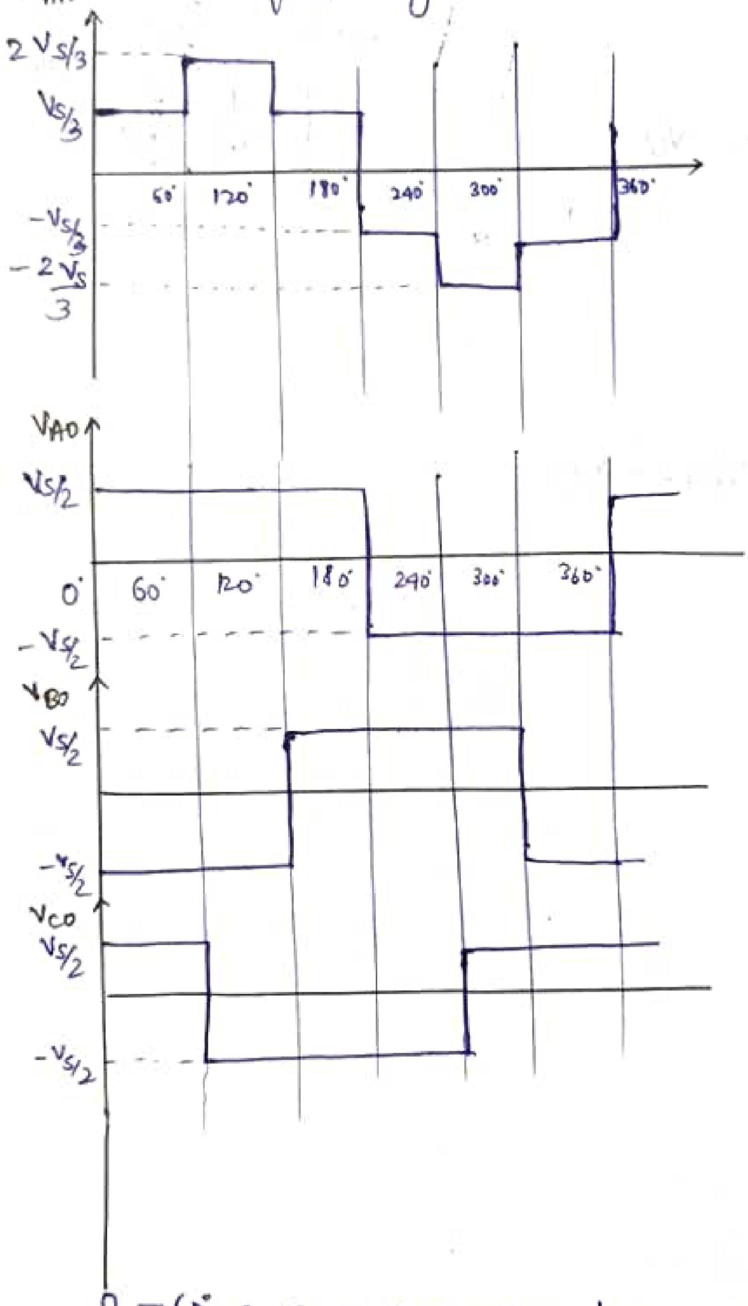
5th harmonic phase sequence : ACB → $\left\{\begin{array}{l}\sin 5\omega t \\ \sin(5\omega t - 240^\circ) \\ \sin(5\omega t - 120^\circ)\end{array}\right\}$ −ve (phase) sequence

7th harmonic → $\left\{\begin{array}{l}\sin 7\omega t \\ \sin(7\omega t - 120^\circ) \\ \sin(7\omega t - 240^\circ)\end{array}\right\}$ +ve sequence

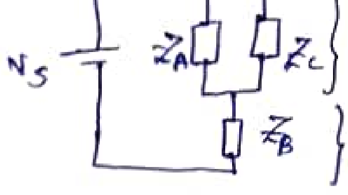
Harmonics: $6n+1 \rightarrow +ve$ sequence $[n = 1, 2, \ldots]$
$6n-1 \rightarrow -ve$ sequence.

Feeding this voltage to a motor, fundamental component rotates it in one dirn, 5th harmonic rotates it in opposite direction $\therefore$ Torque pulsation.

Effective frequency in ACB : 6ω.



$\underline{0 - 60^\circ}$: $S_1 \rightarrow ON$, $S_4 \rightarrow OFF$ | $S_3 \rightarrow OFF$, $S_6 \rightarrow ON$ | $S_5 \rightarrow ON$, $S_2 \rightarrow OFF$.

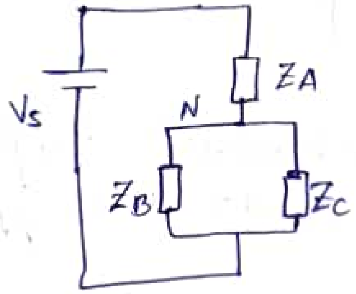


$(Z_A = Z_B = Z_C)$

$V_s/2 = V_{ON}$

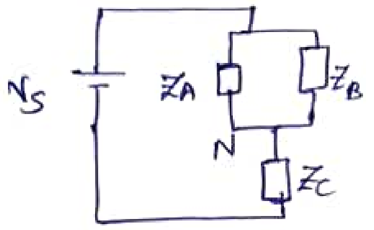
$V_{ON} = -2V_s/3$.

$60^\circ - 120^\circ$



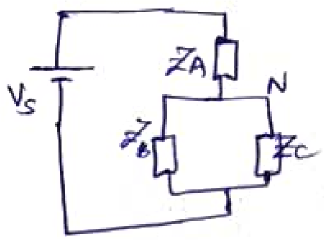
$V_{AN} = 2V_s/3$

$120^\circ - 180^\circ$



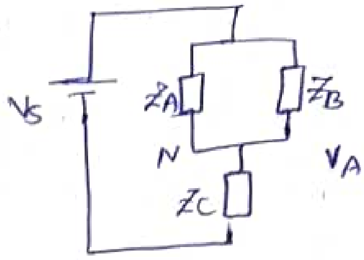
$V_{AN} = V_s/3$

$180^\circ - 240^\circ$



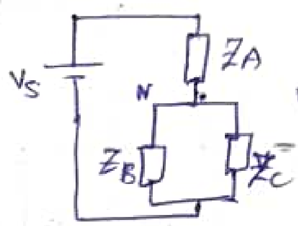
$V_{AN} = -V_s/3$

$240^\circ - 300^\circ$



$V_{AN} = -2V_s/3$

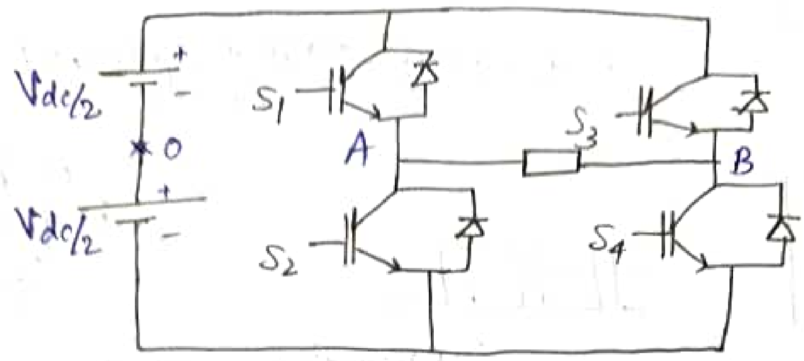
$300^\circ - 360^\circ$



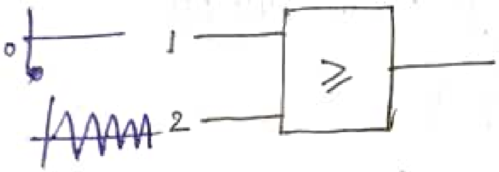
$V_{AN} = -V_s/3$

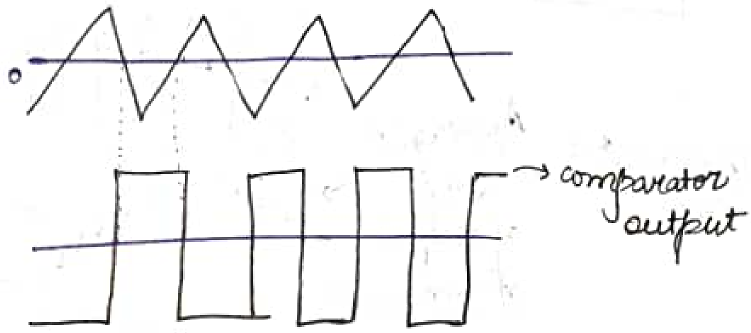
14-10-2024

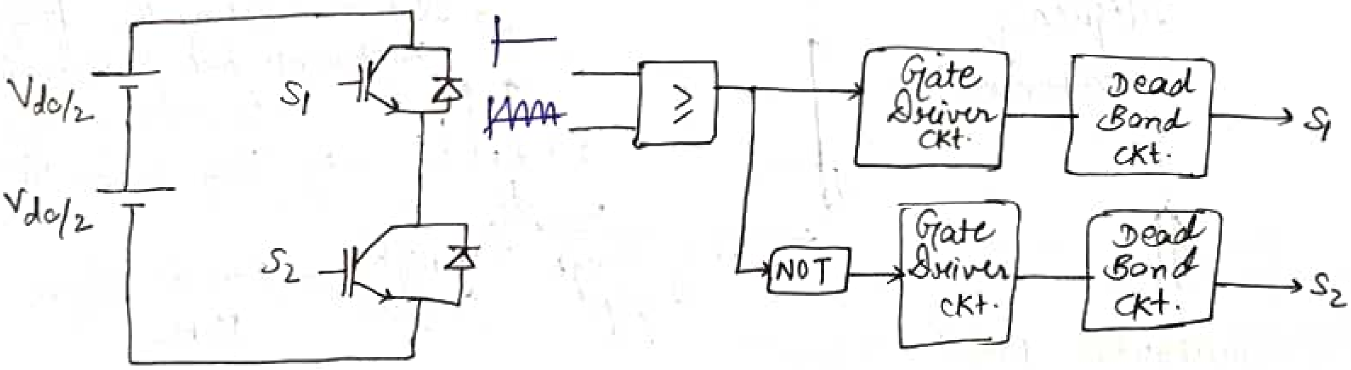
PWM Techniques for Voltage Source Inverter

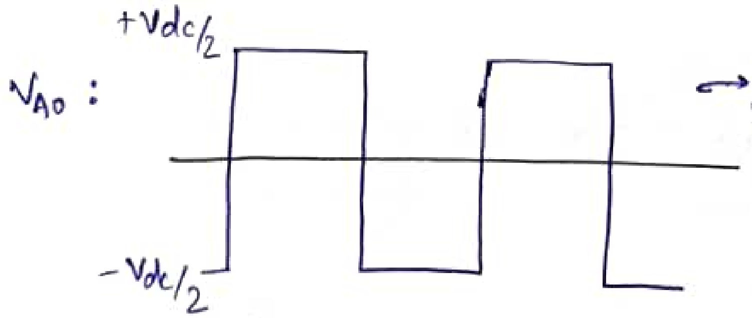


Comparator :
↳ Analog comparator : an opamp





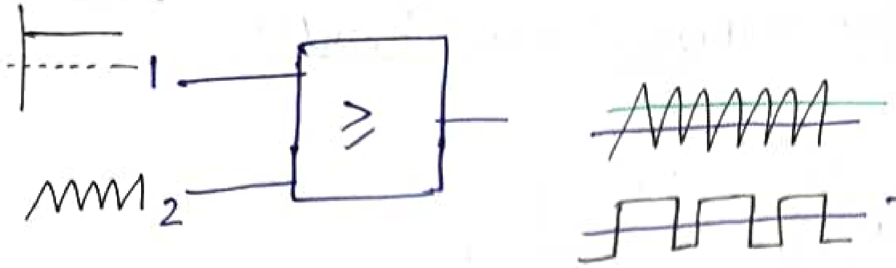




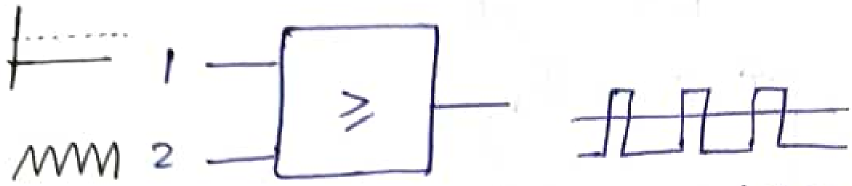
→ frequency same as freq. of triangular wave = fundamental frequency of sinusoids.

↳ Average value = 0.

↳ odd harmonics



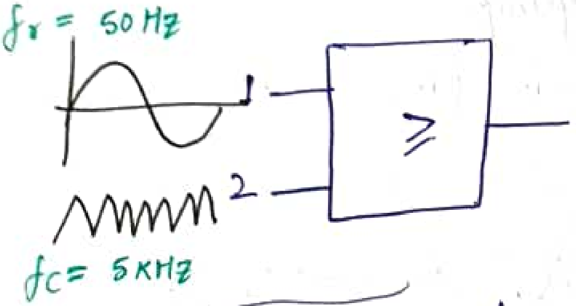
→ Rectangular waveform ⇒ positive average value
⇓
No change in frequency component

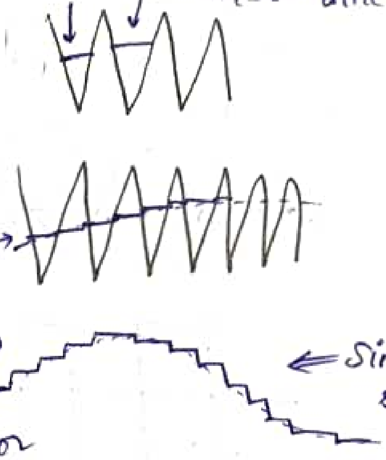


→ negative average value ⇒ No change in frequency component

almost constant

increased little bit



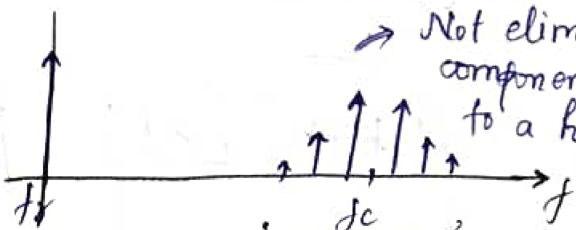


can be implemented in software

Average value of output of comparator

← Sinusoid steps

Frequency components:



→ Not eliminating the frequency components but pushing them to a high value so that they can be eliminated

very large gap

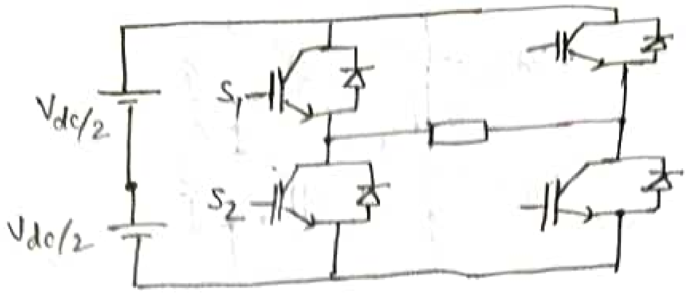
very high frequencies ⇒ Easy to design filter

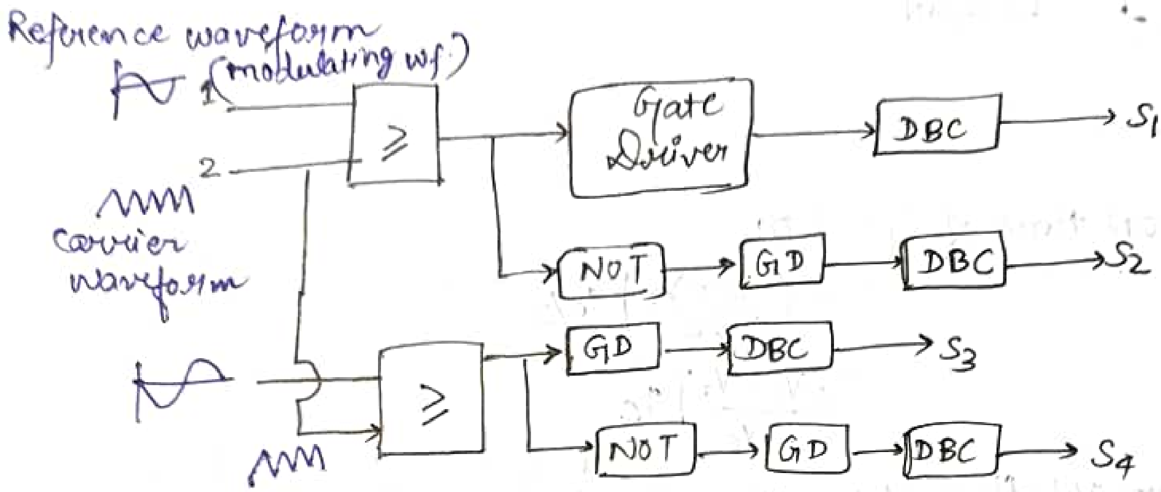
⇑

Sinusoidal PWM (SPWM)

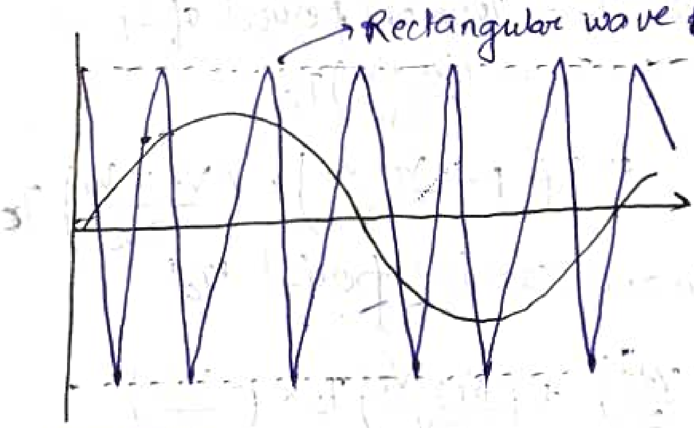
15-10-2024

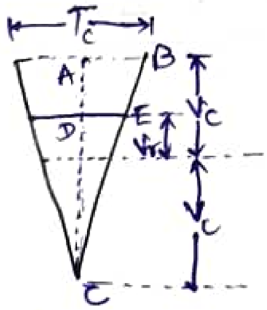
Sinusoidal PWM





Rectangular wave but changing sinusoidally





f_c: frequency of triangular carrier waveform

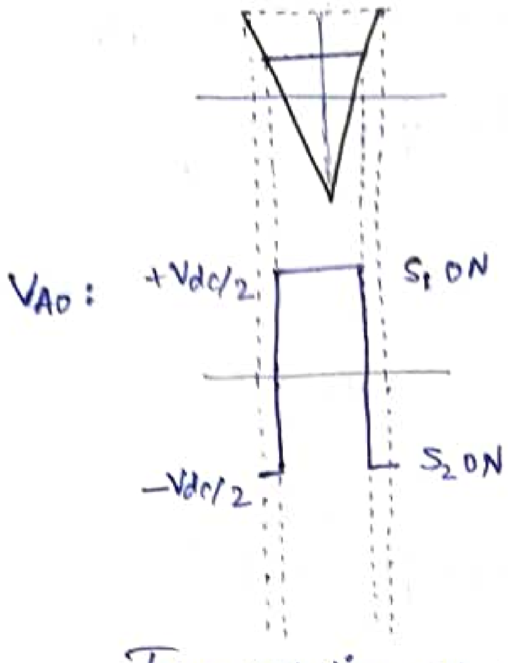
$T_0 = \frac{1}{f_c}$: Period of triangular waveform

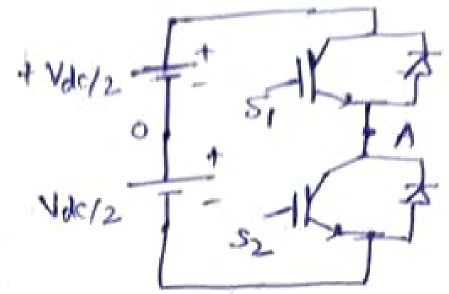
Consider similar Δs ABC & DEC

$$\frac{DE}{AB} = \frac{DC}{AC}$$

$$\Rightarrow \frac{DE}{AB} = \frac{V_c + V_r}{2V_c}$$

$$\Rightarrow DE = \left(\frac{V_c + V_r}{2V_c}\right) AB = \left(\frac{V_c + V_r}{2V_c}\right) T_c/2$$





Turn ON time of $S_1 = 2DE$

$$= 2\left(\frac{V_c+V_r}{2V_c}\right) T_c/2$$

$$= \left(\frac{V_c+V_r}{2V_c}\right) T_c$$

Turn ON time of $S_2 = T_c$ − Turn ON period of S_1

$$= T_c - \left(\frac{V_c+V_r}{2V_c}\right) T_c$$

$$= T_c\left(1 - \frac{V_c+V_r}{2V_c}\right) = \left(\frac{V_c-V_r}{2V_c}\right) T_c$$

Average pole voltage in one carrier period 'T_c'

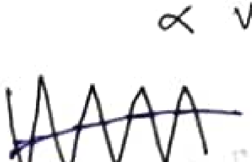
$$= \frac{\left(\frac{V_c+V_r}{2V_c}\right) T_c \times \left(\frac{V_{dc}}{2}\right)' + \left(\frac{V_c-V_r}{2V_c}\right) T_c \times \left(-\frac{V_{dc}}{2}\right)'}{T_c}$$

$$= \frac{V_{dc}}{2}\left[\left(\frac{V_c+V_r}{2V_c}\right) - \left(\frac{V_c-V_r}{2V_c}\right)\right]$$

$$V_{AO}\,(av.) = \left(\frac{2V_r}{2V_c}\right)\frac{V_{dc}}{2} = \left(\frac{V_r}{V_c}\right)\frac{V_{dc}}{2}$$

$$V_{AO}\,(av.) \propto V_r$$

$$\propto V_m \sin\omega t$$



Carrier frequency ↑↑

⇒ Output : more sinusoidal

gap ↑↑

→ very high reactance

→ no impact

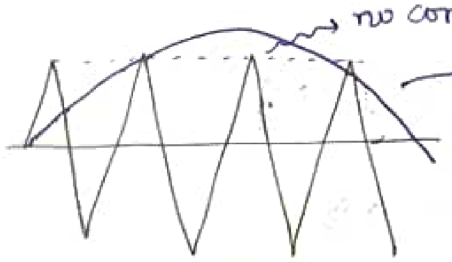
Amplitude Modulation Ratio (Index) [M] $= \dfrac{\text{Peak value of reference sine waveform}}{\text{Peak value of triangular carrier waveform}}$

when sine wave touched the peak $\Rightarrow$ Modulation index $= 1$.

