EE240: Power Engineering LAB

Inverters

Instructor

Prof. B. G. Fernandes

19/3/2021, Friday

Recap

For star connection:

$$I_{L(Y)} = I_{ph} = \frac{V_{ph}}{Z_{ph}} = \frac{V_L}{\sqrt{3}Z_{ph}}$$

$$T_e \propto V_{ph}^2 \qquad T_{e(Y)} \propto \left(\frac{V_L}{\sqrt{3}}\right)^2 = \frac{V_L^2}{3}$$

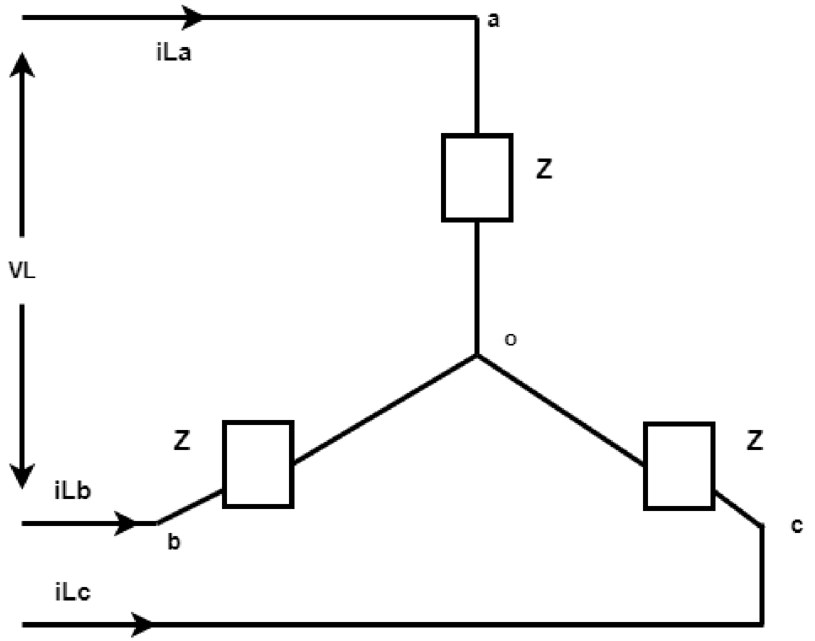
For delta connection:

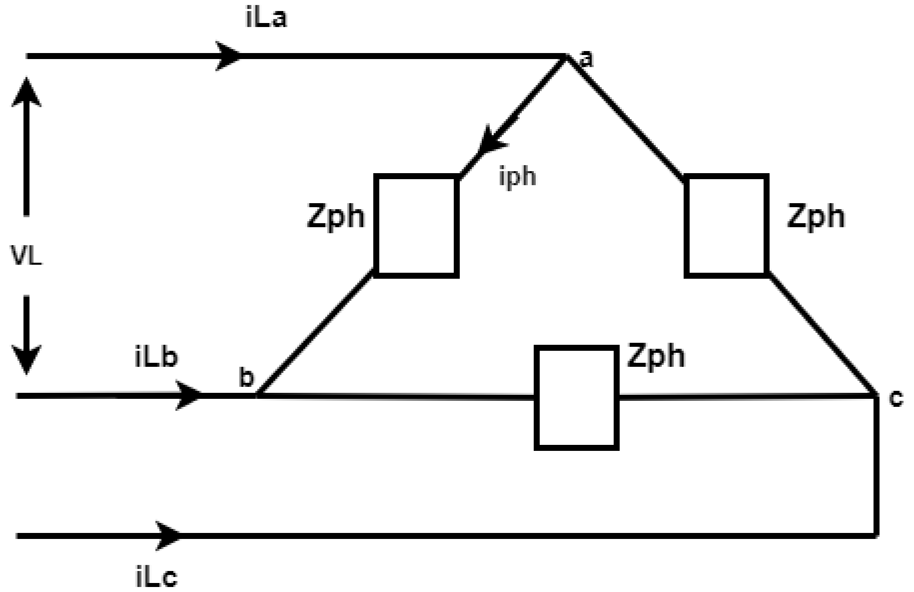
$$I_{ph} = \frac{V_{ph}}{Z_{ph}} = \frac{V_L}{Z_{ph}}$$

$$I_{L(\Delta)} = \sqrt{3}I_{ph} = \frac{\sqrt{3}V_L}{Z_{ph}}$$

$$T_{e(\Delta)} \propto V_{ph}^2 \quad \Rightarrow \quad T_{e(\Delta)} \propto V_L^2$$

$$\boxed{\therefore \frac{T_{e(Y)}}{T_{e(\Delta)}} = \frac{1}{3} \quad and \quad \frac{I_{L(Y)}}{I_{L(\Delta)}} = \frac{1}{3}}$$

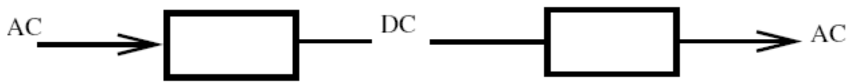




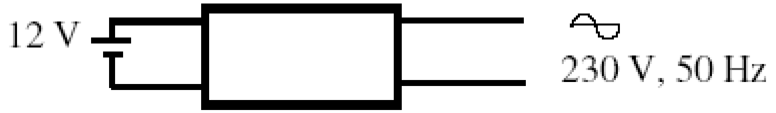
Inverters

DC – AC Converters : Inverters

Why there is a need?
Power is generated → AC
Voltage induced in the conductor rotating in a magnetic field is AC



U.P.S. → Input is 12V
Constant 'V' and constant 'F' supply is required.

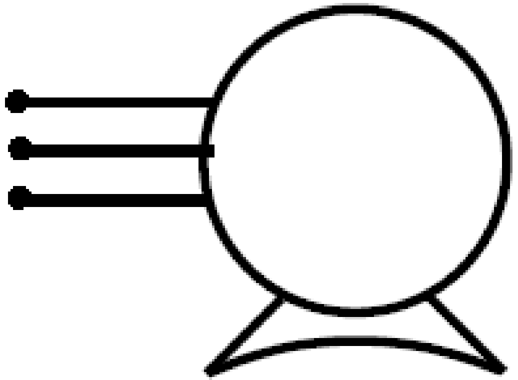


3-φ Induction Motor
Stator field is rotating at $N_s = 120\frac{\mathrm{F}}{\mathrm{P}}$

Rotor is stationary($N_r = 0$)

$$N_s - N_r = N_s$$

⇒ Current in rotor → Current in stator
⇒ Supply current is very high ($\simeq 6\, I_{rated}$)



Assume that $'T_L'$ is constant.

$\therefore$ T_L = developed torque $\approx constant = \frac{P_2}{2\pi\, N_s}$

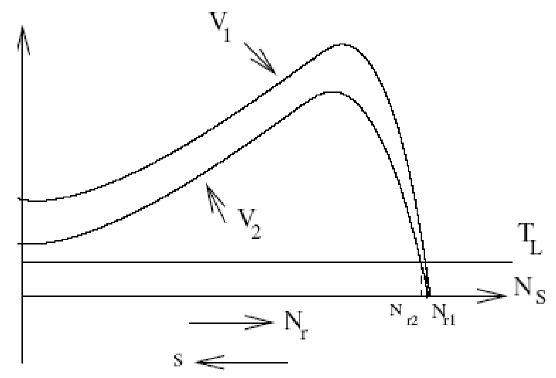
$\Rightarrow$ Air gap power input is constant

$\Rightarrow$ Input power is constant → almost independent of speed

$\Rightarrow$ In order to ↓ the speed, ↓ the applied voltage (F is constant)

$$T \propto V^2$$

$\Rightarrow$ speed from N_{r1} to N_{r2}



$\because$ 'F' is constant, N_s is constant.