Frequency Modulation Ratio (Index) $= \dfrac{\text{Frequency of carrier wave}}{\text{Frequency of reference sine wave}}$

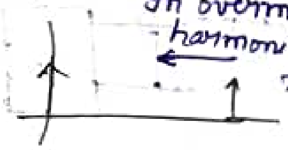
Av. value of o/p voltage $\propto$ Modulation index.

no comparison happens here

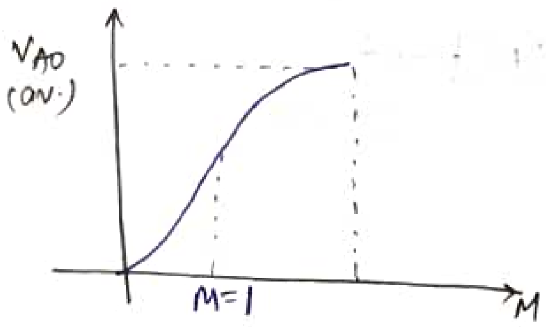


$\boxed{M > 1}$

: Overmodulation Region



In overmod. region harmonics coming towards fund. voltage



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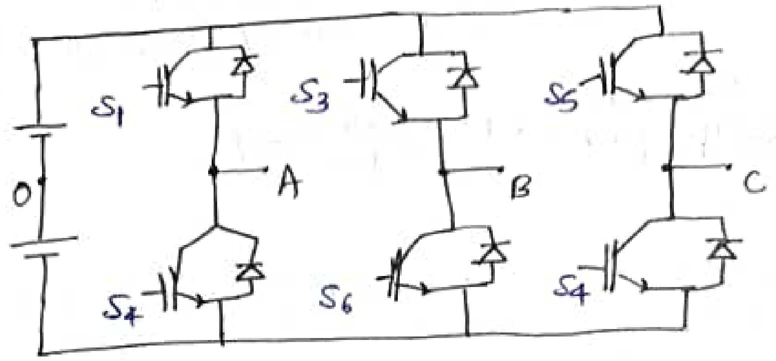
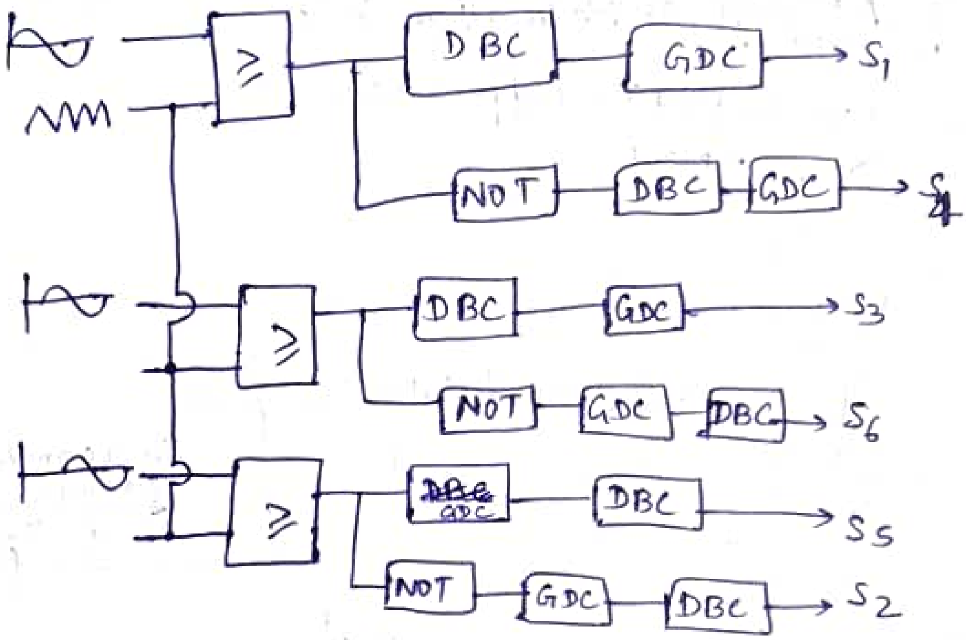
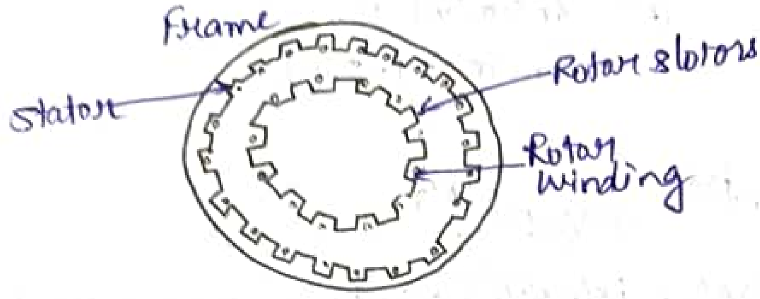
Sinusoidal PWM :





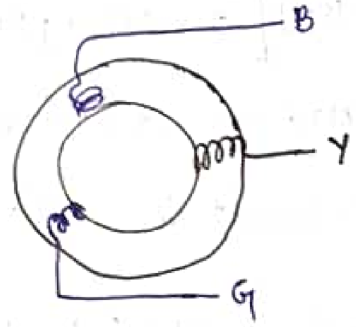
Constructional Features of 3-phase Induction Motor (IM)



Stationary part : stator
Moving part : Rotor

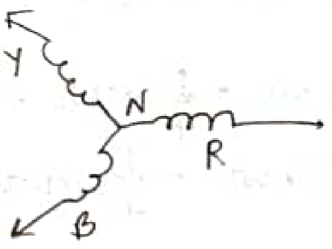
→ Produce 2 magnetic fields ⇓ Cause rotation

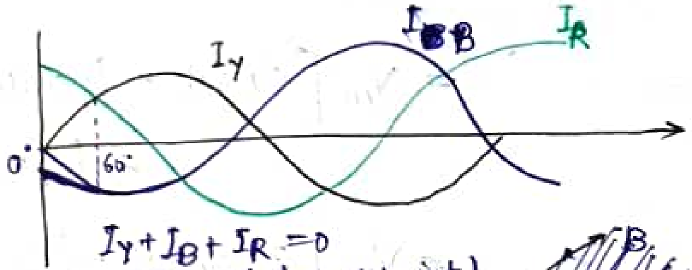
3-phase IM : Orientation of windings :



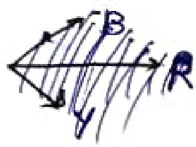
⇒ Spatial rotation of 120°

Generation of Rotating Magnetic Field :





$I_Y + I_B + I_R = 0$
(at any point)



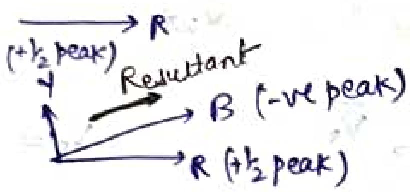
$$\text{Flux} = \frac{\text{Magneto Motive Force}}{\text{Reluctance}} = \frac{MMF}{S} = \frac{NI}{S}$$

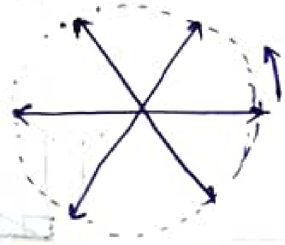
Reluctance ⇝ opposition to flux

flux $\propto I$

0° :

60° :

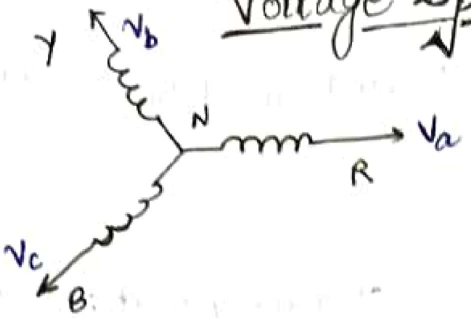




⇒ Rotating magnetic field/flux vector

[Due to voltage vector rotating] ⇒ [due to current space vector rotating in space]

Voltage Space Vector



$$V_a = V_m \sin\omega t$$
$$V_b = V_m \sin(\omega t - 120^\circ)$$
$$V_c = V_m \sin(\omega t - 240^\circ)$$

$$\bar{V}_s = V_a e^{j0} + V_b e^{j2\pi/3} + V_c e^{j4\pi/3}$$
$$= V_a + V_b\left[\cos 2\pi/3 + j\sin 2\pi/3\right] + V_c\left[\cos 4\pi/3 + j\sin 4\pi/3\right]$$
$$= V_m \sin\omega t + V_m \sin(\omega t - 120^\circ)\left[\cos 2\pi/3 + j\sin 2\pi/3\right]$$
$$+ V_m \sin(\omega t - 120^\circ)\left[\cos 4\pi/3 + j\sin 4\pi/3\right]$$
$$= V_m \cdot \Big[\sin\omega t + (\sin\omega t \cos 120^\circ - \cos\omega t \sin 120^\circ)(-0.5 + j\sqrt{3}/2)$$
$$+ (\sin\omega t \cos 240^\circ - \cos\omega t \sin 240^\circ)(-0.5 - j\sqrt{3}/2)\Big]$$

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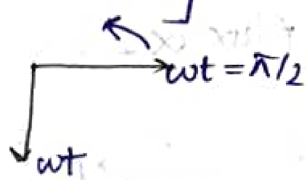
$$= V_m\Big[\sin\omega t + \left(-\tfrac{1}{2}\sin\omega t - \tfrac{\sqrt{3}}{2}\cos\omega t\right)\left(-\tfrac{1}{2} + j\tfrac{\sqrt{3}}{2}\right)$$
$$+ \left(-\tfrac{1}{2}\sin\omega t + \tfrac{\sqrt{3}}{2}\cos\omega t\right)\left(-\tfrac{1}{2} - j\tfrac{\sqrt{3}}{2}\right)\Big]$$

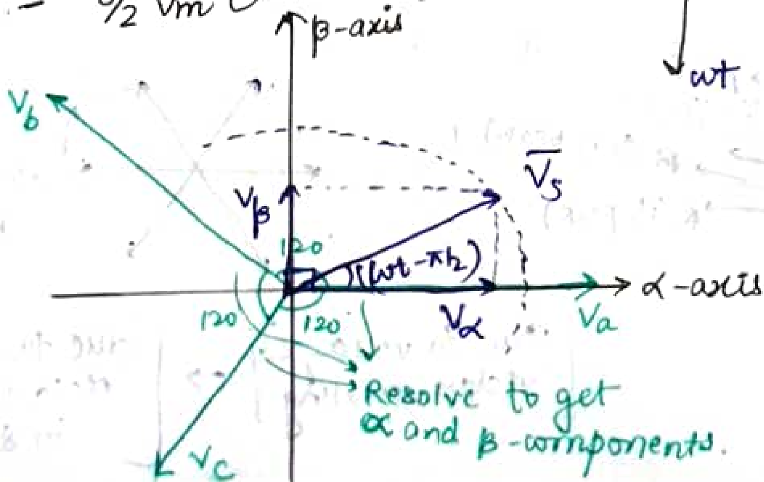
$$= V_m\Big[\sin\omega t + \tfrac{1}{4}\sin\omega t - \cancel{j\tfrac{\sqrt{3}}{4}\sin\omega t} + \cancel{\tfrac{\sqrt{3}}{4}\cos\omega t} - j\tfrac{3}{4}\cos\omega t$$
$$+ \tfrac{1}{4}\sin\omega t + \cancel{j\tfrac{\sqrt{3}}{4}\sin\omega t} - \cancel{\tfrac{\sqrt{3}}{4}\cos\omega t} - j\tfrac{3}{4}\cos\omega t\Big]$$

$$= V_m\left[\tfrac{3}{2}\sin\omega t - j\tfrac{3}{2}\cos\omega t\right]$$
$$= \tfrac{3}{2} V_m\left[\sin\omega t - j\cos\omega t\right]$$
$$= \tfrac{3}{2} V_m\left[\cos(\omega t - \pi/2) + j\sin(\omega t - \pi/2)\right]$$

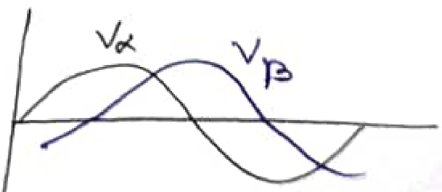


$$\therefore \bar{V} = \tfrac{3}{2} V_m e^{j(\omega t - \pi/2)}$$

$a + jb$



$$V_s = V_\alpha + jV_\beta$$



Two ~~voltages~~ windings of spatial difference of 90° and phase difference of 90° would create a rotating voltage vector, or vice-versa.

$$V_\alpha = V_a - V_b \cos 60° - V_c \cos 60° = V_a - \tfrac{1}{2} V_b - \tfrac{1}{2} V_c$$

$$V_\beta = 0\, V_a + V_b \cos 30° - V_c \cos 30° = 0 + \tfrac{\sqrt{3}}{2} V_b - \tfrac{\sqrt{3}}{2} V_c$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

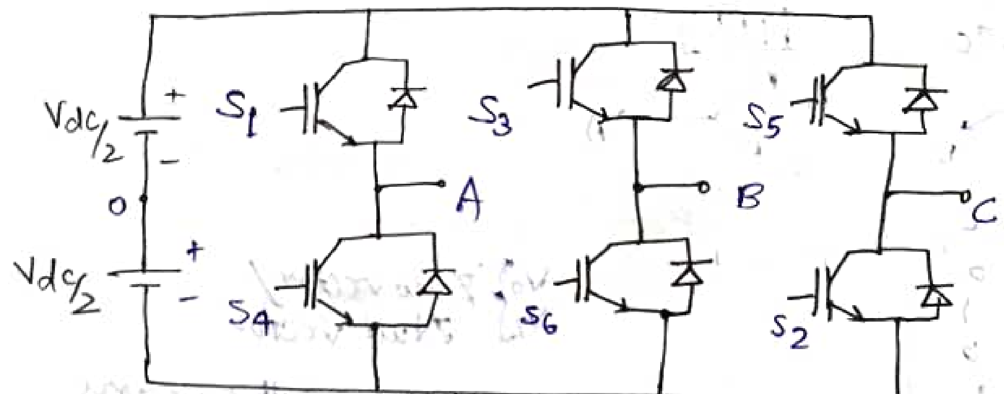
$\rightsquigarrow$ Clarke's Transformation

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

3 phase to 2-phase transformation

→ Three windings of spatial difference of 120° and phase difference of 120° would create a rotating voltage vector, or if we create a rotating voltage vector, we would get 3 sine waves of 120° of phase difference.

Space Vector PWM



S_1 ON → $V_{AO} = +V_{dc}/2$

S_1 OFF → $V_{AO} = -V_{dc}/2$

S_3 ON → $V_{BO} = +V_{dc}/2$

S_3 OFF → $V_{BO} = -V_{dc}/2$

S_5 ON → $V_{CO} = +V_{dc}/2$

S_5 OFF → $V_{CO} = -V_{dc}/2$

3 legs of 2 states possible

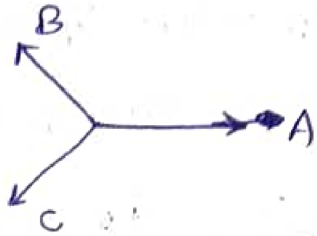
⇓

Total 2^3 states $= 8$.

1 : ON-state of top switch ~~of~~ in a leg of the inverter.
0 : OFF-state " " "

A	B	C
0	0	0
0	0	1
0	1	0
0	1	1
1	0	0
1	0	1
1	1	0
1	1	1

[8 switching states]



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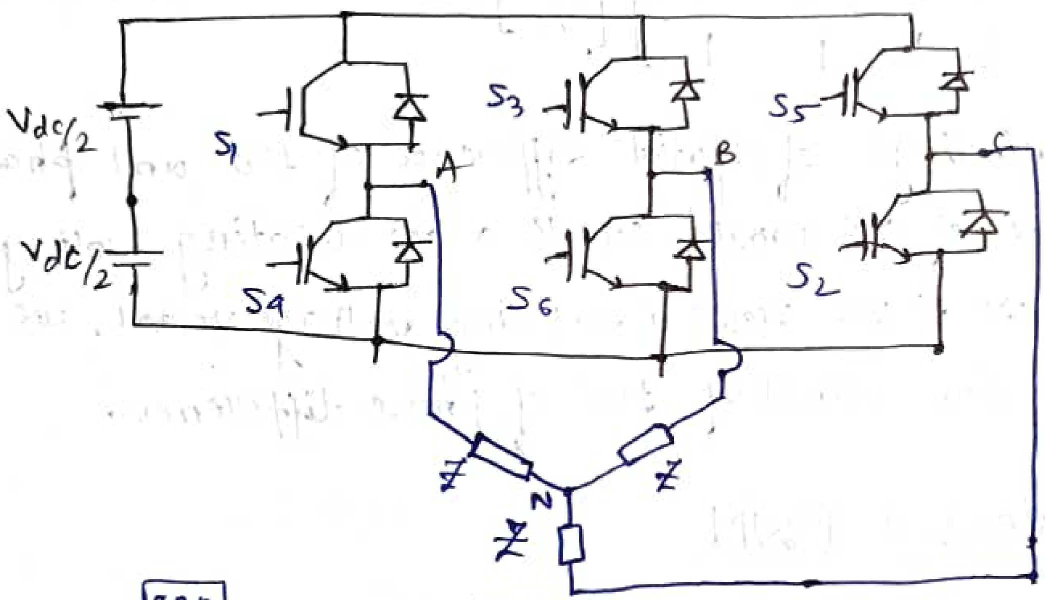
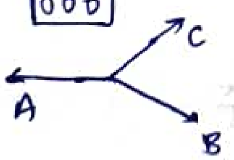
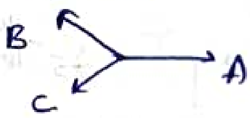


$\boxed{000}$



$\boxed{111}$

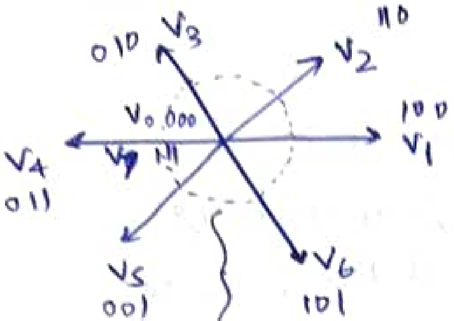


A	B	C
0	0	0
0	0	1
0	1	0
0	1	1
1	0	0
1	0	1
1	1	0
1	1	1

Active vector

$\left.\begin{matrix} V_0 \\ V_7 \end{matrix}\right\}$ Zero vector/ Null vector

V_1 to V_5 → Active vectors

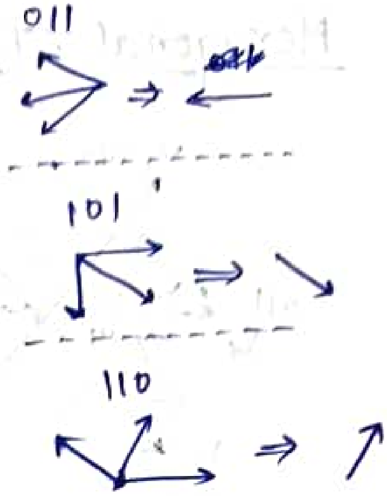


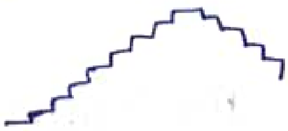
↑ discrete jump

Create a vector and rotate

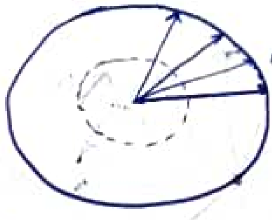
⇓

Use sine PWM

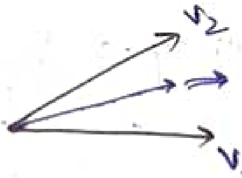




Sample the sine wave



↑ rotating



↑ ⟶ rotate by ↑ time for V_1,

↓ time for V_2

Resultant (in the middle)

$V_1 \xrightarrow{\text{for}} T_s/2$ ↑

$V_2 \xrightarrow{\text{for}} T_s/2$ ↓

$V_1 \longrightarrow T_1'$

$V_2 \longrightarrow T_2'$

$T_1' + T_2' = T_s$

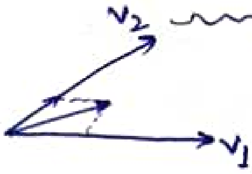
⇓

Also change the magnitude

⇓

Use zero vector

⇒



V_2 ⟶ for some time $\rightarrow V_1$

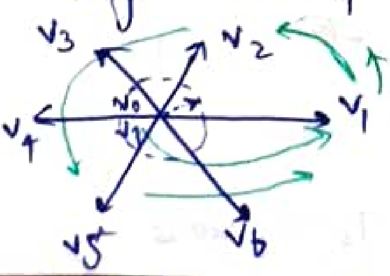
.... time $\rightarrow 0$

Volt-sec. Balance

$$V_S T_S = V_1 T_1 + V_2 T_2 + V_0 T_0$$

$$\boxed{T_1 + T_2 + T_0 = T_S}$$

Infinite sampling frequency → Smooth rotation



$V_0 \rightarrow V_1 \rightarrow V_2 \rightarrow V_7$

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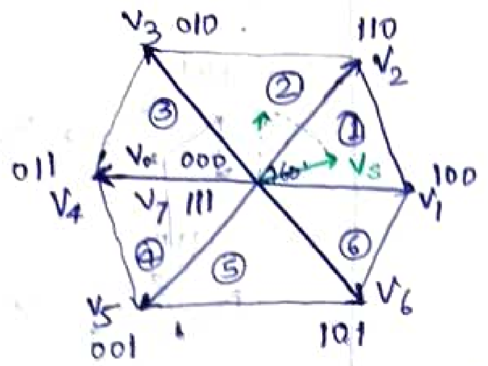
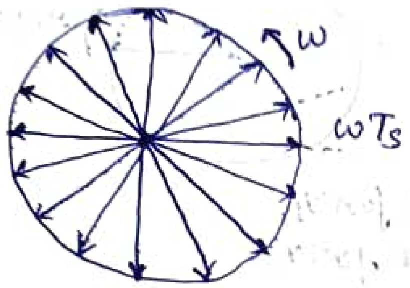
Hexagonal Space Vector Structure



6 sectors: ① to ⑥

V_0, V_7 : Zero vectors

V_1 to V_6 : Active vectors



Use 3 nearest vectors to construct the vector

⇓

Min^m harmonic destruction

Sampling frequency ⇒ Smooth rotation

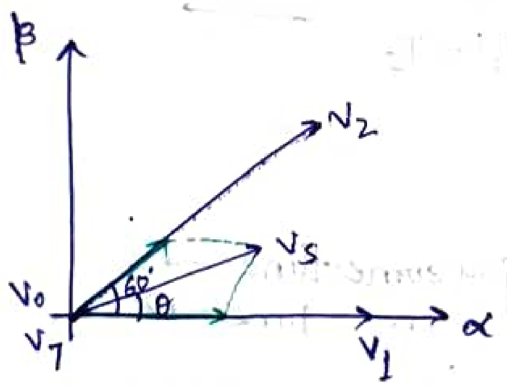
⇓

3 sine waves in 3 phases

Volt-sec Balance:

$$V_1 T_1 + V_2 T_2 + V_0 T_0 = V_s T_s$$

$$T_1 + T_2 + T_0 = T_s$$



[V_2 has to be applied for a longer time]

Apply volt-sec Balance along α-axis

$$V_1 T_1 + V_2 \cos 60° T_2 = V_s \cos\theta \, T_s \quad -①$$

Volt-sec balance along β-axis:

$$0 + V_2 \sin 60° \, T_2 = V_s \sin\theta \, T_s \quad -②$$

$$\Rightarrow T_2 = T_s \cdot \frac{V_s \sin\theta}{\sin 60°} \quad -③$$

③,① ⇒ $$V_1 T_1 + V_2 \cos 60° \cdot \frac{V_s \sin\theta}{\sin 60°} T_s = V_s \cos\theta \, T_s$$

$$\Rightarrow V_1T_1 = T_sV_s\cos\theta - \frac{V_s\cos 60^\circ \sin\theta\, T_s}{\sin 60^\circ}$$

$$= T_sV_s\left[\frac{\sin 60^\circ \cos\theta - \cos 60^\circ \sin\theta}{\sin 60^\circ}\right]$$

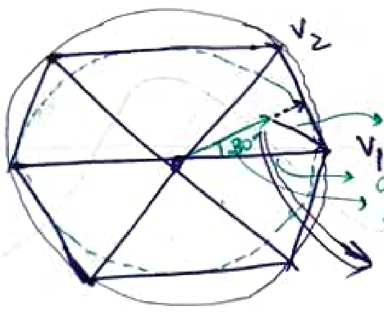
$$\Rightarrow T_1 = \frac{T_sV_s\sin(60^\circ-\theta)}{V_1\sin 60^\circ}$$

$$T_1 = T_s \cdot \frac{V_s}{V_{dc}} \frac{\sin(60^\circ-\theta)}{\sin 60^\circ}$$

$$T_2 = T_s \cdot \frac{V_s}{V_{dc}} \frac{\sin\theta}{\sin 60^\circ}$$

$$T_0 = T_s - (T_1 + T_2)$$

$$\underbrace{000 \xrightarrow{T_0/2} 100 \xrightarrow{T_1} 110 \xrightarrow{T_2} 111}_{T_s} \xrightarrow{T_0/2} \underbrace{111 \xrightarrow{T_0/2} 110 \xrightarrow{T_2} 100 \xrightarrow{T_1} 000}_{T_s}$$



Maximum magnitude realizable is given by the radius of the circle inscribed inside the hexagon.

$$\text{Max}^m\ V_s = V_{dc}\cdot\cos 30^\circ$$
$$= V_{dc}\cdot\frac{\sqrt{3}}{2}$$

$$\text{Max}^m\ V_\alpha\ [V_s \text{ along } V_1] = V_{dc}\cdot\frac{\sqrt{3}}{2}$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

$V_{an} + V_{bn} + V_{cn} = 0$
$(V_{bn} + V_{cn}) = -V_{an}$

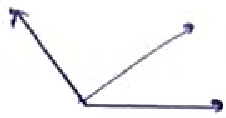
$$V_\alpha = V_{an} - \tfrac{1}{2}V_{bn} - \tfrac{1}{2}V_{cn}$$
$$= V_{an} - \tfrac{1}{2}(V_{bn} + V_{cn}) = V_{an} - \tfrac{1}{2}(-V_{an}) = \tfrac{3}{2}V_{an}$$

$V_\alpha = \frac{3}{2} V_{an}$

$\Rightarrow V_{an} = \frac{2}{3} V_\alpha$

~~Max. m.~~

$$V_{AO(max)} = \underline{\text{Max. mag.}} \; V_{d}/2$$



$$V_{AB} = V_{AO} - V_{BO} = \sqrt{3}\, V_{dc}/2$$

$$V_{AO} = \frac{V_{AB}}{\sqrt{3}}$$

$$V_{an(max.)} = \frac{\sqrt{3}\, V_{dc}/2}{\sqrt{3}} = V_{dc}/2$$

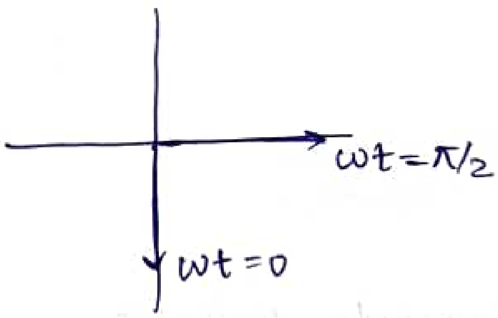
$$= 0.5\, V_{dc}$$

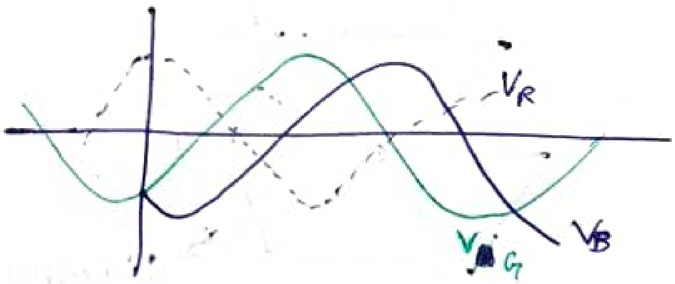
$$\text{Max. mag. of } V_{an} = \frac{2}{3} \cdot V_{dc} \cdot \sqrt{3}/2 = \frac{V_{dc}}{\sqrt{3}}$$

$$= 0.577\, V_{dc}$$

$$\text{\% deviation} = \frac{(0.577 - 0.5)}{0.5} = 15.4\%$$

$$V_0 = \frac{3}{2} V_{an}\, e^{(\omega t - \pi/2)}$$



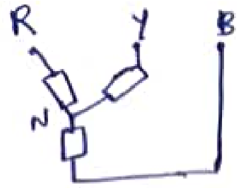


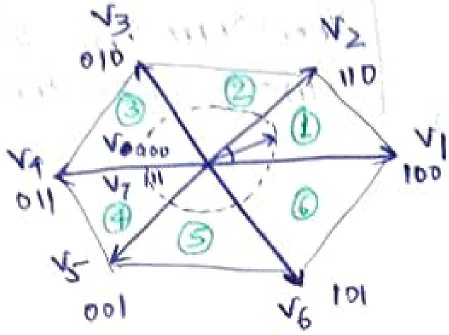
$V_R > V_Y > V_B$: sector-1

$V_Y > V_R > V_B$: sector-2

28-10-2024

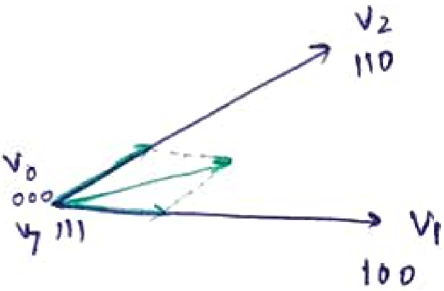
← Conventional SVPWM





Dwell time : T_1, T_2, T_0 ; $T_s = T_0 + T_1 + T_2$

$T_0 = T_s - (T_1 + T_2)$



V_0	V_1	V_2	V_7	V_7	V_2	V_1	V_0
$T_0/2$	T_1	T_2	$T_0/2$	$T_0/2$	T_2	T_1	$T_0/2$
000 →	100 →	110 →	111 →	111 →	110 –	100 –	000

← T_s →

Sector ① : $V_R > V_Y > V_B$

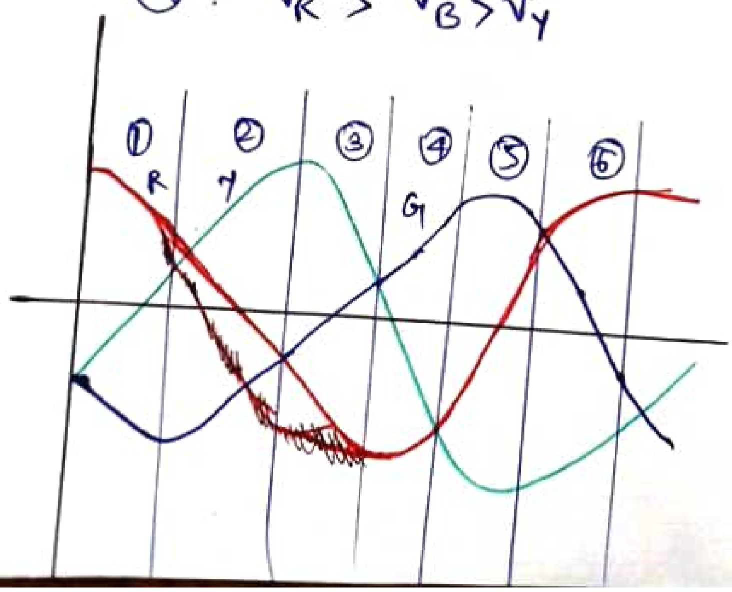
② : $V_Y > V_R > V_B$

③ : $V_Y > V_B > V_R$

④ : $V_B > V_Y > V_R$

⑤ : $V_B > V_R > V_Y$

⑥ : $V_R > V_B > V_Y$



Phase voltages: V_{RN}, V_{YN}, V_{BN}

$$V_{RY} = V_{RN} + V_{NY} = V_{RN} - V_{YN}$$
$$V_{YB} = V_{YN} - V_{BN}$$
$$V_{BR} = V_{BN} - V_{RN}$$

$$\begin{bmatrix} V_{RN} + V_{YN} + V_{BN} = 0 \\ V_{YN} + V_{BN} = -V_{RN} \end{bmatrix}$$

$$V_{RY} - V_{BR} = V_{RN} - V_{YN} - (V_{BN} - V_{RN})$$
$$= 2V_{RN} - (V_{YN} + V_{BN})$$
$$= 2V_{RN} - (-V_{RN}) = 3V_{RN}$$

$$V_{RN} = \frac{V_{RY} - V_{BR}}{3}$$

$$V_{YN} = \frac{V_{YB} - V_{RY}}{3}$$

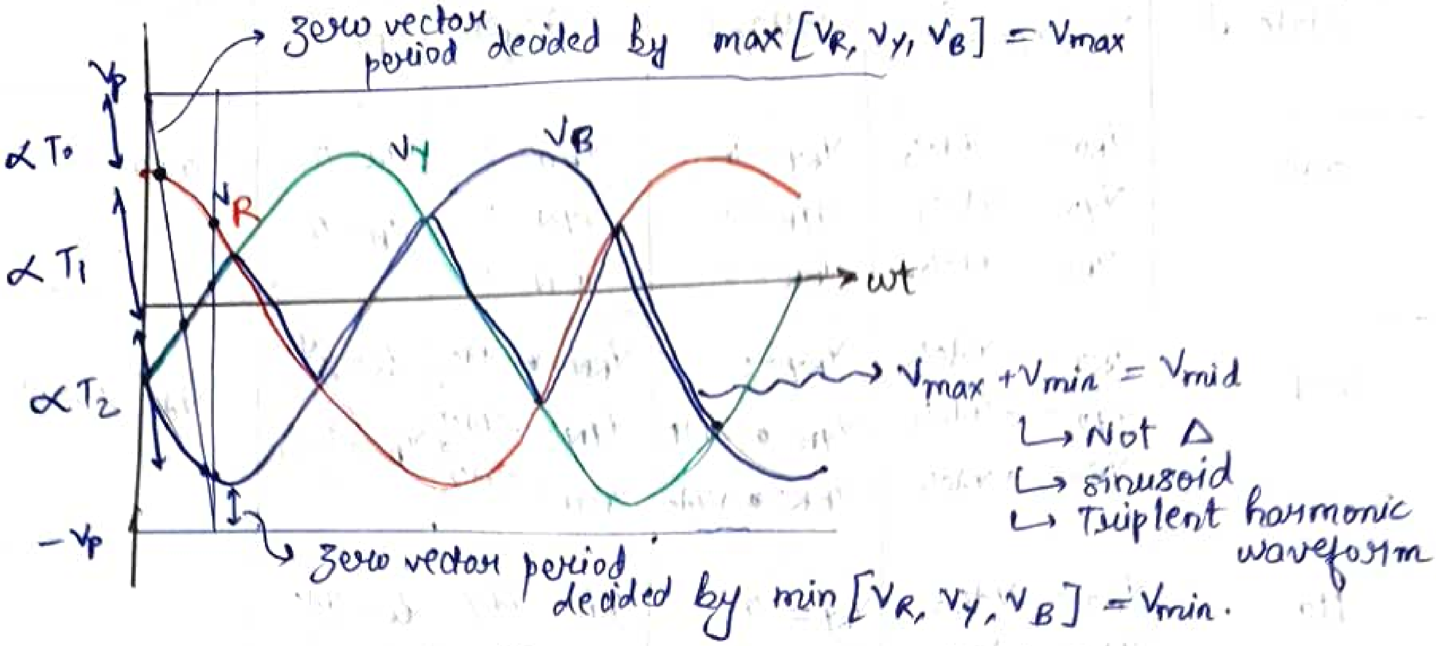
$$V_{BN} = \frac{V_{BR} - V_{YB}}{3}$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_{RN} \\ V_{YN} \\ V_{BN} \end{bmatrix}$$

$$V_\alpha = V_{RN} - \frac{1}{2}(V_{YN} + V_{BN})$$
$$= 3/2\, V_{RN}$$
$$V_\beta = \sqrt{3}/2\,(V_{YN} - V_{BN})$$

$$\therefore \bar{V_s} = V_\alpha + jV_\beta$$

Switching state	Pole voltages, V_{RO}, V_{YO}, V_{BO}	Line voltages	Phase voltages	V_α, V_β	$\bar{V_s}$
000	$V_{RO} = -V_{dc}/2$ $V_{YO} = -V_{dc}/2$ $V_{BO} = -V_{dc}/2$	$V_{RY} = 0$ $V_{YB} = 0$ $V_{BR} = 0$	$V_{RN} = 0$ $V_{YN} = 0$ $V_{BN} = 0$	$V_\alpha = 0$ $V_\beta = 0$	$0\angle 0$
001	$V_{RO} = -V_{dc}/2$ $V_{YO} = -V_{dc}/2$ $V_{BO} = +V_{dc}/2$	$V_{RY} = 0$ $V_{YB} = \cancel{0} -V_{dc}$ $V_{BR} = \cancel{0} +V_{dc}$	$V_{RN} = \cancel{0} -V_{dc}/3$ $V_{YN} = -V_{dc}/3$ $V_{BN} = 2V_{dc}/3$	$V_\alpha = -\frac{V_{dc}}{2}$ $V_\beta = -\frac{\sqrt{3}}{2} V_{dc}$	$V_{dc} \angle 240°$
110	$V_{RO} = V_{dc}/2$ $V_{YO} = V_{dc}/2$ $V_{BO} = -V_{dc}/2$	$V_{RY} = 0$ $V_{YB} = V_{dc}$ $V_{BR} = -\cancel{0}\, V_{dc}$	$V_{RN} = V_{dc}/3$ $V_{YN} = V_{dc}/3$ $V_{BN} = -\frac{2V_{dc}}{3}$	$V_\alpha = \frac{V_{dc}}{2}$ $V_\beta = \frac{\sqrt{3}}{2} V_{dc}$	



000 — 100 — 110 — 111

111 — 110 — 100 — 000

→ Zero vectors are not divided equally in sinusoid PWM.

Adding some common voltage (offset) to all the waveforms

↳ Modified reference waveforms:

$V_R^* = V_R + V_{CM}$ → common mode voltage

$V_Y^* = V_Y + V_{CM}$

$V_B^* = V_B + V_{CM}$

$V_{max}^* = V_{max} + V_{CM}$

$V_{min}^* = V_{min} + V_{CM}$

↳ V_{RO}, V_{YO}, V_{BO} (pole voltages) → affected

Line voltages } No effect
Phase voltages }

↳ No effect on the performance.