N_r has to ↓ $\Rightarrow$ $\therefore$'s'↑

$\because$ P_2 is constant $\Rightarrow$ sP_2 has dissipated as heat.

$\Rightarrow T_e \propto P_2 \propto \frac{I^2 R}{s}$

$$\therefore I \propto \sqrt{s}$$

$\Rightarrow$ Stator core loss ↑

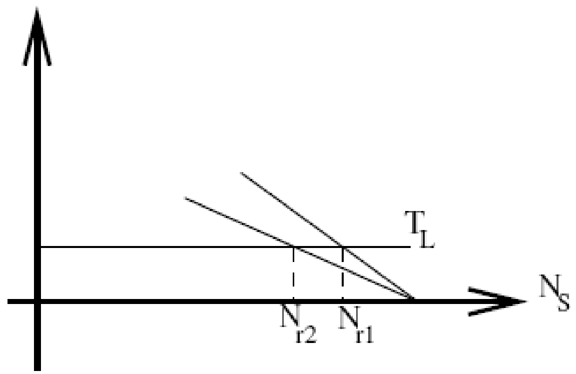
$\Rightarrow$ Heat ↑ and η ↓

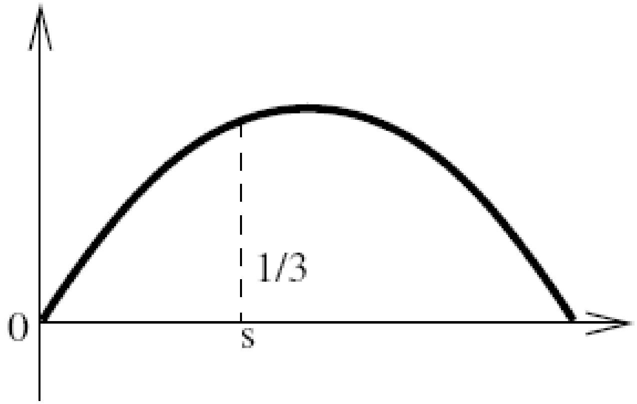
If $T_L \propto N_r^2$ → Fan type of load

$\propto (1-s)^2$

$$T_e \propto \frac{I^2 R}{s}$$

$$\therefore I = (1-s)s^{0.5}$$





If the process requires wide variation in speed

$\Rightarrow$ N_s should be changed especially for T_L = constant

(In principle, this may not be required for fan type of loads)

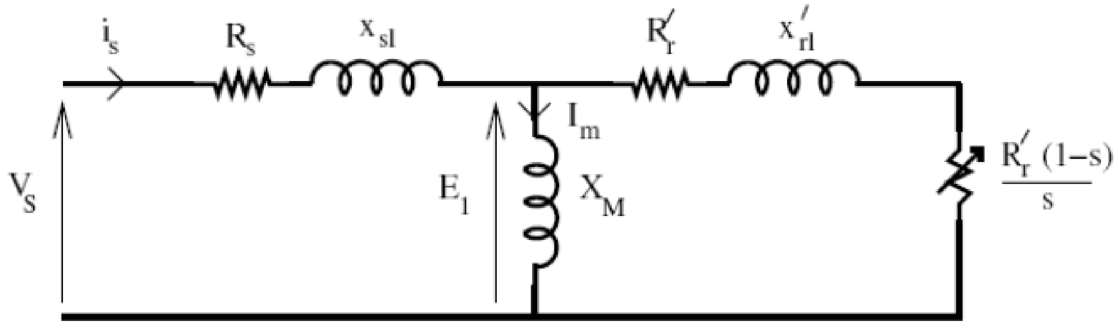
$\Rightarrow$ Even for fan type of load, it is preferred.

$\Rightarrow$ Frequency of stator should be changed.

Relationship between Output Voltage and Frequency

$$T \propto F_{SR}F_r \sin\angle(F_{SR}\ and\ F_r)$$
$$\propto \phi I'_r$$
$$\propto I_m I'_r$$

$$I_m = \frac{E_1}{2\pi f L_m}$$

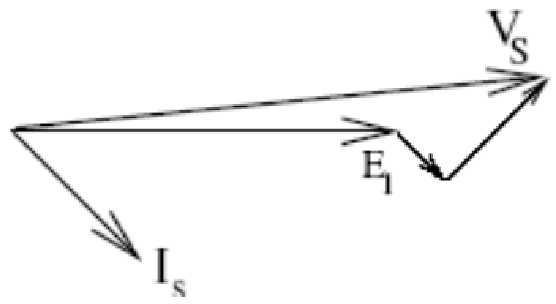


Equivalent circuit of Induction motor

$Generally, R_s and\ x_{sl}\ are\ small$

Also at relatively high frequency i.e at 25-50 Hz

$$|E_1| \simeq |V_s| \Longrightarrow I_m = \frac{V_s}{2\pi f L_m}$$

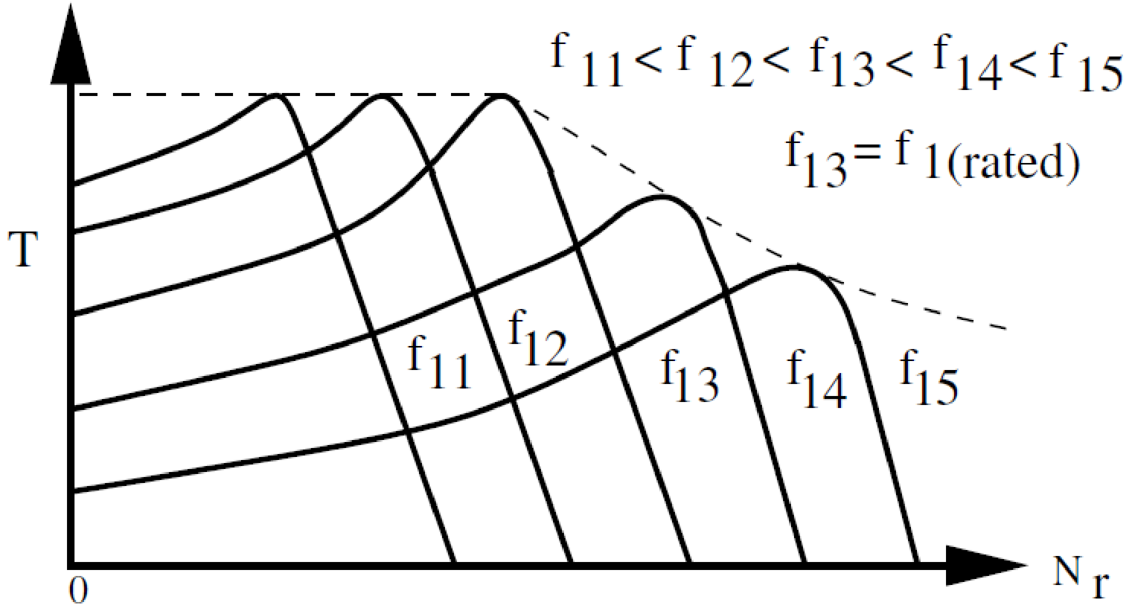


Case 1 : V_s *is constant and* $F \downarrow \Rightarrow N_s$ *decreases*

$|I_m| \uparrow \Rightarrow \phi$ *tends to* $\uparrow$

All magnetic circuits operated at the knee point of magnetising curve.
If magnetising AT ↑ , core gets saturated.
⇒ Input current becomes peaky and core losses ↑

Case 2: V_s *is constant and* $F \uparrow \Rightarrow N_s$ *increases*



$$\Rightarrow I_m = \frac{V_s}{2\pi f L_m} \downarrow \Rightarrow \phi \downarrow$$

$\Rightarrow If\ V_S = V_{rated}$ *and* $F \uparrow$ *above* F_{rated}

$\Rightarrow N_S$ *and* $\therefore N_r$ *also* $\uparrow$ *above rated*

$\Rightarrow |\phi| \downarrow$

$\Rightarrow$ *Similar to the field weakening mode of DC motor*
(V_0 *constant and* $I_r \downarrow$)