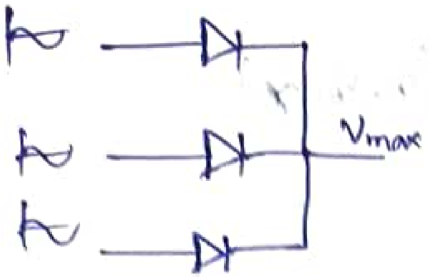
$$V_p - V_{max}^* = V_{min}^* - (-V_p)$$

$$\Rightarrow V_p - V_{max}^* = V_{min}^* + V_p$$

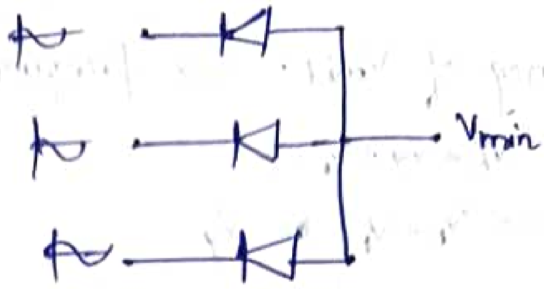
$$\Rightarrow V_{max}^* + V_{min}^* = 0$$

$$\Rightarrow V_{max} + V_{CM} + V_{min} + V_{CM} = 0$$

$$\Rightarrow V_{CM} = -\left(\frac{V_{max} + V_{min}}{2}\right)$$

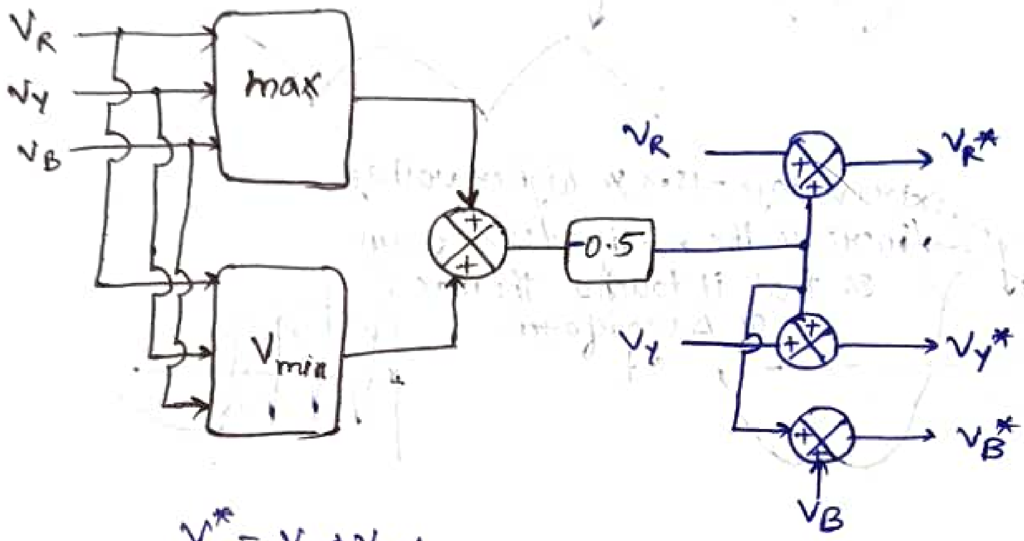


Common cathode



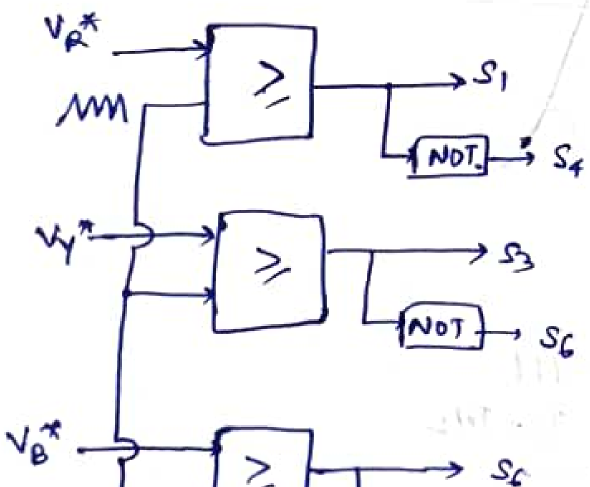
Common anode

$\boxed{01\text{-}11\text{-}2024}$



$$V_R^* = V_R + V_{CM}$$
$$V_Y^* = V_Y + V_{CM}$$
$$V_B^* = V_B + V_{CM}$$
$$V_{CM} = -\left(\frac{V_{max} + V_{min}}{2}\right)$$

$$V_R = V_m \sin \omega t$$
$$V_Y = V_m \sin(\omega t - 120^\circ)$$
$$V_B = V_m \sin(\omega t - 240^\circ)$$



Frequency of v_{mid} = 3 × frequency of (v_R, v_B, v_Y).

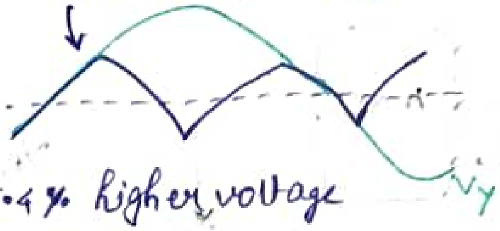
$$v_R + v_Y + v_B = 0$$

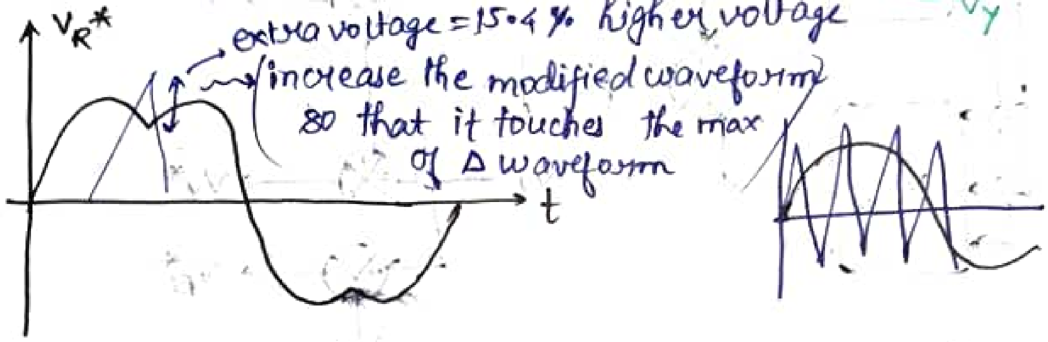
$$\Rightarrow v_R + v_B = 0 - v_Y$$

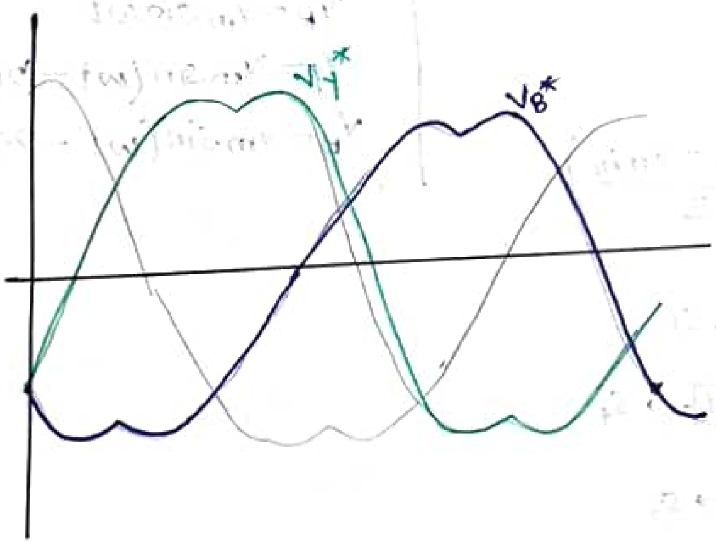
$$v_{CM} = -\left(\frac{v_{max} + v_{min}}{2}\right)$$

$$= -\left(\frac{v_{mid}}{2}\right)$$

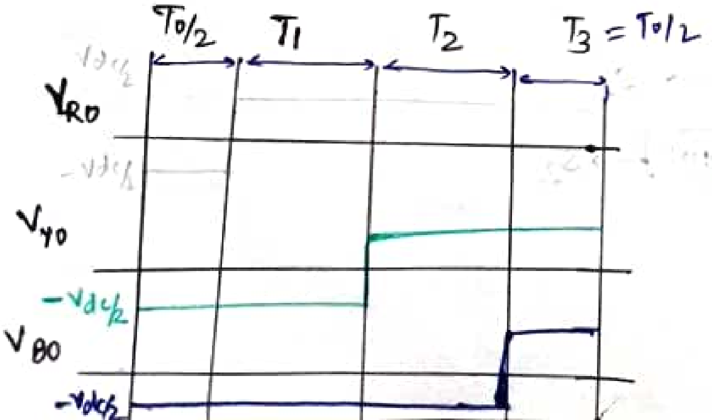
, $v_{mid} = v_{max} + v_{min}$







000 — 100 — 110 — 111



$$T_0/2 + T_1 + T_2 + T_0/2 = T_s$$

$$V_{RO\,(av.)} = \frac{V_{dc}/2}{T_s}\left[-T_0/2 + T_1 + T_2 + T_0/2\right]$$

$$= \frac{V_{dc}}{2}\,\frac{(T_1+T_2)}{T_s}$$

$$V_{YO\,(av.)} = \frac{V_{dc}/2}{T_s}\left[-T_0/2 - T_1 + T_2 + T_0/2\right]$$

$$= V_{dc}/2\,\frac{[-T_1+T_2]}{T_s}$$

$$V_{BO}\,(av.) = \frac{V_{dc}/2}{T_s}\left[-\frac{T_0}{2} - T_1 - T_2 + T_0/2\right]$$

$$= \frac{V_{dc}/2}{T_s}\left[-T_1 - T_2\right]$$

$$= -V_{dc}/2\,\frac{[T_1+T_2]}{T_s}$$

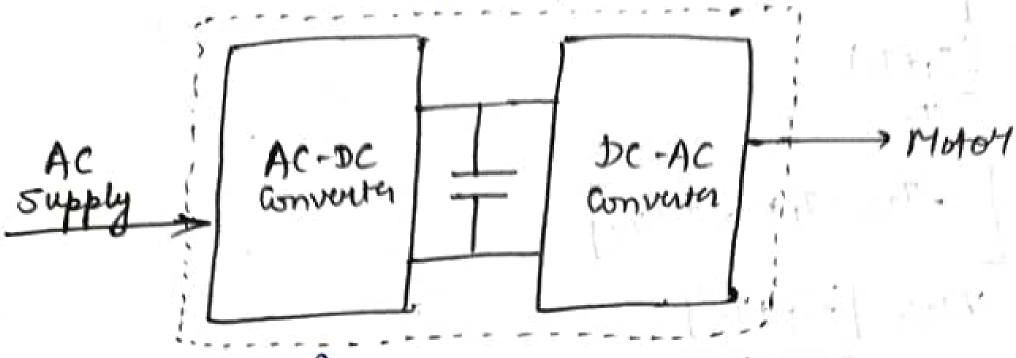
$$= -V_{RO}$$

[Implement in MATLAB]

04-11-2024

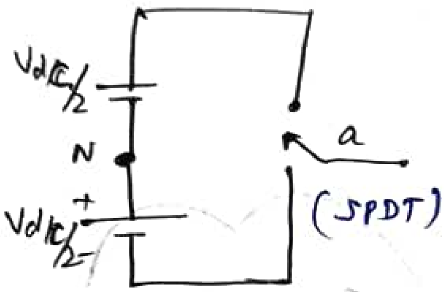
Multilevel Inverters and PWM Schemes

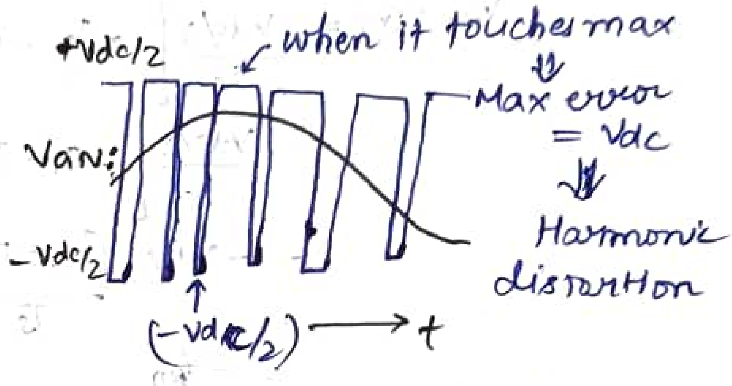
[Multilevel Voltage Source Inverters]



Power electronics converter

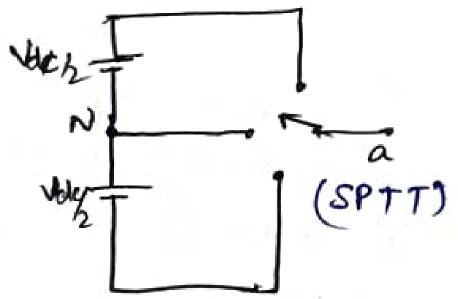
Two-level Inverter - SPWM

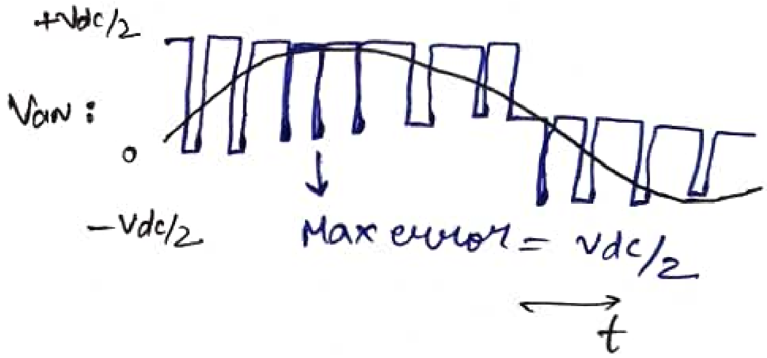




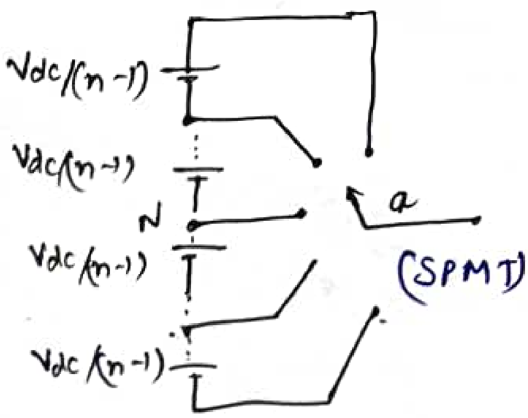
Poles voltages: 2 levels

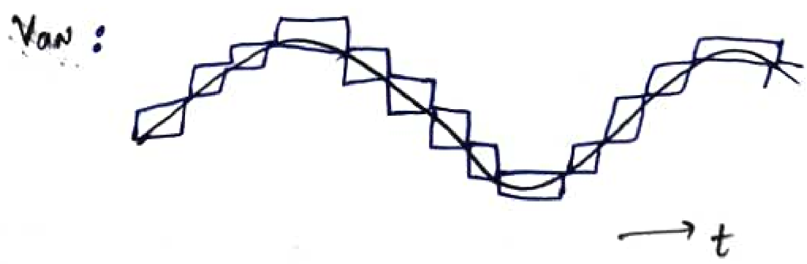
Three-level Inverter





Multilevel Inverter





↳ Quality of o/p voltage ↑
↳ Reduced harmonic distortion.

Multilevel Power Converters - Advantages:

- → Enhanced quality of output waveforms with reduced harmonic distortions.
- → Nearly sinusoidal o/p voltage at higher no. of levels - hence expensive and bulky filters can be avoided, in many applications.
- → High voltage waveform can be generated using switching devices of low voltage ratings without employing series connections.
- → Low voltage stress on semiconductor devices.
- → Transformers for stepping up voltages can be avoided in many applications.

Multilevel Inverters - Advantages:

- → Enhanced quality of the output voltage at low switching frequencies. Hence, switching loss reduces.
- → Reduction in torque pulsation in drives.
- → Reduction in dv/dt.
- → Reduced EMI problems.
- → Reduction in CM voltage and associated problems.
- → Facilitates elimination of CM voltages, etc.

Multilevel Inverters - Disadvantages:

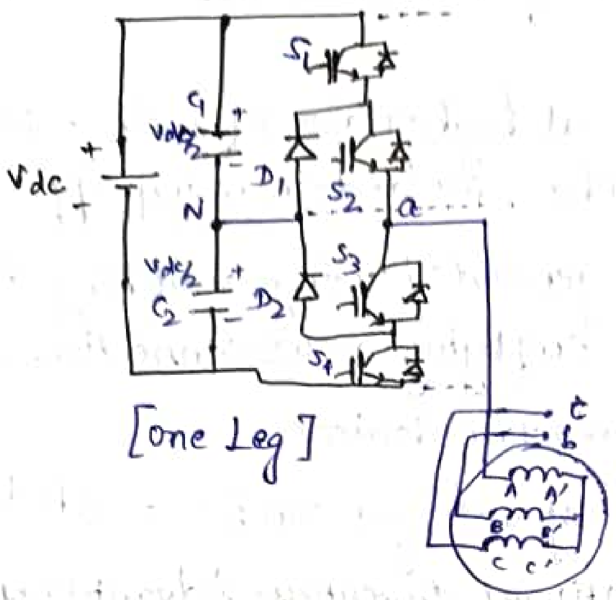
(As the no. of levels increases)

- → Complexity of the power and control circuits increases.
- → Large no. of components increases costs.
- → Reliability decreases due to the presence of large no. of devices - each device is a potential failure point.

Conventional Multilevel Inverters Topologies:

- → Neutral Point Clamped (NPC) topology
- → Flying capacitor (FC) topology
- → Cascaded H-Bridge (CHB) topology.

3-Phase, 3-Level NPC Inverter [Diode clampled MLI]



[one Leg]

$C_1, C_2 \rightarrow$ split DC link voltage into two.
$N \rightarrow$ Neutral point
Diodes clamp the switch voltages to $V_{dc}/2$.

$S_1, S_2, S_3, S_4 \rightarrow$ current bidirectional 2-quadrant sc switches.

$\left.\begin{matrix} S_1, S_3 \\ S_2, S_4 \end{matrix}\right\}$ operate in complementary manner

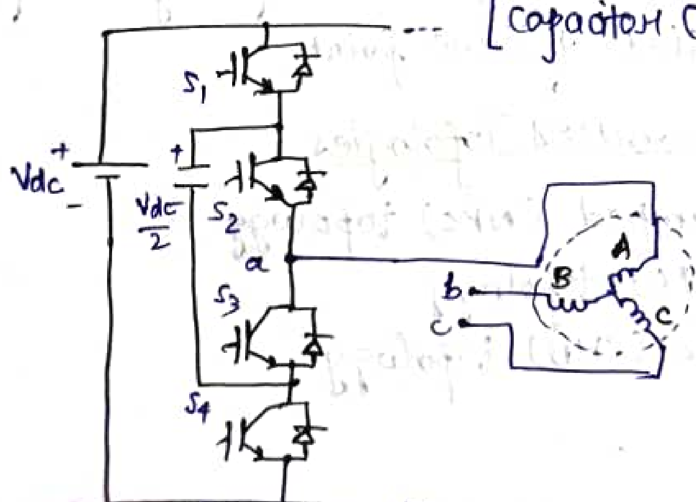
Pole voltage V_{aN}
$\rightarrow +V_{dc}/2$
$\rightarrow 0$
$\rightarrow -V_{dc}/2$

Switch states				Pole voltage V_{aN}
S_1	S_2	S_3	S_4	
1	1	0	0	$+V_{dc}/2$
0	1	1	0	0
0	0	1	1	$-V_{dc}/2$

NPC Inverter - Disadvantages: Fluctuations in capacitor voltage depending on the load current drawn from DC link.
↳ Requires large no. of clamping diodes as the no. of levels increases.
↳ N-level NPC inverter requires $3(N-1)(N-2)$ clamping diodes of voltage rating $\left(\frac{V_{dc}}{N-1}\right)$.

Flying Capacitor Multilevel Inverter (FCMLI)

[Capacitor Clamped MLI]



[one leg]

→ Floating voltages across the capacitors are used for generating different voltage level.

→ 3-Level, 3-Phase FCI.

→ Capacitor voltages have to be maintained at the required level under all conditions of operation. This can be achieved by making use of the redundancy in switching states that exists for generating different voltage levels.

S_1, S_2, S_3, S_4 → current bi-directional 2 quadrant SC switches

Capacitor C is charged to a voltage of $V_{dc}/2$

V_{ao} (pole voltage) → V_{dc}, → $V_{dc}/2$, → 0

Switch States S_1	S_2	S_3	S_4	Pole voltage V_{ao}
1	1	0	0	V_{dc}
0	1	0	1	$V_{dc}/2$
1	0	1	0	$V_{dc}/2$
0	0	1	1	0

3-Level FCMLI – Balancing of capacitor voltages:

→ Capacitor-voltage is not affected while generating V_{dc} and 0.

→ There are 2 methods for generating $V_{dc}/2$ – called redundancy.

→ For a given dirn of the load current, these two methods produce opposite effects (charging / discharging) on the capacitor.

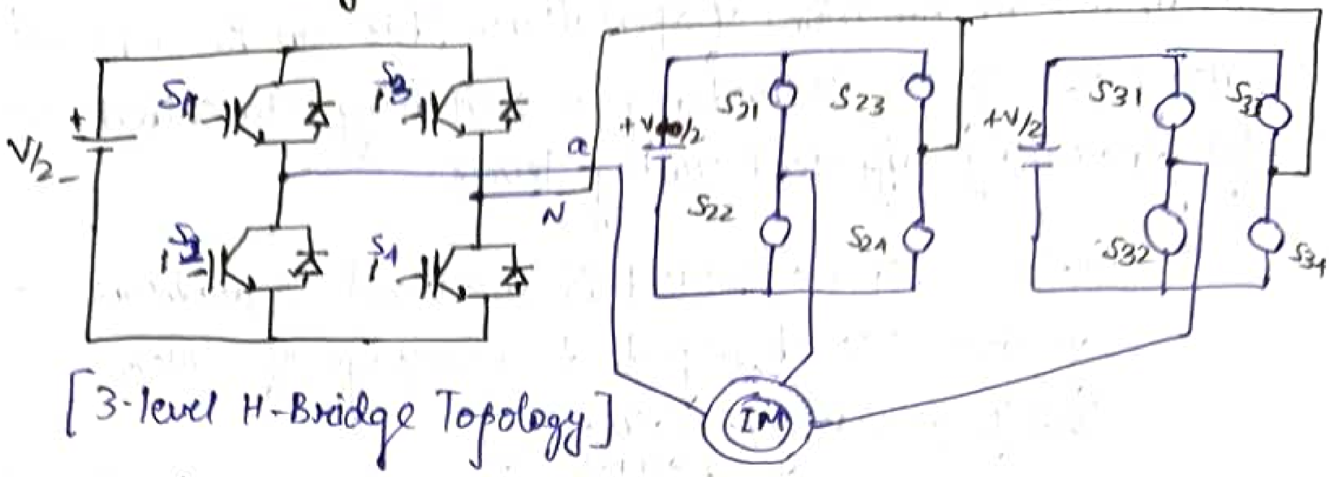
→ The method of generation of $V_{dc}/2$ is selected based on the voltage level of the capacitor & the dirn of load current so as to keep the capacitor voltage within a specified band ($V_{dc}/2 \pm \Delta V$).

FCMLI – Features:

↳ Requires large no. of capacitors to achieve higher no. of voltage levels.

↳ A 3-phase N-level flying capacitor based MLI with a DC link voltage of V requires $\frac{3(N-1)(N-2)}{2}$ capacitors of voltage rating $\left(\frac{V}{N-1}\right)$.

Cascaded H-Bridge(CHB) Inverter



[3-level H-Bridge Topology]

↳ H-bridge cells fed from isolated DC voltage sources are connected in series to realize MLI structure. The no. of H-bridge cells per phase required depends on the no. of voltage levels.

↳ <u>Disadvantage</u>: Requirement of large no. of isolated DC voltage sources.

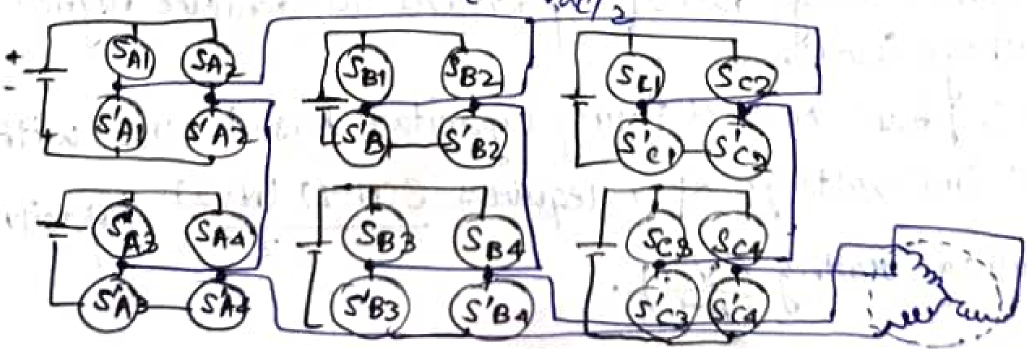
$\left.\begin{matrix} S_1, S_2 \\ S_3, S_4 \end{matrix}\right\}$ operate in complementary manner.

Pole voltage : V_{aN} → $+V/2$, → $-V/2$, → 0

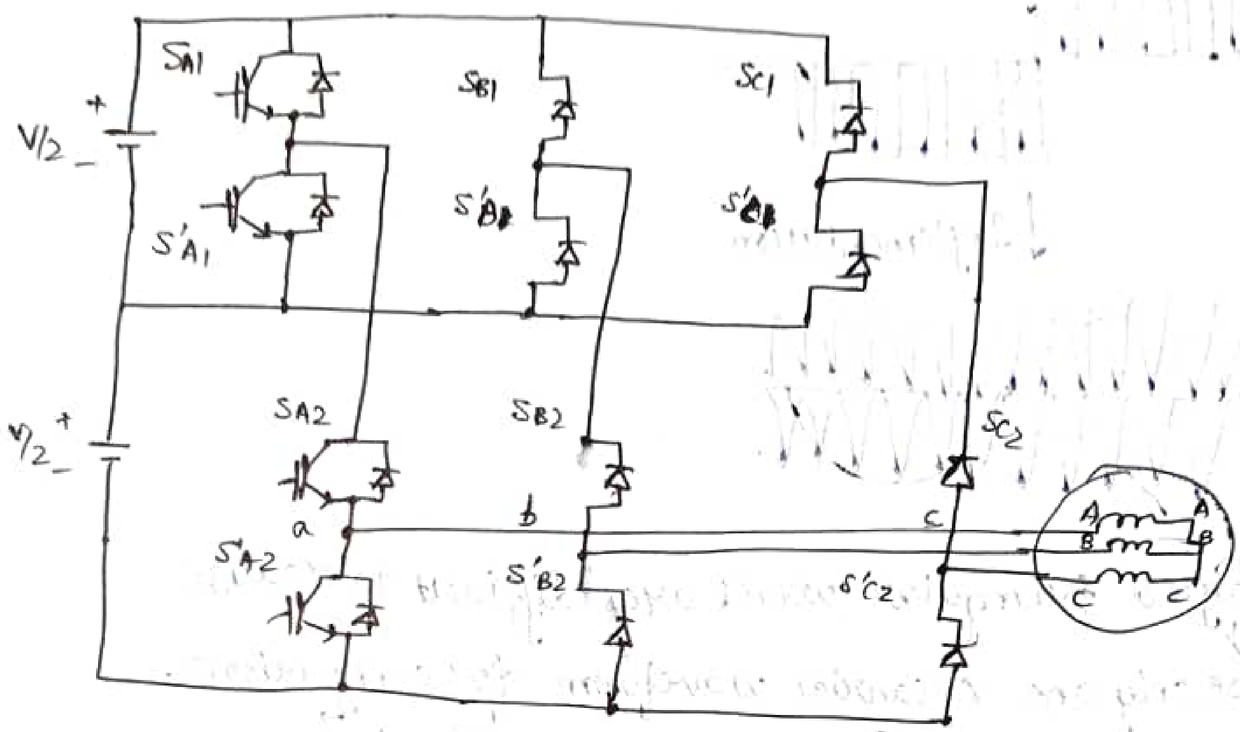
Switch states				Pole voltage V_{aN}
S_1	S_2	S_3	S_4	
1	0	0	1	$+V/2$
0	1	1	0	$-V/2$
1	1	0	0	0
0	0	1	1	0

5-level, 3-phase, Cascaded H-Bridge Inverter :

Pole voltage levels : $\begin{cases} +V_{dc}/2 \\ +V_{dc}/4 \\ 0 \\ -V_{dc}/4 \\ -V_{dc}/2 \end{cases}$



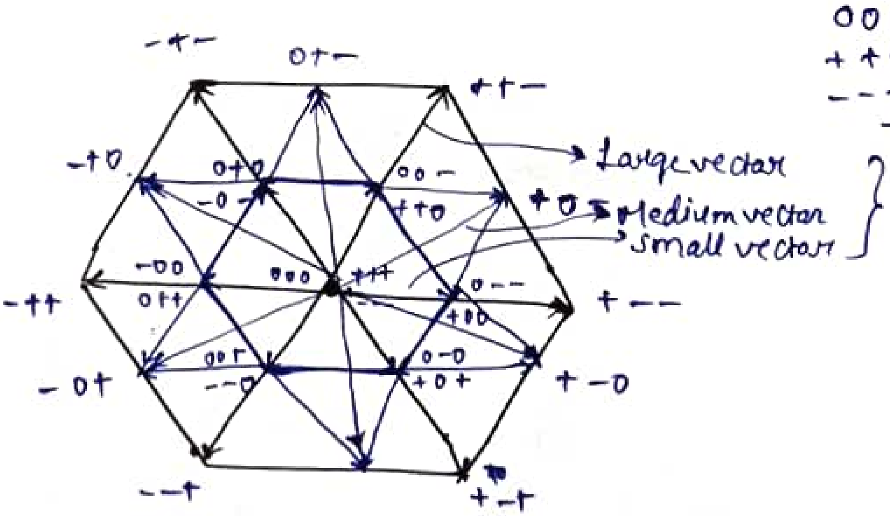
Multilevel Inverter by cascading two-level Inverters

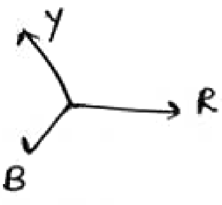


Switch states				Pole voltage V_{AO}
S_{A1}	S'_{A1}	S_{A2}	S'_{A2}	
1	0	1	0	V
0	1	1	0	V/2
0	0	0	1	0

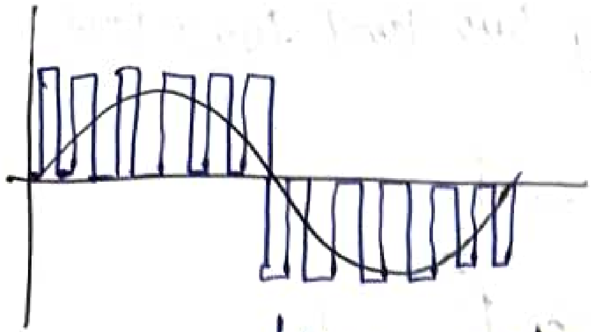
3 ~~states~~ Levels: $+V/2 \rightarrow +$
$0 \rightarrow 0$
$-V/2 \rightarrow -$
} $3^3 = 27$ states
↳ 24 active vectors

000
+++
--- } Zero vectors
→ 19 space vector locations

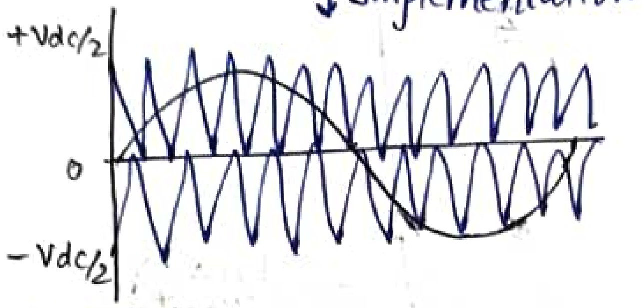




[RYB]



↓ Implementation

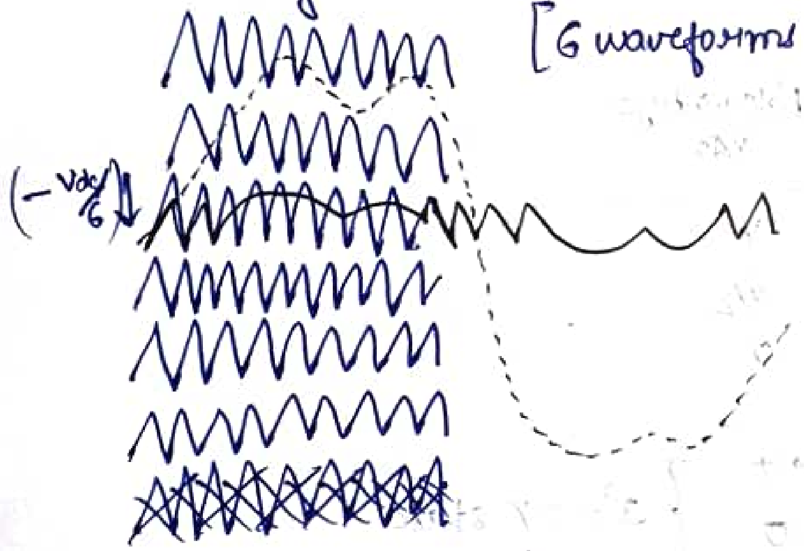


↪ Shifted triangular wave are difficult to realize.

⇓

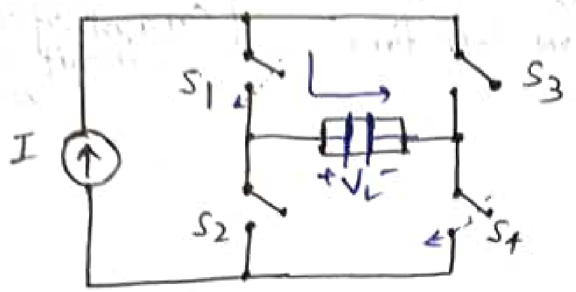
Use only one Δ carrier waveform for comparison.

[6 waveforms for 7 levels]

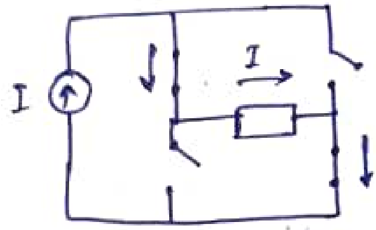


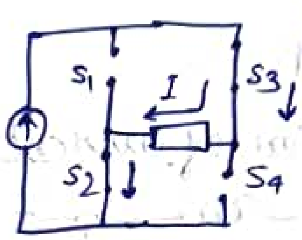
→ Whenever ref. voltage waveform traverses from one carrier region to the next, it is shifted and scaled to reside within one triangle.

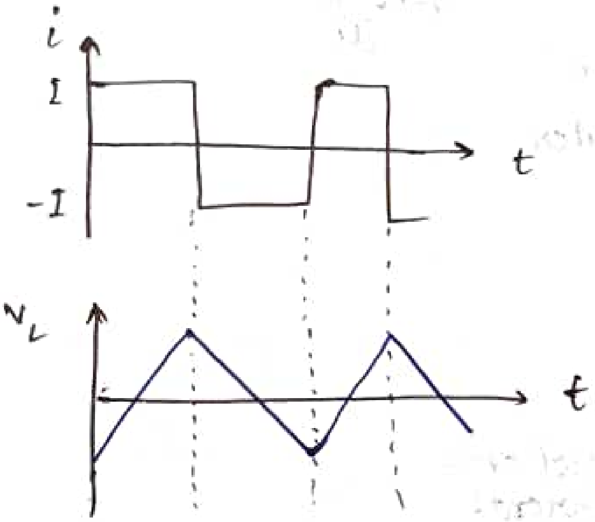
Current Source Inverters (CSI)



⇓



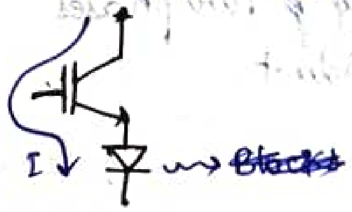


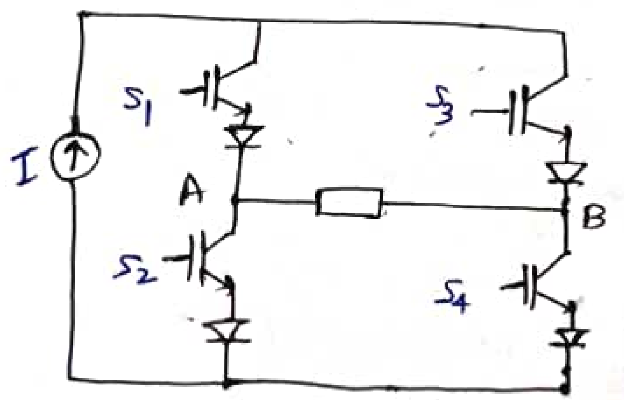


[Capacitor circuit]

→ Switch conducts current only in forward dirn & voltage switches.

⇒ voltage bidirectional two quadrant switch.



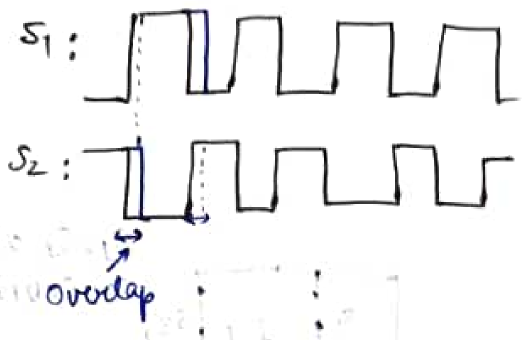


→ Controlled current

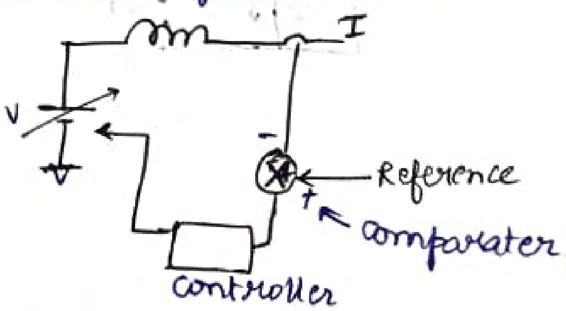
↳ No failure of components due to current.

Turn ON S_1, S_4 ⇒ Turn OFF S_1, S_4 ⇒ Any delay would cause damage (blast).
OFF S_2, S_3 ON S_2, S_3 simultaneously
⇓
But finite T_{ON}, T_{OFF} time

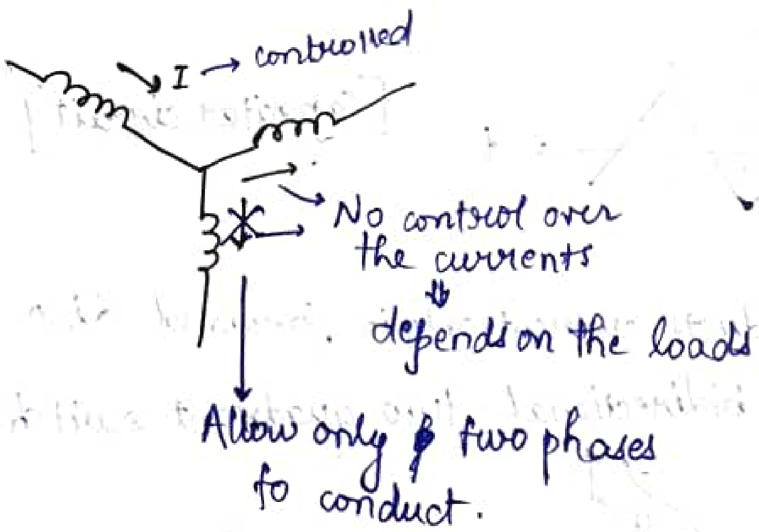
[Cannot open circuit current source]



Realisation of current source:

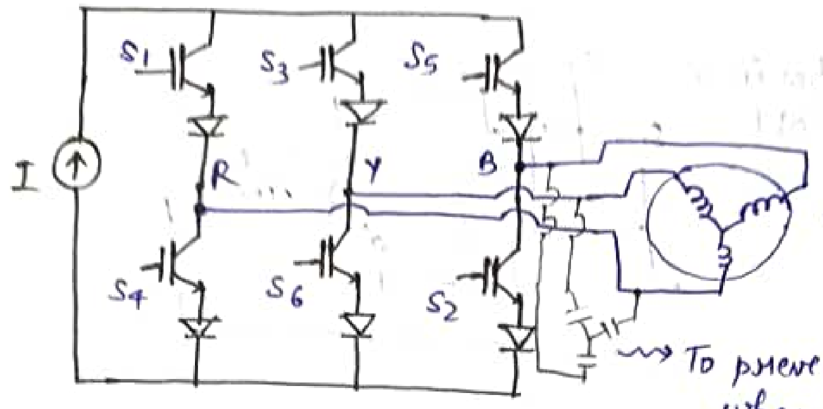


$V = L\frac{di}{dt}$



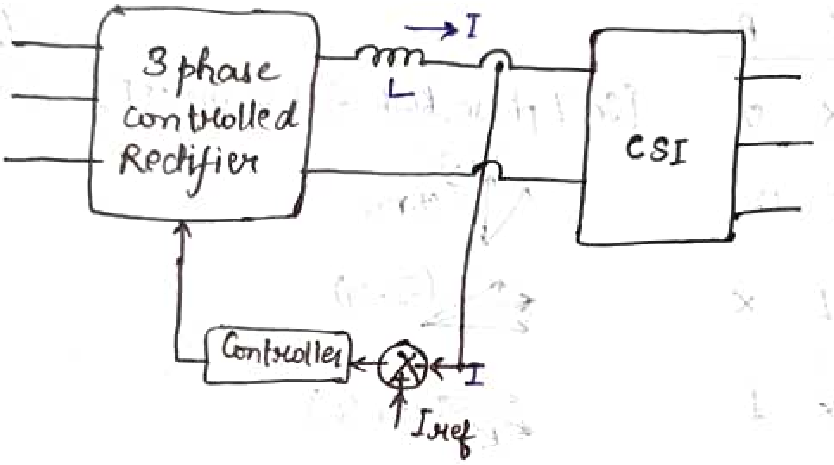
08-11-2024

Three Phase Current source Inverters

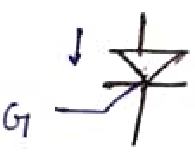


Two phase conduction Mode
⇑
→ Only two phases can be allowed to conducted.