⇒ Possible mode of operation

⇒ **DC/AC converter should have the feature that** $|V_S| = V_{rated}$
and F should be able to increase

Case 3: *Variable voltage and variable frequency* $\Rightarrow$ N_s *can increase* and decrease

$$\Rightarrow I_m = \frac{V_s}{2\pi f L_m} \ constant \quad \Rightarrow \quad \phi \ is \ constant (\text{in speed range 0 to } N_{rated})$$

$$\Rightarrow T_{max} \ is \ constant \ \because \ \phi \ is \ constant$$

$$\Rightarrow fast \ variation \ in \ acceleration \ can \ be \ achieved \ by \ stator \ current \ control$$

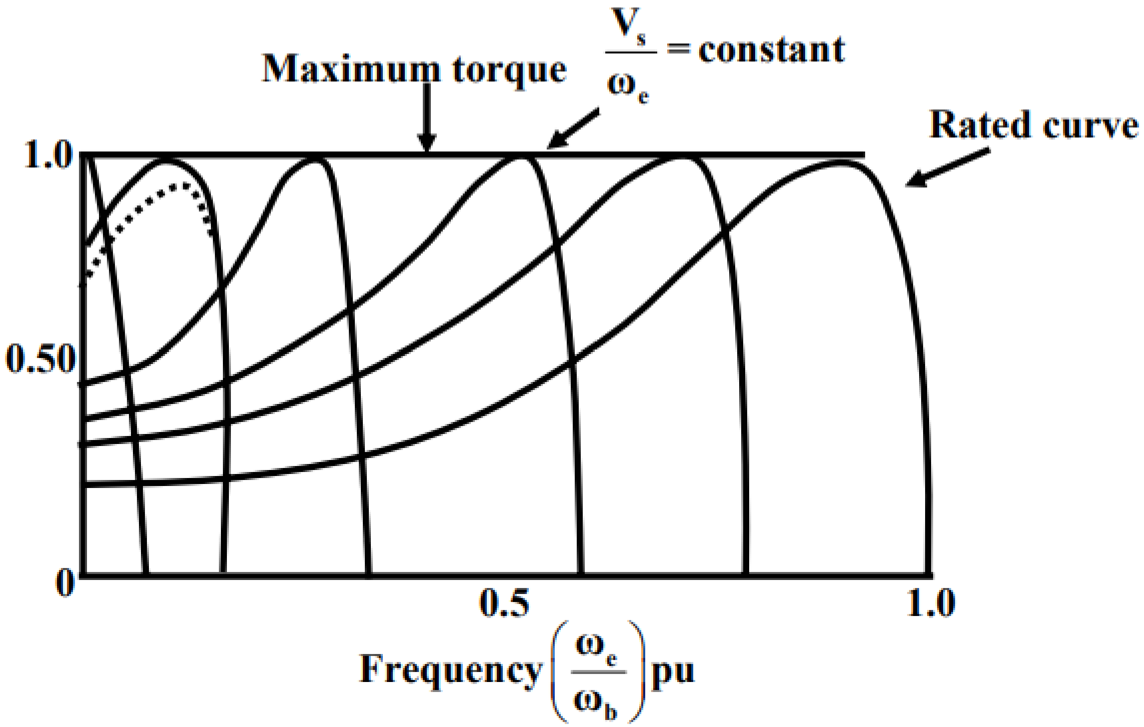
$$\Rightarrow high \ \frac{T}{I} \ ratio$$

$\Rightarrow$ *variable volatge and variable freqeunct till* V_{rated} *and constant V and variable frequency above rated*

Therefore DC-AC converter should have feature of "Variable voltage and Variable frequency"

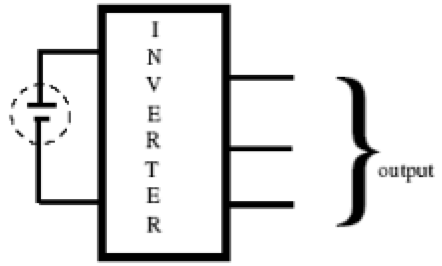
The source should have following features:

(a) Output voltage should vary with frequency
(b) Voltage magnitude should remain constant for rise in frequency >50 Hz.

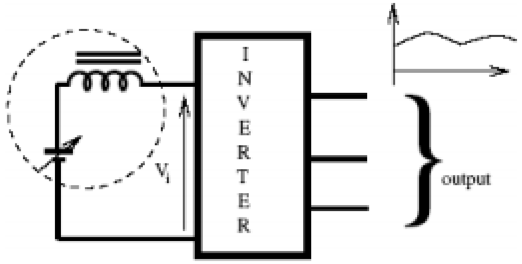


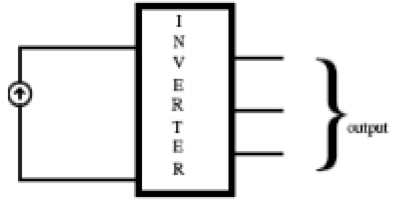
Types of Inverters

Voltage Source Converter (VSC): If the input to the inverter is a voltage source
⇒ Battery or large 'C' (input impedance 'Z' ⟶ 0)
⇒ DC-AC ⟶ **Voltage Source Inverter (VSI)**
⇒ ′I′ can reverse but not ′V′
⇒ Anti –parallel diodes are essential



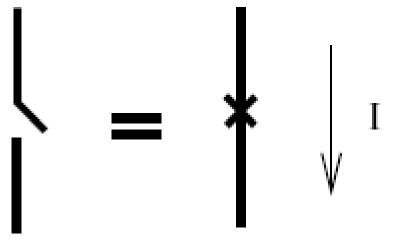
Current Source Inverter (CSI):
⇒ ′V′ can reverse but not ′I′
⇒ Input L is very high, hence no possibility of shoot through fault.
⇒ Circuit is rugged and reliable
⇒ Device having anti-parallel diode can not be used.





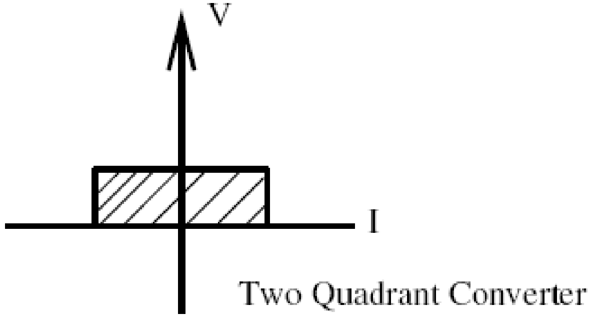
Single Phase Voltage Source Inverter

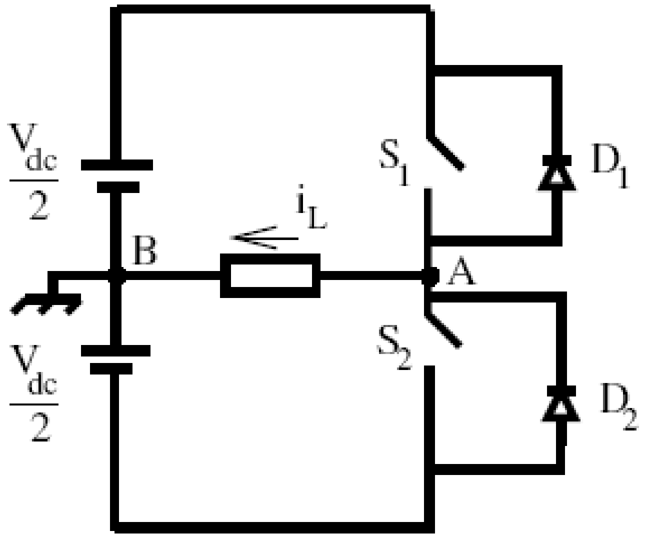
<u>Circuit configuration of V.S.I. :</u>



Basic Block : Half bridge

Since ‘i’ can reverse, switches should be able to carry bi-directional ‘I’
⇒ Connect a diode in anti-parallel fashion

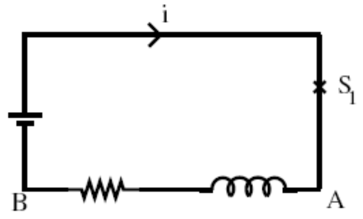




<u>In V.S.I. :</u>
Switching signal for S_1 & S_2 (same leg) are always <u>complimentary</u> (Ideal condition).

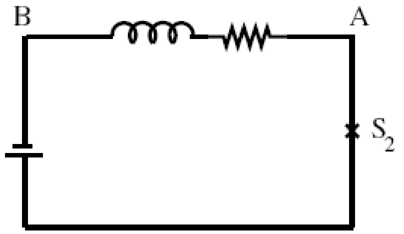
Case 1: R-L load
<u>S_1 ON:</u>
For $\frac{T}{2}$ duration, $V_{AB} = \frac{V_{DC}}{2}$

Load ⇒ R-L $\qquad i = \frac{V}{R}\left(1 - e^{-\frac{t}{T}}\right)$



$\underline{S_2 \text{ ON and } S_1 \text{ OFF :}}$

For $V_{AB} = -\frac{V_{DC}}{2}$
'i' will decay and become negative.



Observations:

Time for which S_1/S_2 is ON will determine the frequency of 'V_0'.

$\Rightarrow$ If $\frac{T}{2} = 10ms$, F =50Hz

= 100ms, F =5Hz

At steady state:

P-Q : V applied to the load = +ve, i_L is –ve (I flowing from B to A)

$\Rightarrow$ 'D_1' is carrying 'I'

Q-R : 'V' and 'I' are +ve

$\Rightarrow$ 'S_1' is carrying 'I'

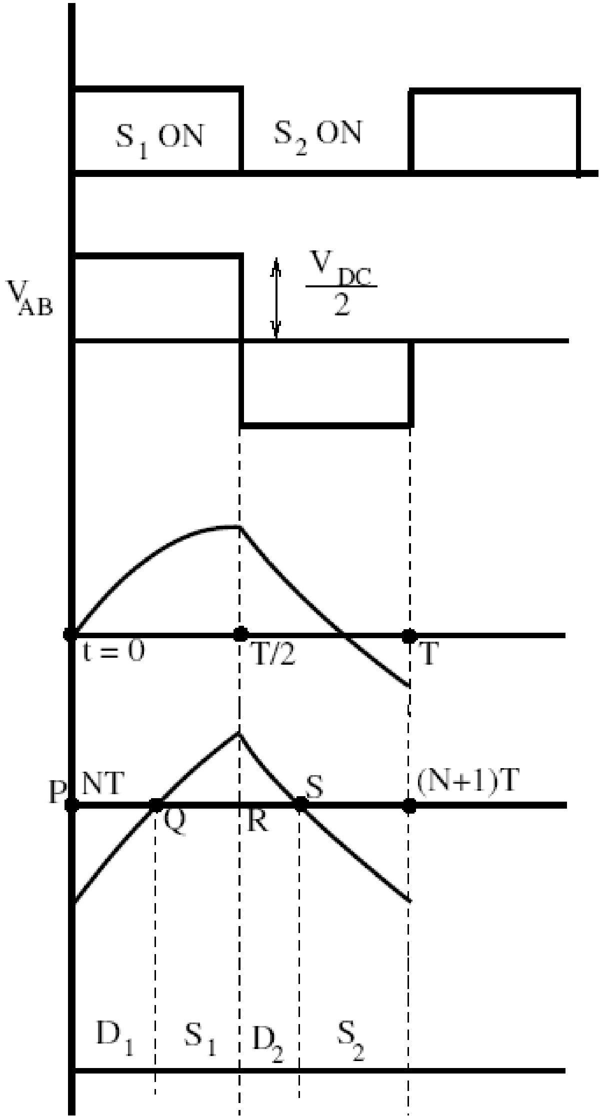
R-S : 'V' is –ve and 'i' is +ve

$\Rightarrow$ 'D_2' is carrying 'I'

S-T: 'V' and 'I' are –ve

$\Rightarrow$ 'S_2' is carrying 'I'

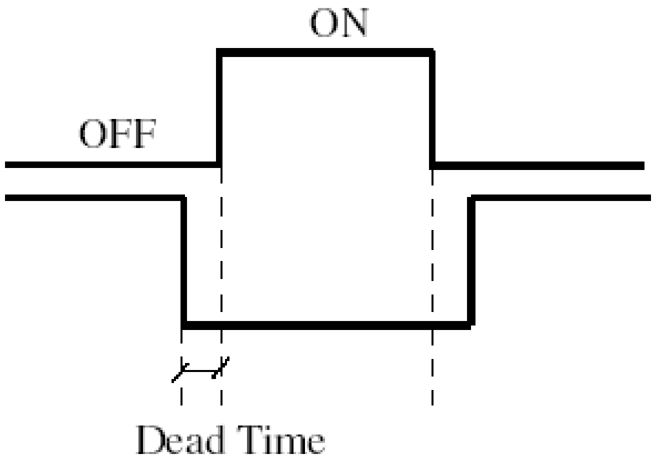
- If load is not purely resistive, switch should have a diode across it.

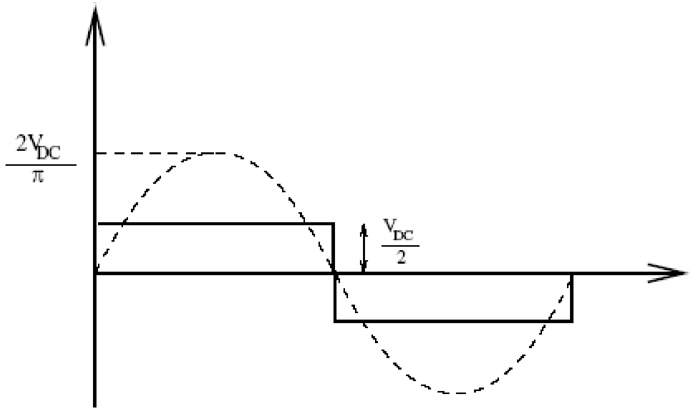


Dead Time:
To avoid shoot through across DC bus.

⇒ Input 'V' = V_{DC} Output $V = \frac{V_{DC}}{2}$

⇒ Has 3rd, 5th , 7th … all odd harmonics.
THD ≈ 48%

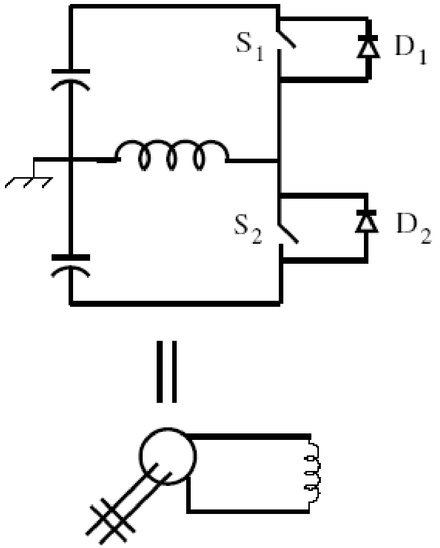


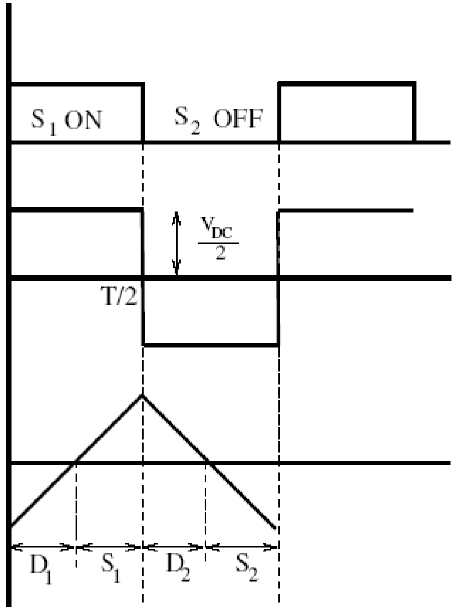


Case 2: Load = L

γ for D = γ for $S = \frac{\pi}{2}$ radians
Average power = 0
Input power = 0 (neglect loss)