⇝ To prevent voltage spike : $v = L\frac{di}{dt}$ when current is turned ON/OFF.



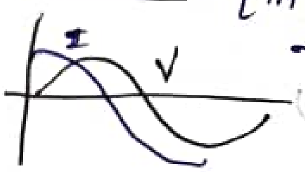
SCR: silicon Controlled Rectifier



⇝ blocks voltage in both dirn
↳ allows current in one dirn.

⇝ can be turned ON
↳ cannot be turned off;
To turn OFF, ~~voltage~~ current has to fall [decided by load] ⇗ NO PWM
below certain level.

Load Commutation [in synchronous motor drives]



→ current leads

Zero State: Current does not flow through the load.
OR, By passing current away from the load.
↳ In voltage source, turn OFF the source.

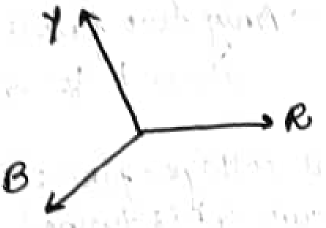
Zero vector
$$\begin{cases} (S_1, S_4) - ON \\ (S_3, S_6) - ON \\ (S_5, S_2) - ON \end{cases}$$

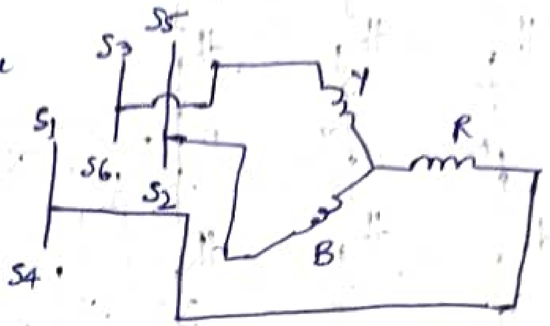
States:

$1 \to ON$

$0 \to OFF$

$X \to$ Both switches in a leg are OFF

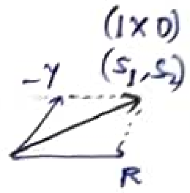


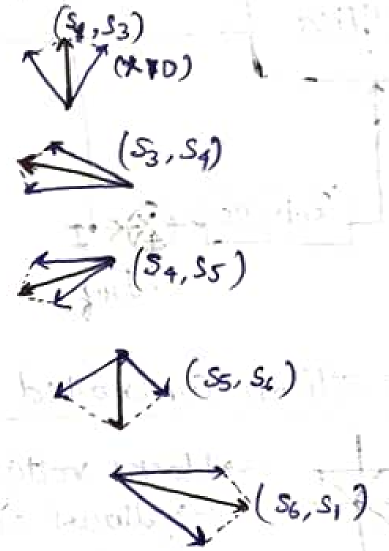


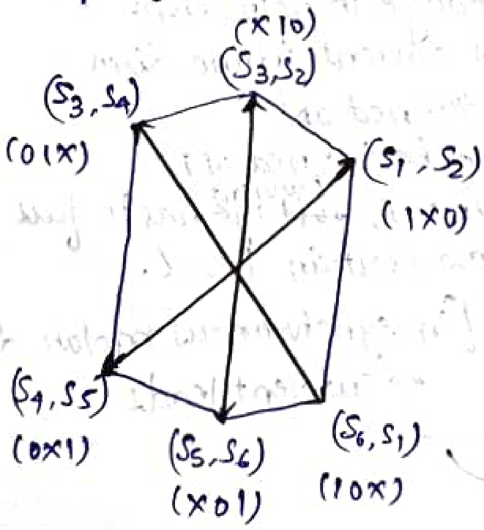
Switching states:

ON states	R	Y	B
S_1, S_2 ON	1	X	0
S_1 S_3	X	1	0
S_3 S_4	0	1	X
S_4 S_5	0	X	1
S_5 S_6	X	0	1
$S_6 - S_1$	1	0	X

[In Y phase, both S_3 & S_6 are OFF]

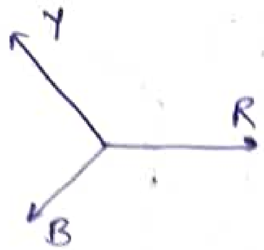


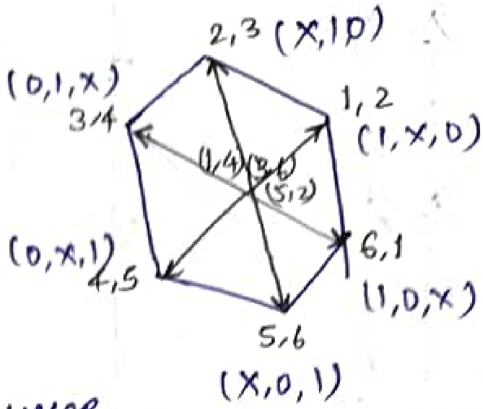




Active : (1, 2), (2,3), (3,4), (4,5), (5,6)

Zero : (1,4), (3,6), (5,2)





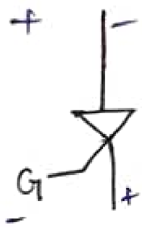
30° phase shift in current source inverter in comparison to voltage source inverter.

Applying Ampere-second balance :

$$I_r T_S = I_1 T_1 + I_2 T_2 + I_0 T_0$$

[I_r is the current we want to generate.]

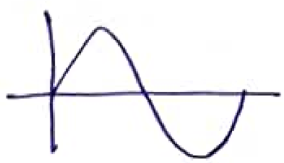
→ Voltage Source Inverter : Buck Inverter
→ Current Source Inverter : Boost Inverter.



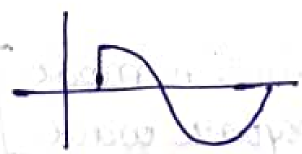
SCR (Silicon Controlled Rectifier)

For making it to conduct we have to add gate drive current.

→ voltage bidirectional switch
→ Equivalent to 



Normal diode

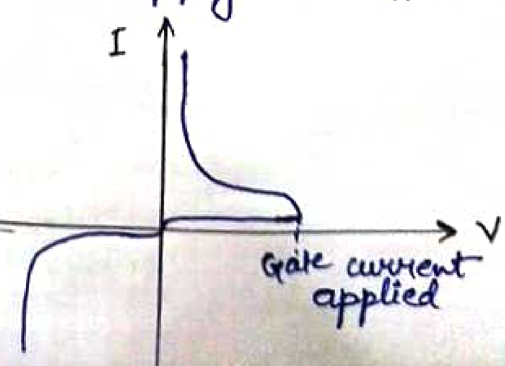


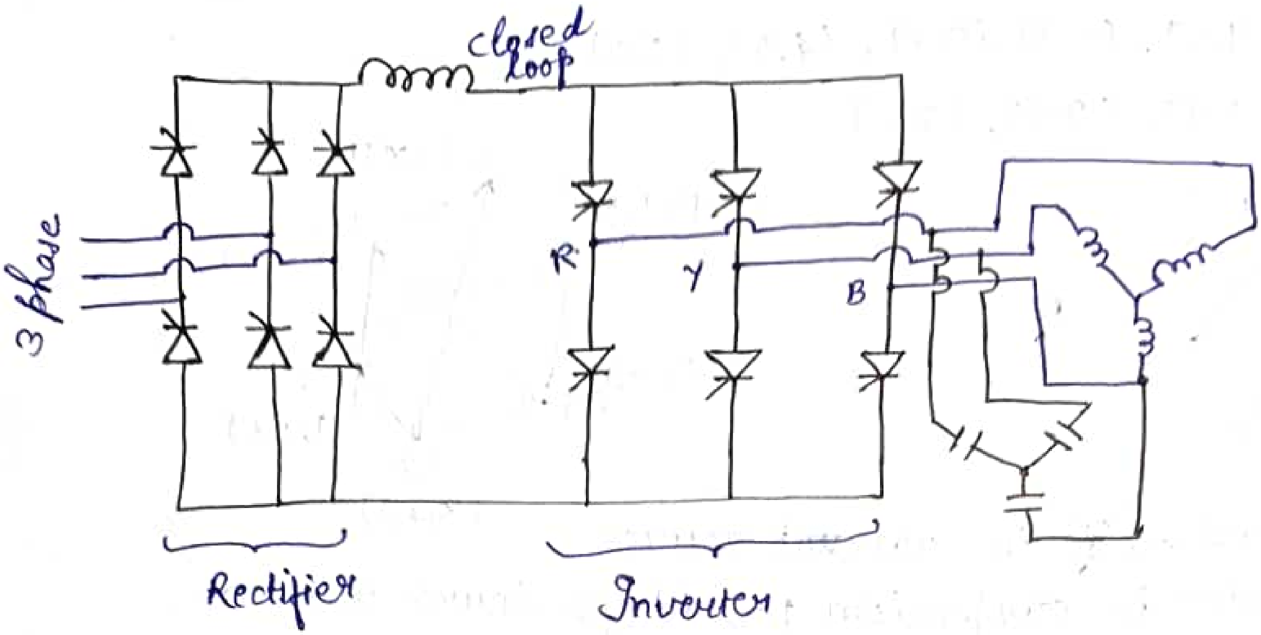
SCR diode

[we can apply controlled voltage]

→ To switch OFF, reduce the current

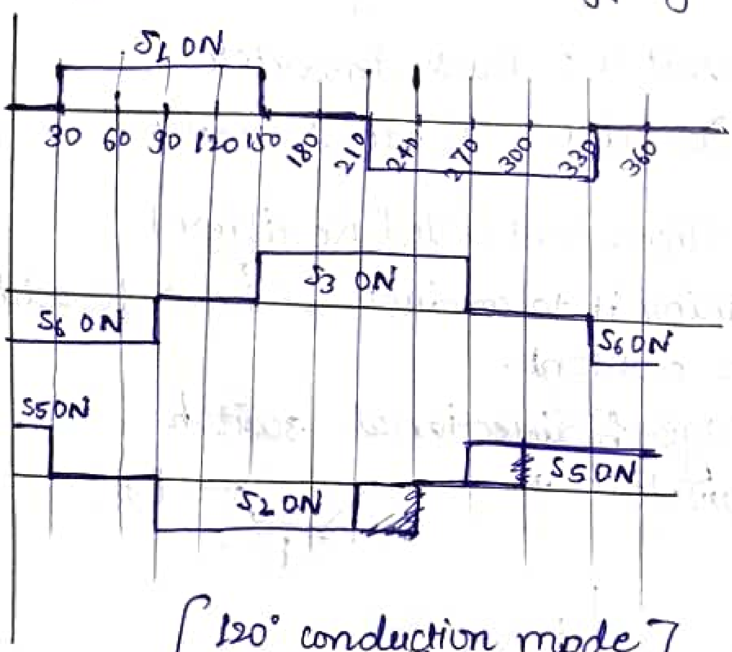
↳ Semi-controlled device.





Synchronous Motor: can be controlled to be leading or lagging power.

Non-synchronous Motor: Lagging current.



[120° conduction mode
Quasi-square wave]

12-11-2024

Control of Electric Motors

Electrical energy $\rightarrow$ Motor $\rightarrow$ Mechanical energy   Mechanical energy $\rightarrow$ Generator $\rightarrow$ Electrical energy

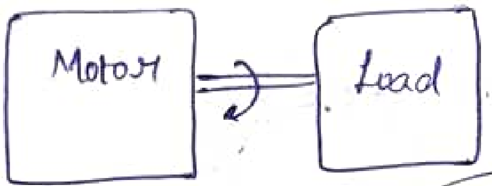
↳ To control: Torque (T) $\rightarrow$ N.m
Speed (ω) $\rightarrow$ rad/sec.

Mechanical power $= \omega . T$

Motor $\longrightarrow$

Electrical domain $\Longrightarrow$ Magnetic domain $\Longrightarrow$ Mechanical Domain

Generator $\longleftarrow$

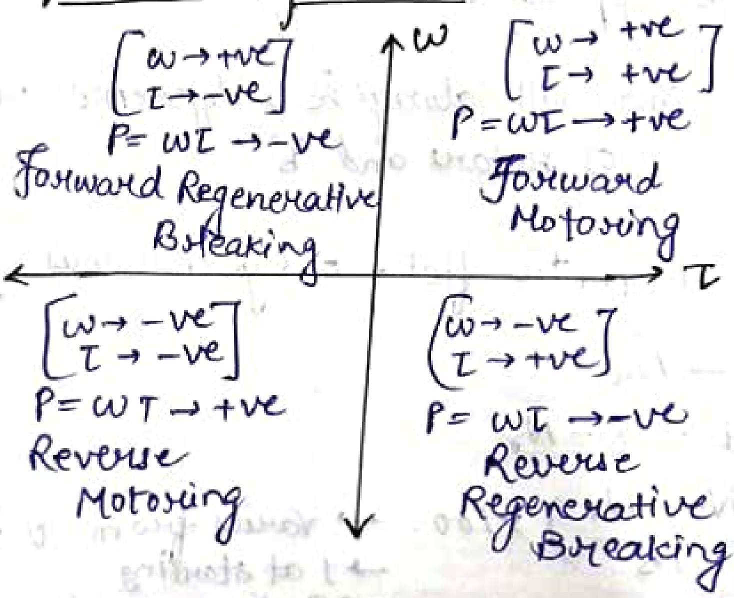


dominate while accel^n / take-off

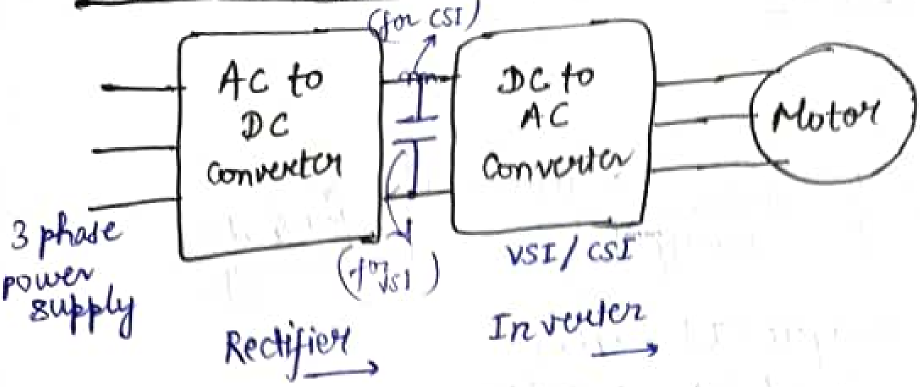
$$T_e = J\frac{d\omega}{dt} + B\omega + T_L$$

T_L : load torque
ω : velocity (rad/sec)
J : MI
B : coeff. of friction.

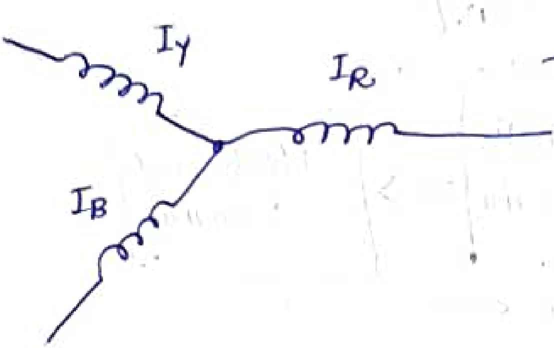
Four quadrant operation:



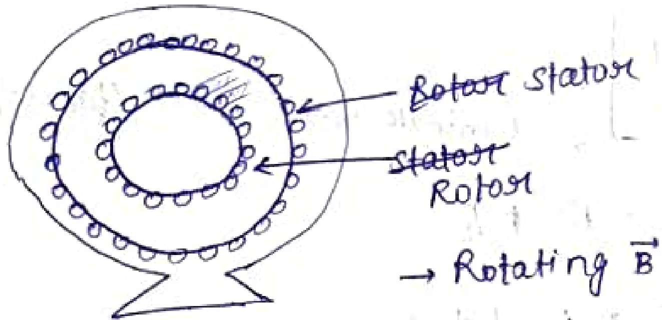
Electric Motor Drive

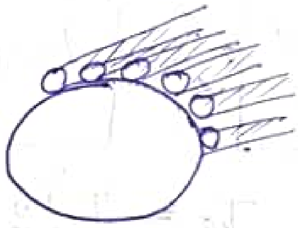


18-11-2024



→ 3 windings of 120° spatial difference carrying currents with 120° phase difference.





→ Rotating $\vec{B}$ with constant magnitude.

↳ ~~Con~~ Rotor conductors oppose the rotating magnetic field by rotating themselves, along with rotating $\vec{B}$ and try to achieve its speed.

⇓

$\vec{B}$ appears stationary wrt rotors.

⇓

There will always be a difference in speed of rotors and $\vec{B}$.

Speed of rotating magnetic field = Synchronous speed (N_s)

Speed of rotor → N_r

Slip speed = $N_s - N_r$

slip (S) = $\left(\frac{N_s - N_r}{N_s}\right) \times 100$. → varies from 0 to 1.
→ 1 at starting
→ 0 when $N_s = N_r$.

↳ $s > 1$ when N_s & N_r rotates in opposite direction

↳ Regenerative breaking. (due to torque in opposite dirn)

↳ $s < 0$ → not possible in motor.

↳ in generator

→ Back EMF

↳ Asynchronous Motor: Induction motor

↳ works on ~~the~~ speed less than synchronous speed.

↳ Based on electromagnetic induction.

→ Frequency / voltage induced in rotor depends on the slip (relative speed).

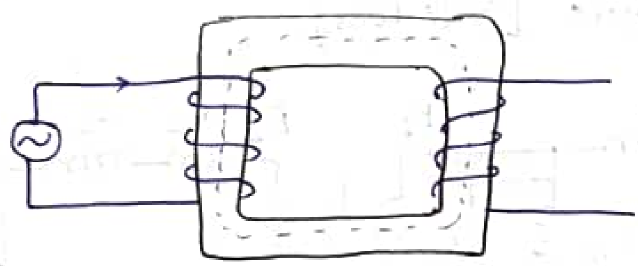
f_s → stator frequency

f_r → rotor frequency

$$f_r = s f_s$$

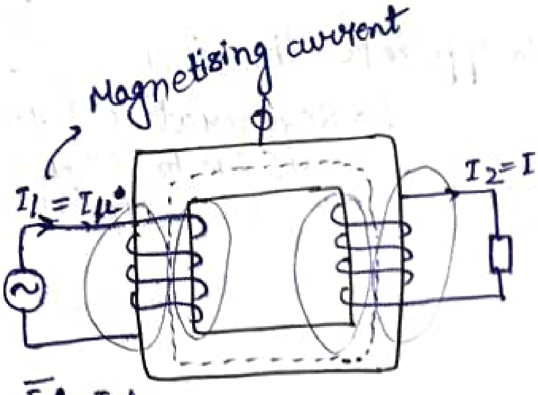
↳ Analysis of torque, speed using motor modelling in steady or transient state.

#

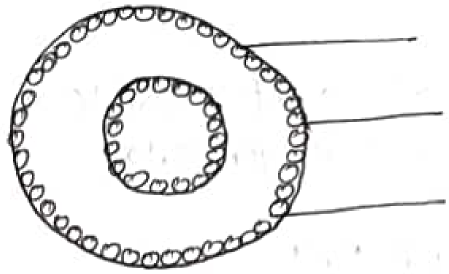


$$\text{flux} = \frac{\text{mmf} = NI}{\text{Reluctance}}$$

19-11-2024



$I_1 = \bar{I_\mu} + I_2'$



Magnetising current $= \frac{N d\phi}{dt}$

Magnetising current flows even when there is no load; to magnetise the core.