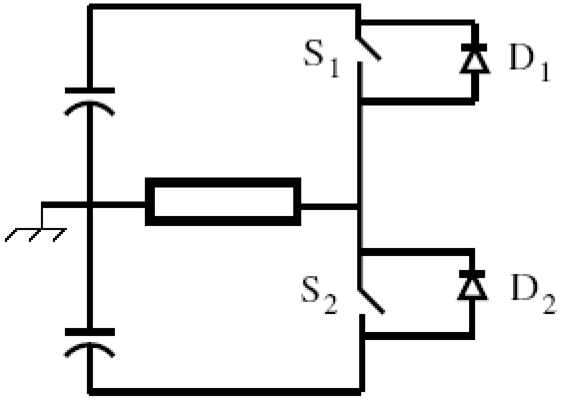
⇒ replace battery by 'C'
⇒ VSI can supply reactive power
⇒ active input = inverter losses

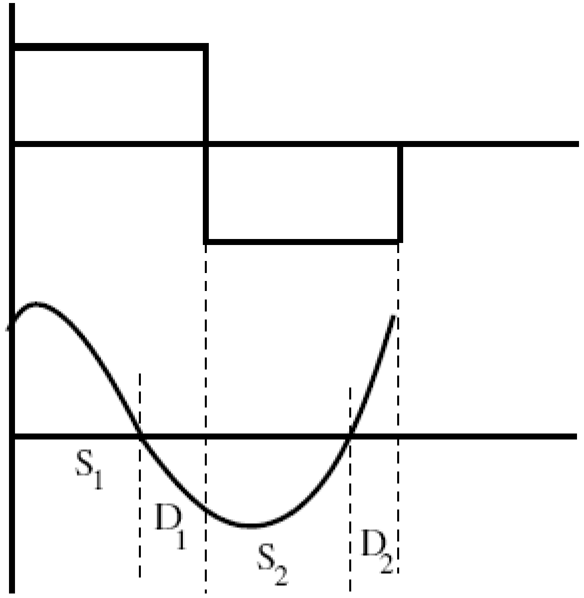




Case 2: Load = R-L-C

⇒ Series R-L-C with $w < w_r, X_c > X_L$
⇒ P.F. is leading
⇒ i_l is sinusoidal
⇒ 'i' through the device has become zero much before it is turned
⇒ Device is turned off of its own
⇒ Reason: Load 'I' is leading
⇒ Load commutation



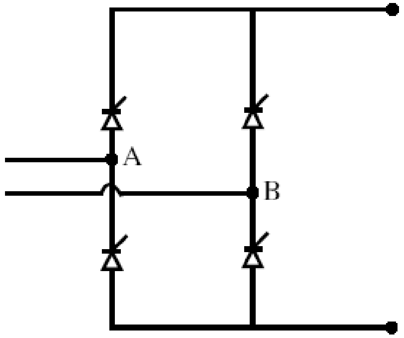


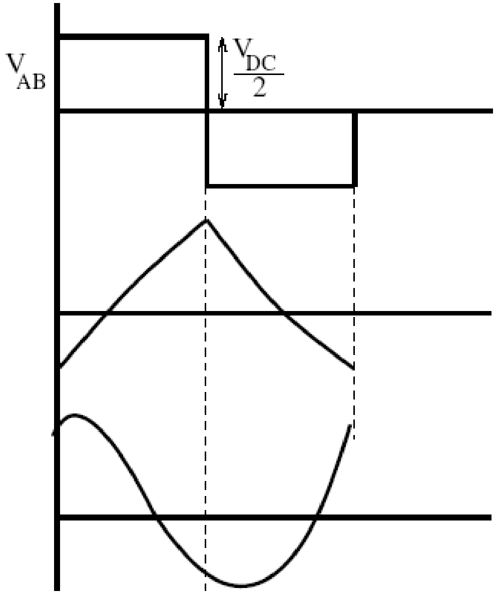
If all the switches are SCR's & Load is R-L

Input to DC : SCR cannot be turned OFF through gate

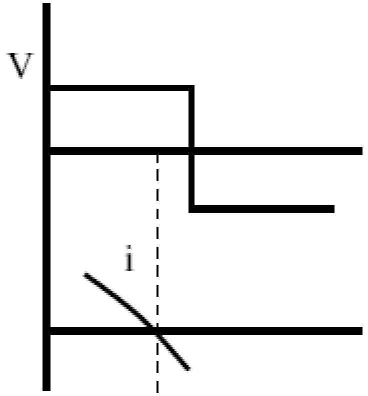
$$i_{device} < i_{holding}$$

Reverse voltage should be applied to turn it OFF
⇒ Separate L&C
⇒ Forcibly turned OFF
⇒ Forced commutation
⇒ Bulky and noisy
⇒ Inverter grade SCR's are required





If P.F. is leading:



'i' through the device = 0 & flows through the diode of its complimentary switch before the voltage is reversed.

⇒ SCR has turned OFF

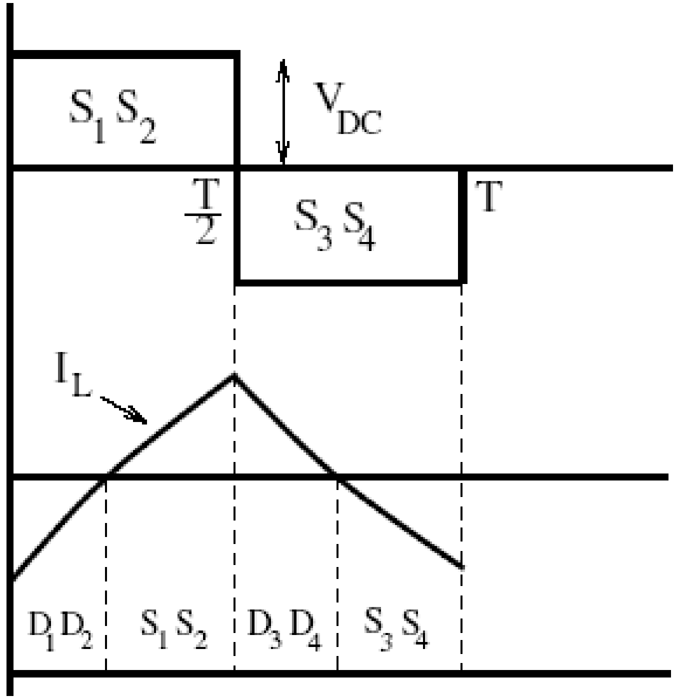
⇒ No external L-C circuit is required.

⇒ Inverter using SCR's feeding a leading P.F. load is quite attractive.

⇒ Inverter feeding over-excited synchronous motor

⇒ Large power

⇒ Load commutated inverter fed synchronous motor.

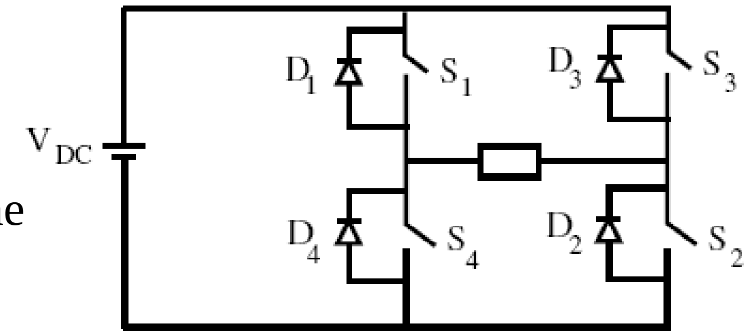


Limitations of Half Bridge Inverter:

Input = V_{DC}

Output = $\frac{V_{DC}}{2}$

⇒ One device is conducting at a time



Instead use a full bridge.

⇒ 2 devices are conducting at a time.

⇒ Centre point of DC link is not required.

Three Phase Inverters

Required output : 3φ AC
Phase displacement between S_1 & S_3 = 120°

S_1 ON : $V_{AO} = \frac{V_{DC}}{2}$

S_1 OFF : $V_{AO} = -\frac{V_{DC}}{2}$

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

From 0 to $\frac{2\pi}{3}$

$$V_{AO} = \frac{V_{DC}}{2} \qquad V_{BO} = -\frac{V_{DC}}{2} \qquad \therefore V_{AB} = V_{DC}$$

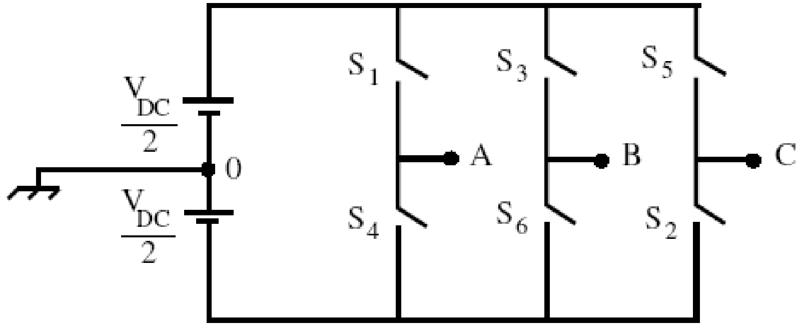
From $\frac{2\pi}{3}$ $to\ \pi$

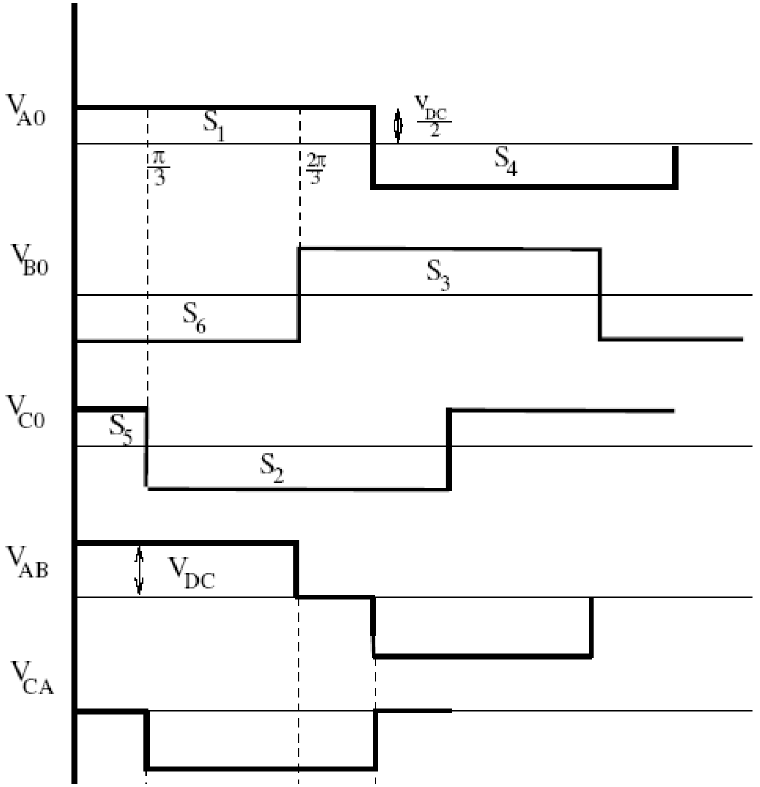
$V_{AO} = V_{BO} = \frac{V_{DC}}{2}$

$$\therefore V_{AO} = 0$$

Potential of A = Potential of B
⇒ Either +ve DC bus or –ve DC bus

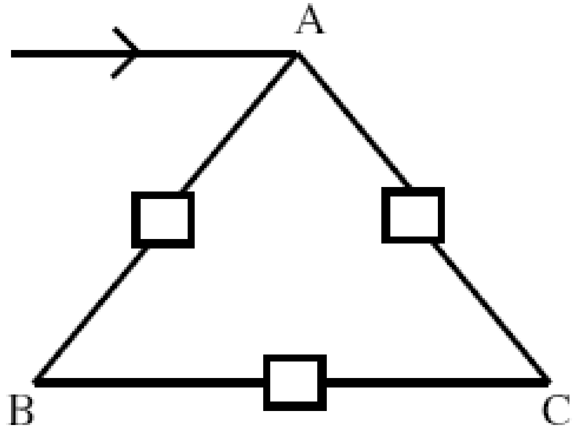
V_{CA}: $\quad 0 - \frac{\pi}{3} = 0 \qquad \frac{\pi}{3} - \pi = -V_{DC}$





Δ Connected Load

$$i_{AB} = \frac{V_{AB}}{Z} \qquad\qquad i_A = i_{AB} - i_{CA}$$



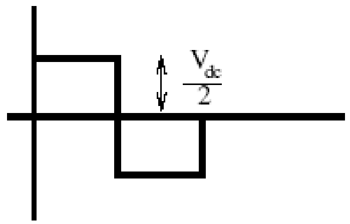
$\Rightarrow$ Observations:

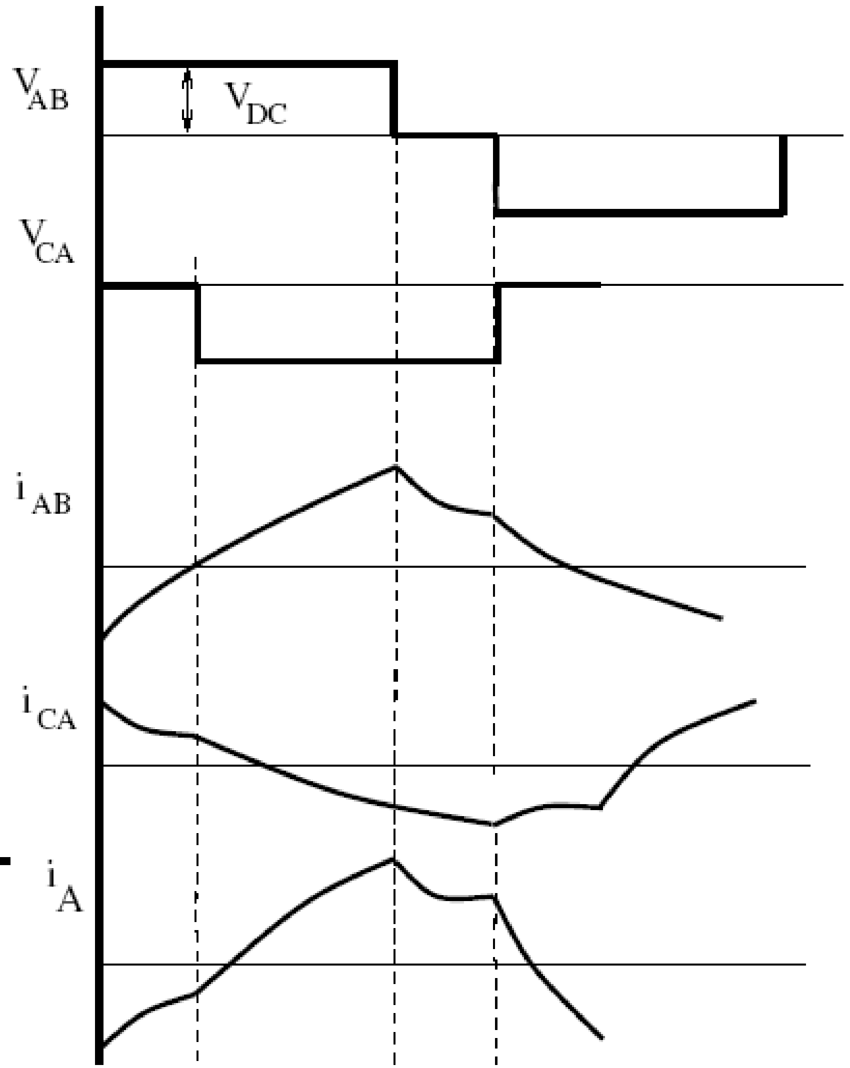
There are 6 steps/cycle in load current

$\Rightarrow$ Six step inverter

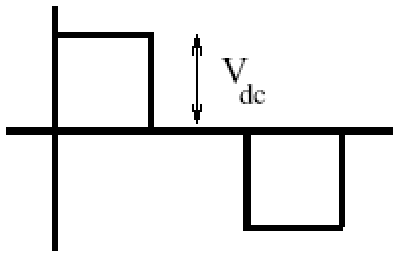
$\Rightarrow$ V_{AO}, V_{BO}, V_{CO} $\rightarrow$ pole voltage

V_{AB}, V_{BC}, V_{CA} $\rightarrow$ predominant harmonic is 5^{th}, 7^{th}, … $= (6N \pm 1)$





$$V_{AB} = \frac{2\sqrt{3}}{\pi} V_{dc} \left\{ \sin wt - \frac{1}{5}\sin 5wt - \frac{1}{7}\sin 7wt - \ldots \right\}$$



R.M.S. of L-L is $\sqrt{\frac{2}{3}} V_{DC} = 0.816\, V_{DC}$ Fundamental $= \frac{\sqrt{6}}{\pi}\, V_{DC} = 0.78\, V_{DC}$

⇒ $Y\ Connected\ Load$

⇒ $180°\ mode\ of\ conduction\ (square\ wave\ operation)$

⇒ VSI ⟶ switching signals for the leg of the inverter are complimentary

⇒ If status of S_A, S_B, S_C are known, the status of the other switches will also be known.

⇒ 8 possible combinations {0,0,0} – {1,1,1}

⇒ {0,0,0} ⟶ S_A, S_B, S_C are OFF

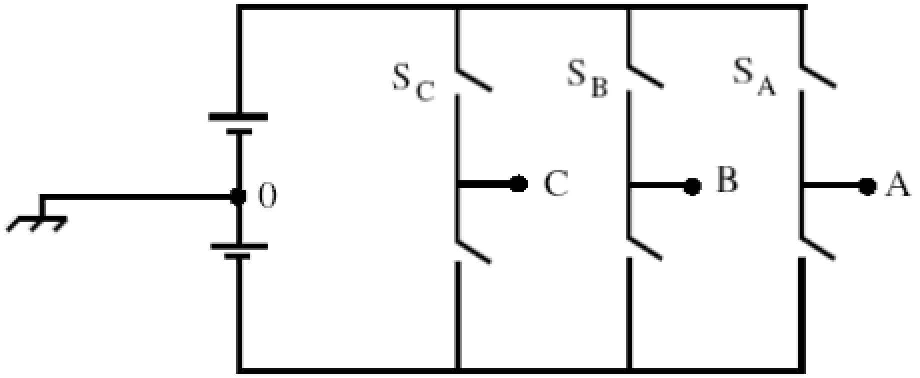
⟶ Points A,B and C are connected to –ve DC bus

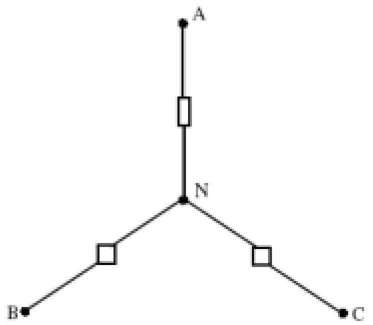
⟶ I_L is freewheeling through –ve DC bus

$$\Rightarrow V_{AB} = V_{BC} = V_{CA} = 0$$

⇒ True for {1,1,1}

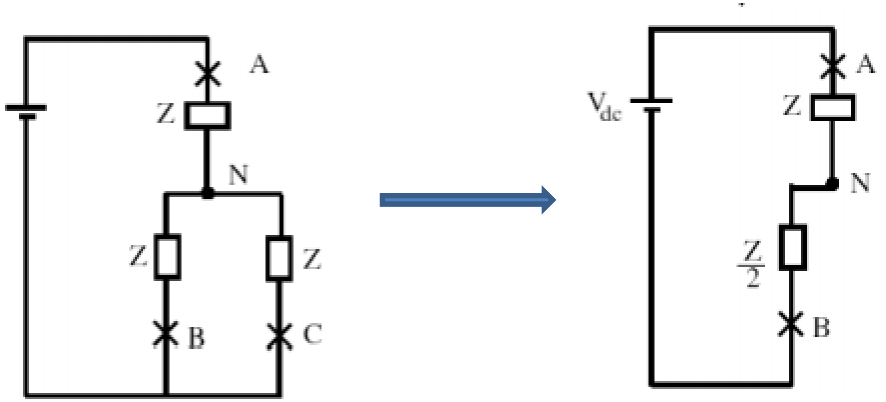
⇒ known as "0 Voltage Vectors"





$S_A \longrightarrow 1, S_B \longrightarrow 0, S_C \longrightarrow 0$

$$\therefore V_{AN} = \frac{2}{3}V_{DC} \qquad V_{BN} = V_{CN} = -\frac{1}{3}V_{DC}$$

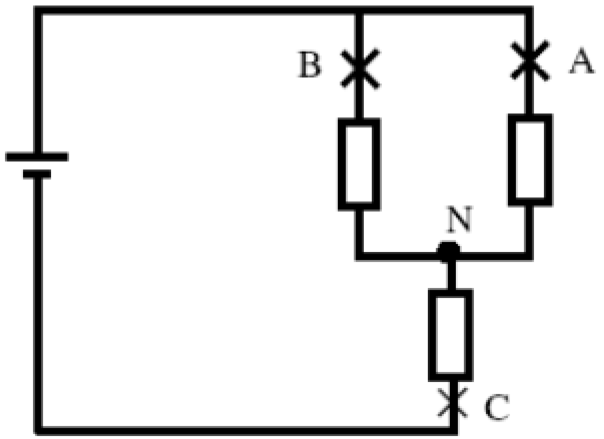


$S_A \longrightarrow 0, S_B \longrightarrow 1, S_C \longrightarrow 0$

$$\therefore V_{BN} = \frac{2}{3}V_{DC} \qquad V_{AN} = V_{CN} = -\frac{1}{3}V_{DC}$$