$f_r = s f_s$, $s = \frac{N_s - N_r}{N_s}$
(slip)

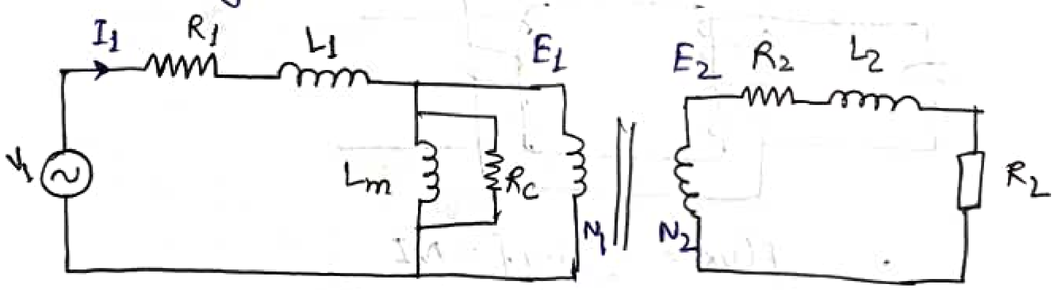
f_s : frequency of the voltage applied to the stator;

$\phi \angle \frac{MMF}{Reluctance} = \frac{NI}{S}$ ← high for air, so low leakage

| f_r: frequency of induced voltage in rotor

→ Resistance of coil also contributes to the loss.

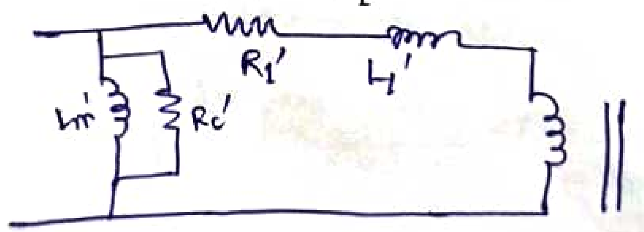
Loss (magnetic)
- → Hysteresis
- → Eddy current [core loss]



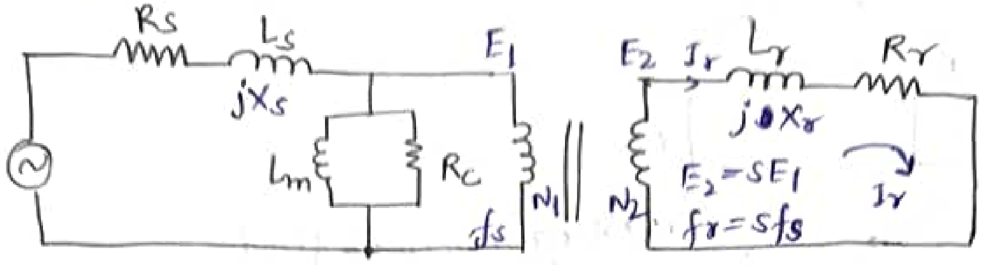
$I_1^2 R_1 = I_2^2 R_1'$ (R_1' after transforming)

$\frac{E_2}{E_1} = \frac{N_2}{N_1} \Rightarrow \frac{E_1}{N_1} = \frac{E_2}{N_2}$

$\frac{N_1}{N_2} = \frac{I_2}{I_1}$



In motor



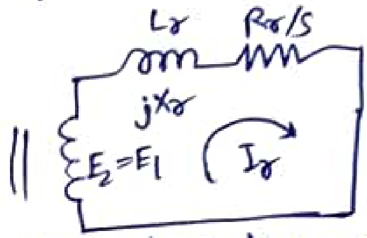
$$I_r = \frac{SE_1}{R_r + jsX_r} = \frac{E_1}{\frac{R_r}{s} + jX_r}$$

$X_s = 2\pi f_s L_s$
$X_r = 2\pi f_s L_r$

If $R_r = \frac{R_r}{s}$, then can say $E_2 = E_1$, $sX_y = X_y$.

Mechanical energy $= I_r^2 \frac{R_r}{s}$

Equivalent circuit (after transforming):

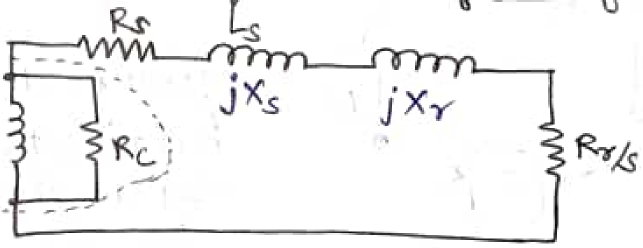


Freq. dependence gone↓

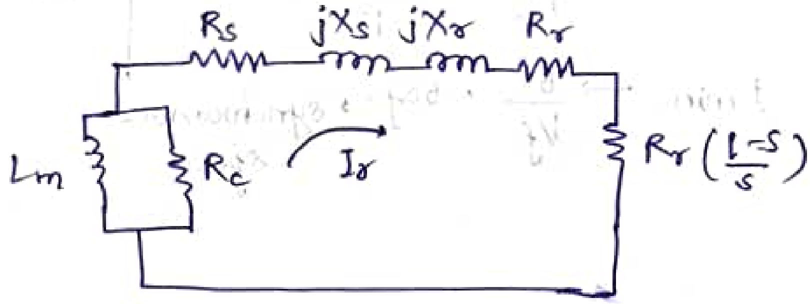
Power dissipated at rotor $= I_r^2 \frac{R_r}{s}$

Loss in secondary = copper loss + Mechanical loss

Shifting its position won't affect much as Rs & jXs are very small



$$R_r/s = R_r + R_r\left(\frac{1-s}{s}\right)$$



$$P_{mechanical/phase} = I_r^2 \frac{R_r(1-s)}{s}$$

For 3-phase, $P_{mech.} = 3I_r^2 \frac{R_r(1-s)}{s}$

$= \omega_{mech.} \times T$

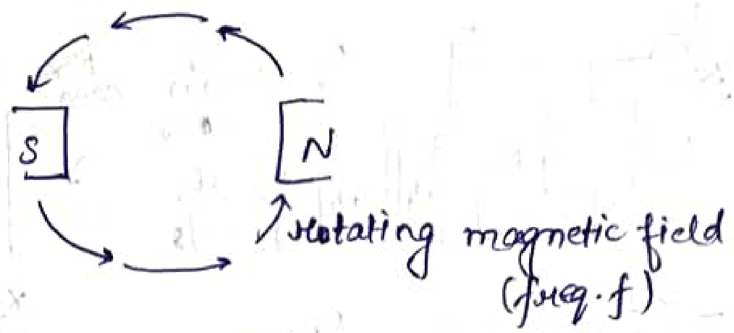
$\omega_{mech.} = \omega_s - s\omega_s$
$= \omega_s(1-s)$

Torque, $T = 3I_r^2 R_r \frac{(1-s)}{s \cdot \omega_{mech.}}$

$= 3I_r^2 R_r \frac{(1-s)}{s} \cdot \frac{1}{\omega_s(1-s)}$

$= \frac{3I_r^2 (R_r/s)}{\omega_s}$.

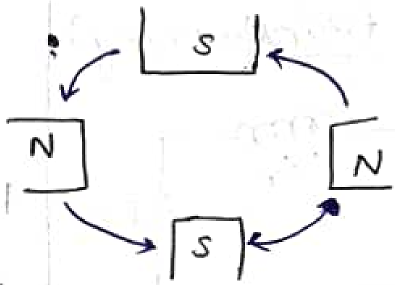
$\rightarrow \omega_{mech.} = \omega_s$, $\omega_r = \omega_s(1-s)$



(Synchronous speed) No. of rpm = $60f$.

Mechanical speed Vs. Electrical speed

$$W_{mech} = \frac{W_{electrical}}{P/2}$$



Four part, mechanical it has to rotate by 180° to rotate electrical field by 360°.

$$(\text{Syn. speed})\ N_s = \frac{60f}{P/2} = \frac{120f}{P}.$$

RPM → Rev. per minute

$$1\ \text{min.} \rightarrow \frac{60}{1/f} = 60f \rightarrow \text{synchronous speed}$$

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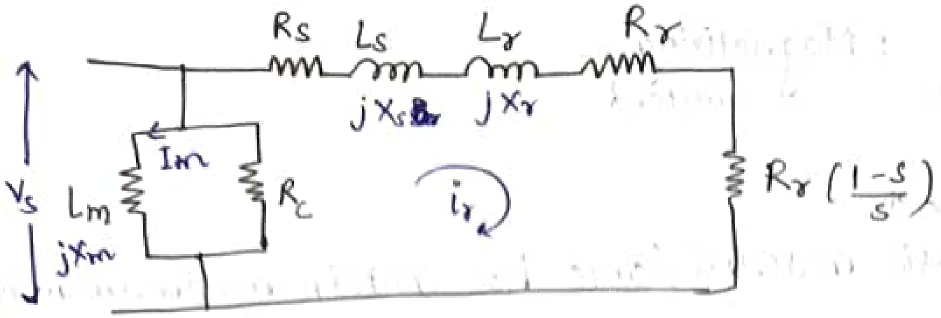


$[X_m = 2\pi f L_m]$ $\quad X_s = 2\pi f L_s$ $\quad T = \dfrac{3 I_r^2 R_s / s}{\omega_s}$

$X_r = 2\pi f L_r$

$$I_r = \frac{V_s}{\sqrt{(R_s+R_r)^2 + (X_s+X_r)^2}}, \quad T = \frac{3 V_s^2 R_r}{s\omega_s\left[\left(R_s + \frac{R_r}{s}\right)^2 + (X_s+X_r)^2\right]}$$

$$\boxed{I_r = \frac{V_s}{(R_s + R_r/s) + j(X_s+X_r)}}$$

→ Torque is very sensitive to voltage.

→ If s is very small, i.e., very small slip

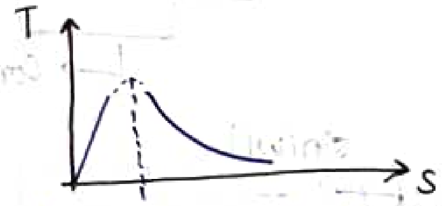
$$T \propto \frac{V_s^2 (R_r/s)}{\omega_s (R_r/s)^2} = \frac{V_s^2}{\omega_s (R_r/s)} = \frac{s V_s^2}{\omega_s R_r}$$

$$\Rightarrow \boxed{T \propto s}$$

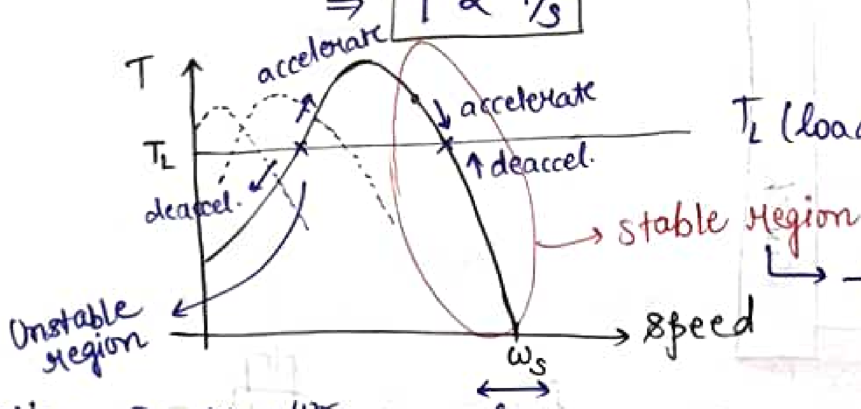
For large values of s,

$$T \propto \frac{V_s^2 - R_r}{s\omega_s}$$

$$\Rightarrow \boxed{T \propto 1/s}$$



At some point, torque will be maximum.



└→ -ve slope

└→ Maximum slip

slip, $S = \dfrac{\omega_s - \omega_r}{\omega_s}$

this range of speed is only possible here.

→ we can change freq. to change ω_s to get wider range of speed variations.

$$|I_m| = \frac{V_s}{X_m} = \frac{V_s}{2\pi f L_m}$$: Magnetising current

$f\downarrow$, $|I_m|\uparrow$

↳ flux ↑

→ Every magnetic material / core has certain maximum limit.

$T \propto \phi^2 \omega_{slip}$

→ we need to keep $|I_m|$ constant.

→ $\frac{V_s}{f}$ should remain constant (Vs should be such.)

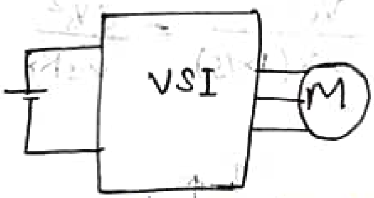
Constant V/f Ratio control

$\frac{V}{\omega} \rightarrow \frac{V}{rad/sec} \rightarrow$ Volt-sec. $\quad\Big|\; v = \frac{d\psi}{dt}$

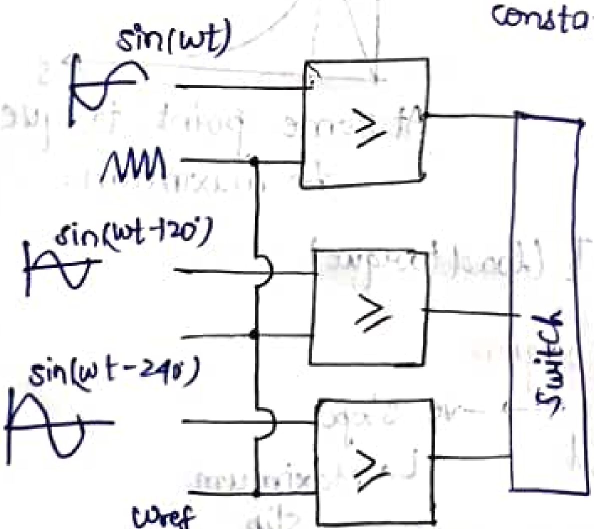
→ $\frac{V}{\omega}$ = constant ⇒ flux = constant

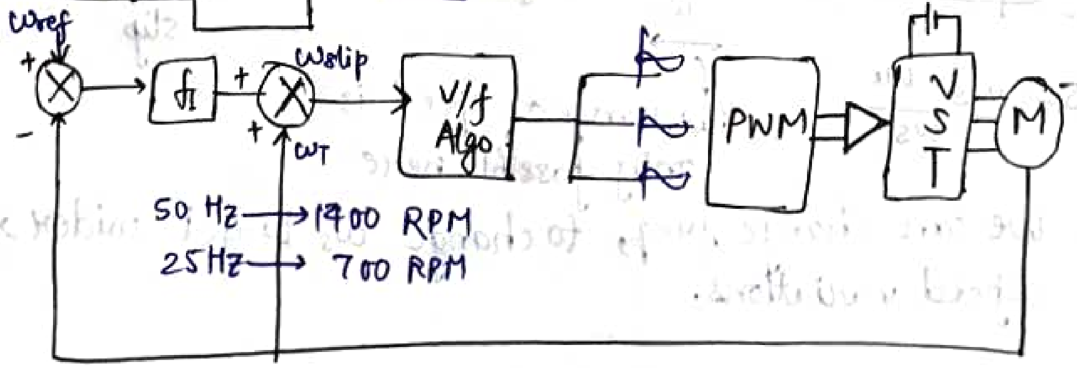
⇒ Deliver Rated torque.

→ At rated flux, machine can deliver rated torque only when load requires it.



↳ Control it to have constant $\frac{V}{f}$.





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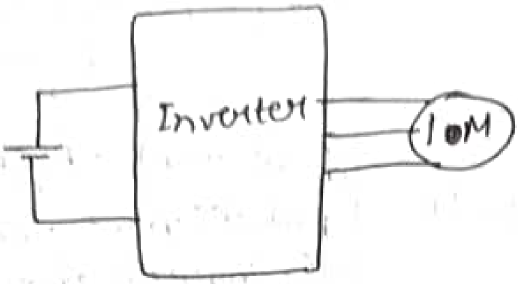
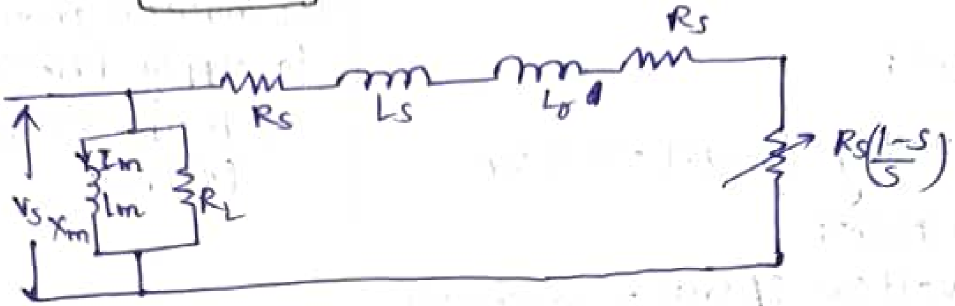
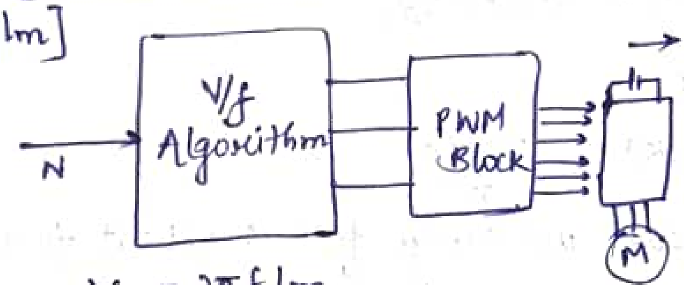
Constant V/f Ratio Control



$N_s = \frac{120f}{P}$



$[X_m = 2\pi f l_m]$



→ Rated speed (Base speed)

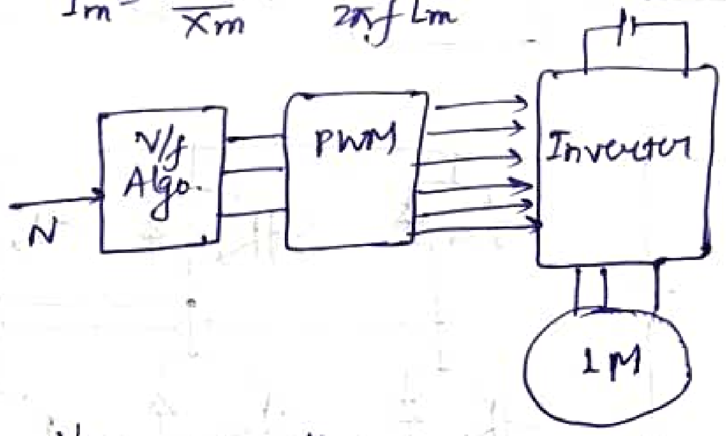
$X_m = 2\pi f l_m$

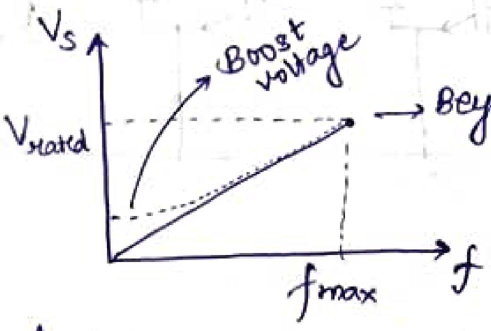
$\boxed{415V,\ 3ph,\ 50Hz,\ 1440\ RPM}$ → Rated speed (Base speed)

$\frac{415}{2}$, 25 Hz → 720 RPM

$\phi = L_m I_m$

$I_m = \frac{V_s}{X_m} = \frac{V_s}{2\pi f L_m}$





→ bounded by battery / DC source

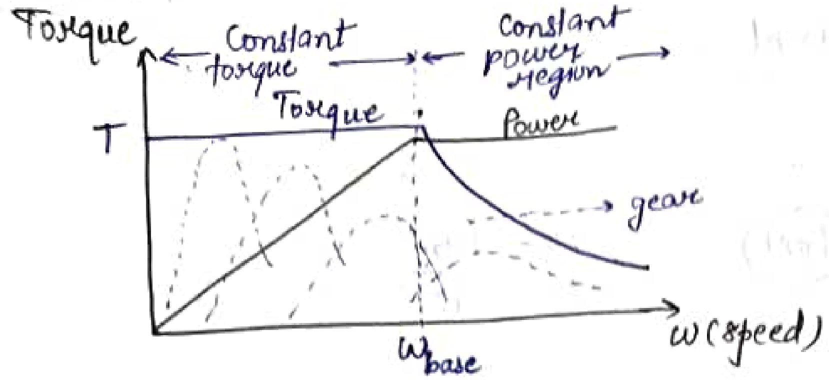
→ Beyond this, V doesn't increase ⇒ Increase speed

$\left(\frac{V}{f\uparrow}\right) \Rightarrow \phi\downarrow$ (flux decreases) (field)

Actual voltage applied to the machine $= V_s - \underbrace{I_s R_s}_{\text{Voltage drop}}$

At high speed, $I_sR_s \downarrow\downarrow$ as $V_s \uparrow\uparrow$
but at low speed overcome I_sR_s to have rated performance.

→ Machine does not get actual voltage at the low speed
↳ Give boost voltage



$\omega \times T = \text{Power} = \text{constant}$ beyond ω_{base}

If we want a higher speed but still want constant vector, the inverter should be able to supply higher voltage to be able to maintain (V/f) ratio.

Linear Modulation:

Sinusoid PWM:

Phase voltage (peak) $= 0.5\ V_{dc}$

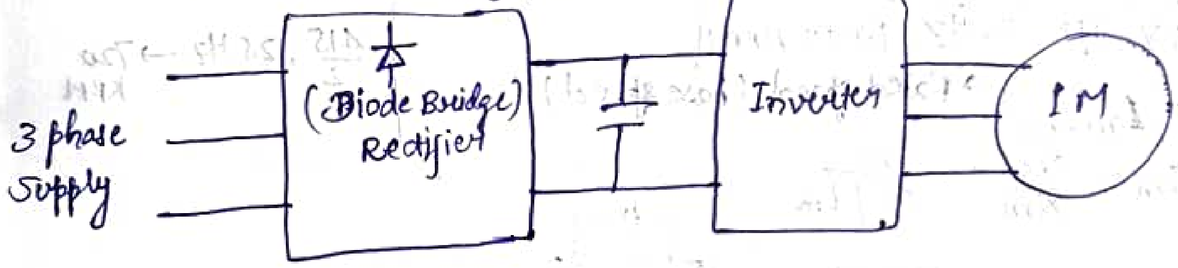
Space-vector PWM:

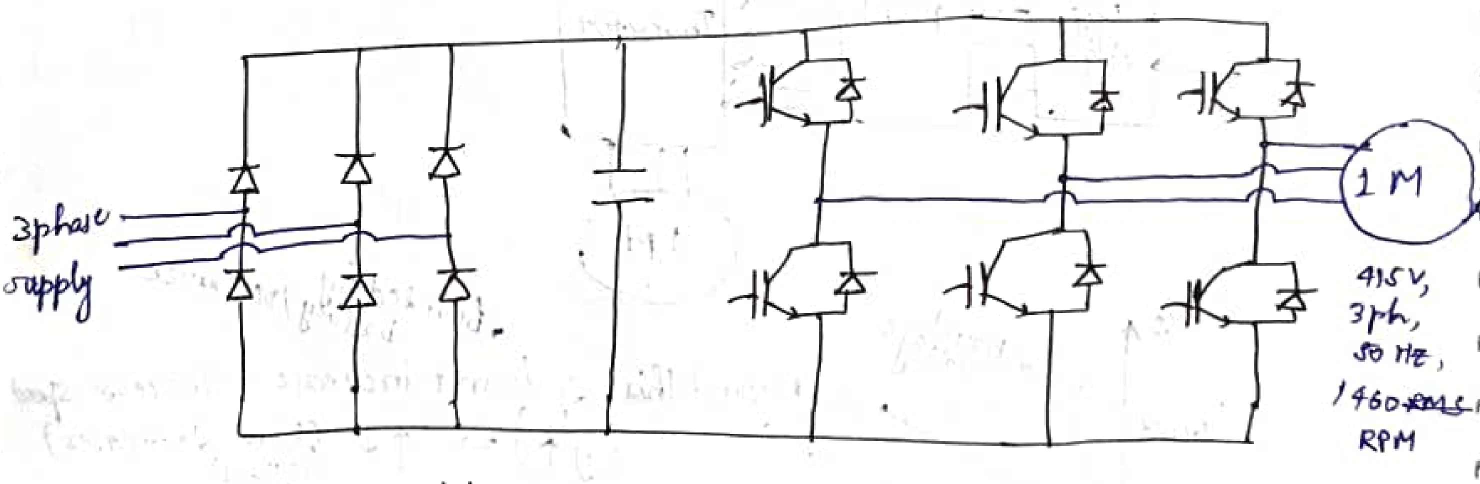
Phase voltage (peak) $= 0.577\ V_{dc}$

Square wave operation:

Phase voltage (peak) $= \frac{2 V_{dc}}{\pi}$

→ Upto phase voltage (peak), we can go for constant torque.





$$V_{dc} = \frac{3 V_{ml\,peak}}{\pi}$$

For 415V,

$$V_{dc} = \frac{3 \times 415 \times \sqrt{2}}{\pi} = 560.4\ V$$

SPWM:

$$V_p(rms) = \frac{Vdc}{2\sqrt{2}} = \frac{560.4}{2\sqrt{2}} = 198.14$$

Phase voltage required to run the motor at rated speed

$$= \frac{415}{\sqrt{3}} = 239.6\ V$$

239.6 V ⟶ 50 Hz

198.14 ⟶ 41.34 → for const. torque

↓

1270RPM

1460 → 50 Hz

1270 ← 41.34

SVPWM:

$$V_p(rms) = \frac{0.577\ vdc}{\sqrt{2}} = 228.48$$

$$228.48 \longrightarrow \frac{50}{239.6} \times 228.64 = 47.67\ Hz \longrightarrow 1372\ rpm$$

Square wave operation: (6-steps)

$$\frac{2\ Vdc}{\sqrt{2}\pi} = \frac{2 \times 560.4}{\sqrt{2} \times \pi} = 252.05$$

Inverter in
↳ overmodulation region.

Q) A 3 phase 400V (RMS), 50Hz, 4-pole-star connected squirrel cage induction motor is driven by a 3phase two level voltage source inverter (VSI) operated with sinusoidal PWM. The VSI is fed from a 600 V DC source. The motor is controlled by maintaining constant V/f ratio. The equivalent circuit paramator are as given below.

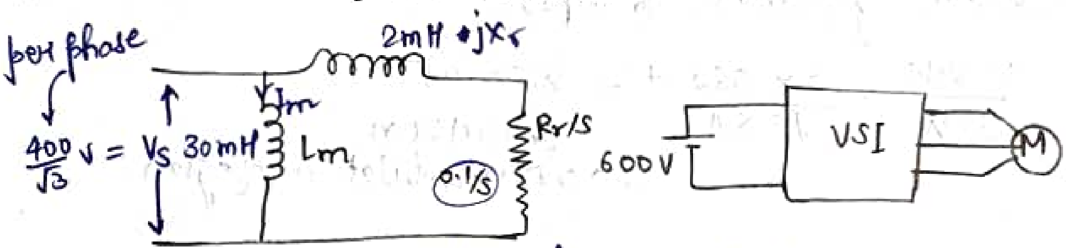
Rotor resistance, $R_r = 0.1\Omega$

Rotor leakage inductance, $L_r = 2\,mH$

Magnetizing inductance, $L_m = 30\,mH$.

The other parameters can be neglected.

If the motor has to run at 700 RPM and produces a torque of 100 Nm. Determine the amplitude modulation index at which the inverter has to be inverted.



(per phase equivalent circuit)

Magnitude of magnetizing current, $I_m = \frac{V_s}{\omega_s L_m}$

$\omega_s(\text{electrical}) = 2\pi f = 2\pi \times 50 = 100\pi$ rad/s.

$V_s = \frac{400}{\sqrt{3}} = 230.94$ V

$\frac{V_s}{\omega_s} = \frac{230.94}{100\pi} = 0.7351$

Torque output, $T = \frac{3(P/2)\, I_r^2 R_r (1-s)/s}{\omega_r}$

$$= \frac{3 \times \frac{P}{2} \times \frac{I_r^2 R_r (1-s)}{s}}{\omega_s (1-s)} = \frac{3\left(\frac{P}{2}\right) I_r^2 \frac{R_r}{s}}{\omega_s}$$

$$= \frac{3\left(\frac{P}{2}\right)\left[\frac{V_s^2}{(R_r/s)^2 + (X_r)^2}\right]\left(\frac{R_r}{s}\right)}{\omega_s}$$

$$= \frac{3P/2}{s^2\omega_s^2}\left[\frac{V_s^2 + s^2\omega_s}{(R_r^2/s^2) + (\omega_s L_r)^2}\right]\left(\frac{R_r}{s}\right) \quad [X_r = \omega_s L_r]$$

$$= \frac{3\left(\frac{P}{2}\right) V_s^2 R_r \, s\omega_s}{\omega_s^2 (R_r^2 + (s\omega_s L_r)^2)} \qquad [s\omega_s = \omega_s - \omega_r = \omega_{slip}]$$

$$= \frac{3\left(\frac{P}{2}\right)\left(\frac{V_s}{\omega_s}\right)^2 R_r \cdot \omega_{slip}}{R_r^2 + (\omega_{slip} L_r)^2}$$

For small values of s, $(\omega_{slip} L_r)^2$ can be neglected.

$$\Rightarrow T \approx 3\left(\frac{P}{2}\right)\left(\frac{V_s}{\omega_s}\right)^2 \left(\frac{R_r \omega_{slip}}{R_r^2}\right)$$

$$\Rightarrow \boxed{T \approx 3\left(\frac{P}{2}\right)\left(\frac{V_s}{\omega_s}\right)^2 \left(\frac{\omega_{slip}}{R_r}\right)}$$

$T = 100$ Nm, $\frac{V_s}{\omega_s} = 0.7351$

$$\Rightarrow 100 = 3(4/2) \times (0.7351)^2 \left(\frac{\omega_{slip}}{0.1}\right)$$

$\Rightarrow \omega_{slip} = 3.0843$ rad/sec. (Electrical)

Synchronous speed $= \omega_s = \omega_r + \omega_{slip}$

Rotor mech. speed $= \omega_{r\,mech.} = 700$ RPM $= 700 \times \frac{2\pi}{360} = 23.3\pi$ rad/sec.

$= 73.3$ rad/sec.

Rotor electrical speed, $\omega_{re} = \omega_{rm} \times \frac{P}{2} = 73.3 \times \left(\frac{4}{2}\right) = 146.61$ rad/sec.

Synchronous speed, $\omega_{se} = \omega_{re} + \omega_{slip}$

$= 146.61 + 3.0843$

$= 149.692$ rad/sec.

Stator fundamental frequency $= \frac{149.692}{2\pi} = 23.82$ Hz.

Stator voltage to be applied, $= \left(\frac{V_s}{\omega_s}\right)_{rated} \times 149.692 = 110.04$ V

RMS value

For sinusoid PWM,

peak value of fundamental phase voltage $= m \frac{V_{dc}}{2}$

$V_{dc} = 600$ V

$V_{s,peak} = 110.04\sqrt{2} = 155.618$ V

$\Rightarrow 155.618 = m \times \frac{600}{2}$

$\Rightarrow m = 0.5187$

modulation index.

27-11-2021

Q) The equivalent circuit parameter (per phase values) of a 3-phase, 440 V, 50 Hz, 4-pole, 1440 RPM star connected induction motor driven by a 3-phase voltage source inverter (VSI) is given below.

$R_s = 0.2\,\Omega$, $R_r = 0.4\,\Omega$.

Stator leakage reactance, $X_s = 2\,\Omega$

Rotor leakage reactance, $X_r = 2\,\Omega$

Magnetising reactance, $X_m = 40\,\Omega$

(All reactances at 50 Hz)

Resistance representing core loss $= 200\,\Omega$.

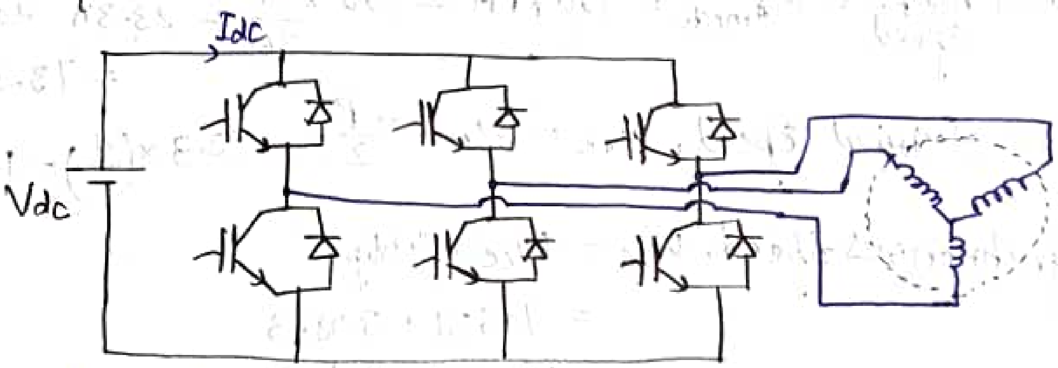
If the mechanical loss is ~~now~~ 100 W, evaluated the following at rated speed:

(a) shaft torque of motor.

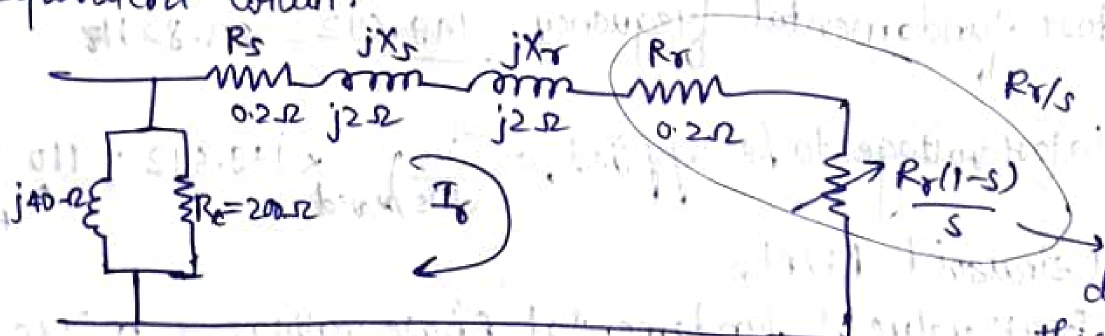
(b) efficiency of the motor.

(c) DC voltage requirements of the inverter if it is operated in square mode.

Soln:



Equivalent circuit:



→ Power developed in this resistor is mechanical power

$$\text{Synchronous speed} = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500\,\text{RPM}$$

$$\text{Slip} = \frac{1500 - 1440}{1500} = 0.04$$

Rotor current, $I_r = \dfrac{440/\sqrt{3}}{\sqrt{\left(\frac{R_r}{s}+R_s\right)^2 + (X_s+X_r)^2}} = \dfrac{254}{\sqrt{10.2^2+4^2}} = 23.183\,A.$

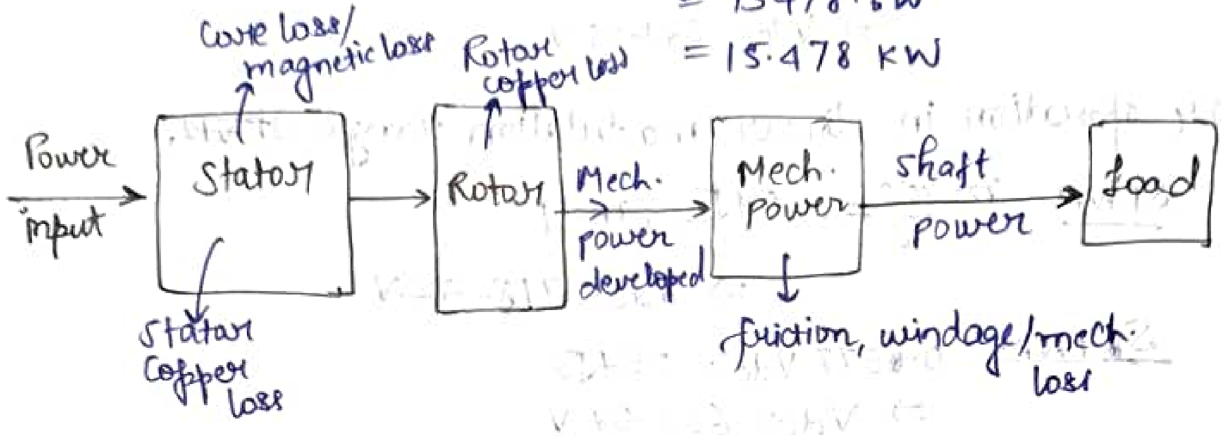
Mechanical power developed $= 3\, I_r^2 \times R_r \dfrac{(1-s)}{s}$

3 ↳ for all 3-phases

$= 3\,(23.183)^2\, \dfrac{0.4\,(1-0.04)}{0.04}$

$= 15478.6\,W$

$= 15.478\,kW$



Shaft power $= 15478.6 - \underset{\text{Mechanical loss}}{100} = 15378.6\,W$

Shaft Torque $= \dfrac{\text{Shaft power}}{\text{Mechanical speed}} = \dfrac{15378.6}{(?)}$

Mechanical speed $= 1440$ RPM

$= 1440 \times \dfrac{2\pi}{60}$

$= 48\pi$ rad/sec.

$\therefore$ Shaft torque $= \dfrac{15378.6}{48\pi} = 101.982\,N\text{-}m$

Efficiency $= \dfrac{\text{Output power}}{\text{Input power}} = \dfrac{\text{Output Power}}{\text{Output Power + Losses}}$

$= \dfrac{\text{Output power}}{(\text{O/p power + mech. losses + rotor copper loss + core loss + stator copper loss})}$

(P) Total active power

total 3 phases

core loss $= \dfrac{3 \times 254^2}{200}$

$= 967.74\,W$

Total copper loss $= 3 I_r^2 (R_r + R_s) = 3 (23.183)^2 (0.2 + 0.4)$
$= 967.413 \text{ W}$

$$\text{Efficiency} = \frac{15378.6}{15378.6 + 967.74 + 967.413 + 100} = 0.8831$$
$= 88.31\%$

Square wave mode operation :

peak fundamental voltage $= \frac{4 V_{dc}/2}{\pi} = 254\sqrt{2}$

$\Rightarrow V_{dc} = 564.25 \text{ V}$

For operation in linear modulation range ~~SPWM~~,

SPWM $\quad m \frac{V_{dc}}{2} = 254\sqrt{2}, \; m = 1$

$\Rightarrow V_{dc} = 718.42 \text{ V}$

SVPWM $\quad 0.577 V_{dc} = 254\sqrt{2}$
$\Rightarrow V_{dc} = 622.54 \text{ V}.$

Apparent power, $S = \sqrt{P^2 + Q^2}$

Active power, $P = \sqrt{3} V I \cos\phi$

Reactive power, $Q = \sqrt{3} I \sin\phi$

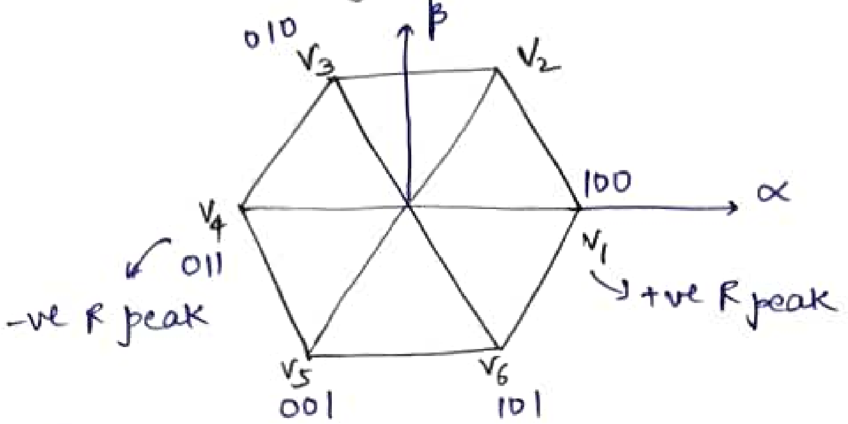
$$Q = \left(\frac{V_s^2}{X_m} + I_r^2 (X_s + X_r)\right) \times 3$$

Power factor $= \frac{P}{S}$

$\boxed{1 \text{ HP} = 746 \text{ W}}$

→ Inverter rating is based on apparent power (VA rating).
→ Reactive power is not supplied by DC source.
→ Inverter switching takes care of reactive power. (circulating inside circuit)
→ $V_{dc} \times I_{dc}$ → Total active power.
→ Active power includes all losses also.
→ Depending on active-reactive current, switch rating can be determined.

Q) What is the magnitude of reference space vector?



Sol: When reference vector coincides with α-axis, V_α is the magnitude of reference vector.

$$V_\alpha = \frac{3}{2} V_a.$$

#	111	011	001	000
	V_7	V_4	V_5	V_0

$V_7 \to T_0/2$, $V_0 \to T_0/2$

$V_5 \to T_2 = \dfrac{V_{ref}\cdot \sin\theta}{V_{DC}\cdot \sin 60^\circ}$

$V_4 \to$

$$T_1 = \left(\frac{V_{ref}\ \sin(60^\circ-\theta)}{V_{DC}\ \sin(60^\circ)}\right) T_s$$

$$T_0 = T_s - (T_1 + T_2), \quad T_s = 1/f_s.$$