$S_A \longrightarrow 1, S_B \longrightarrow 1, S_C \longrightarrow 0$

$$\therefore V_{CN} = -\frac{2}{3}V_{DC} \qquad V_{BN} = V_{AN} = \frac{1}{3}V_{DC}$$



$$0 - \frac{\pi}{3}:\ S_A = 1, S_C = 1, S_B = 0$$

$$\therefore\ V_{AN} = \frac{1}{3} V_{DC}$$

$$\frac{\pi}{3} - \frac{2\pi}{3}:\ S_A = 1, S_C = 0, S_B = 0$$

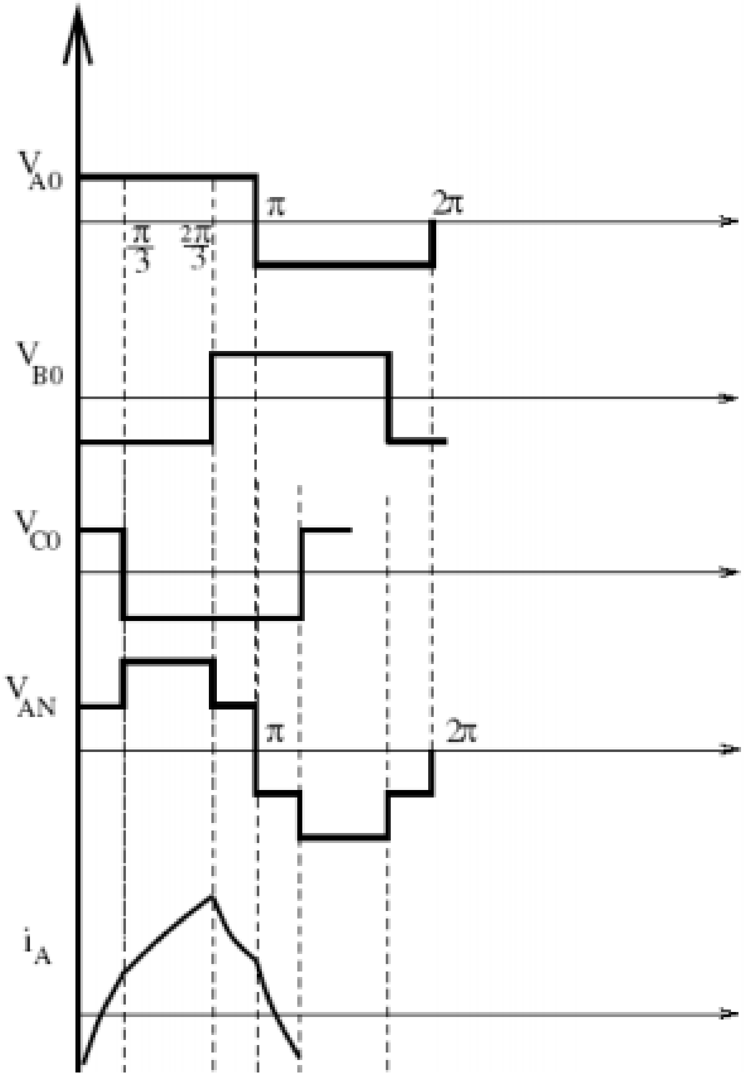
$$\therefore\ V_{AN} = \frac{2}{3} V_{DC}$$

$$\frac{2\pi}{3} - \pi:\ S_A = 1, S_C = 0, S_B = 1$$

$$\therefore\ V_{AN} = \frac{1}{3} V_{DC}$$

$$\Rightarrow\ V_{AN} \longrightarrow 6\ steps/cycle$$

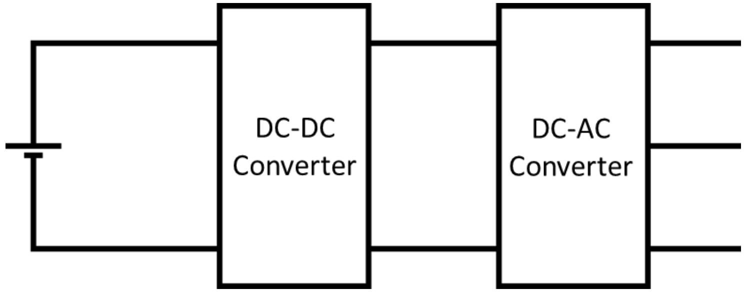
$$\longrightarrow 6\ step\ inverter$$



DC-AC Conversion: Varying the Voltage

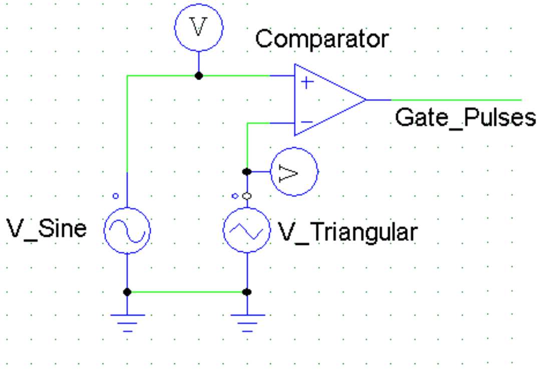
- Frequency variation can be obtained by changing the value of ‘T’, the time period
- How to vary the voltage value?

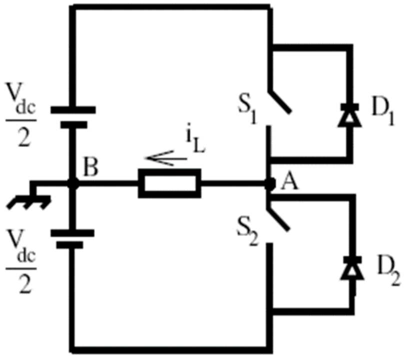
- A straight forward approach: Vary the input DC supply of the inverter (DC-AC Convertor) using a DC-DC converter
- In this method, the efficiency of the system is $\eta_{dc-dc} \times \eta_{dc-ac}$
- Also, the device count is high → low reliability
- Here, the switches are allowed to conduct for 180° (50% of T)

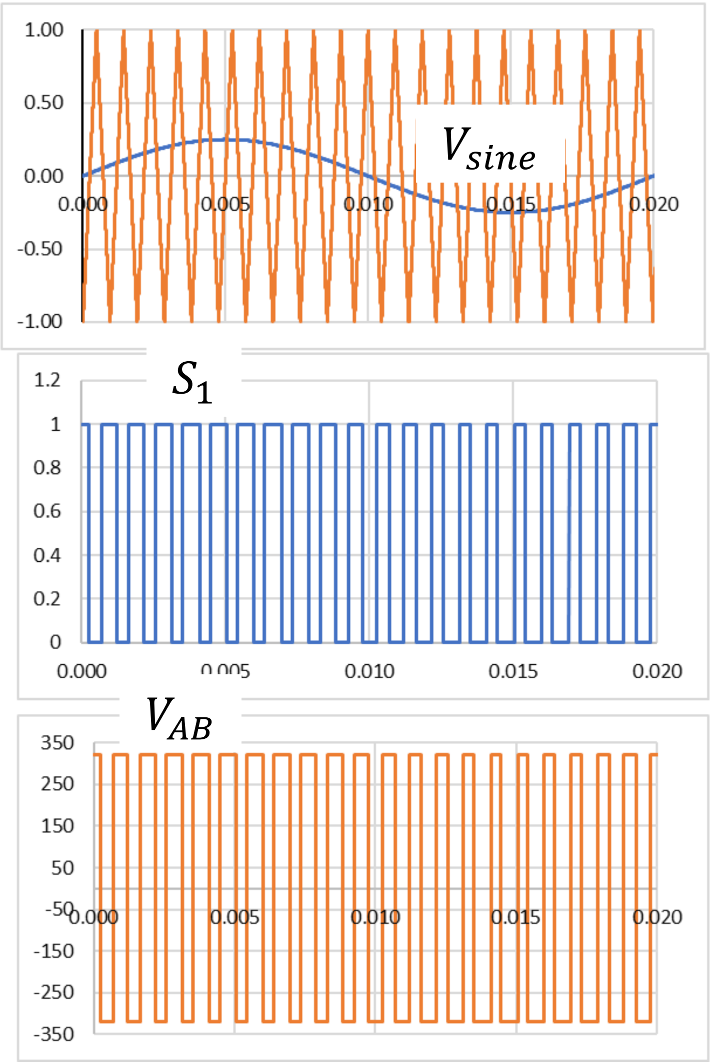


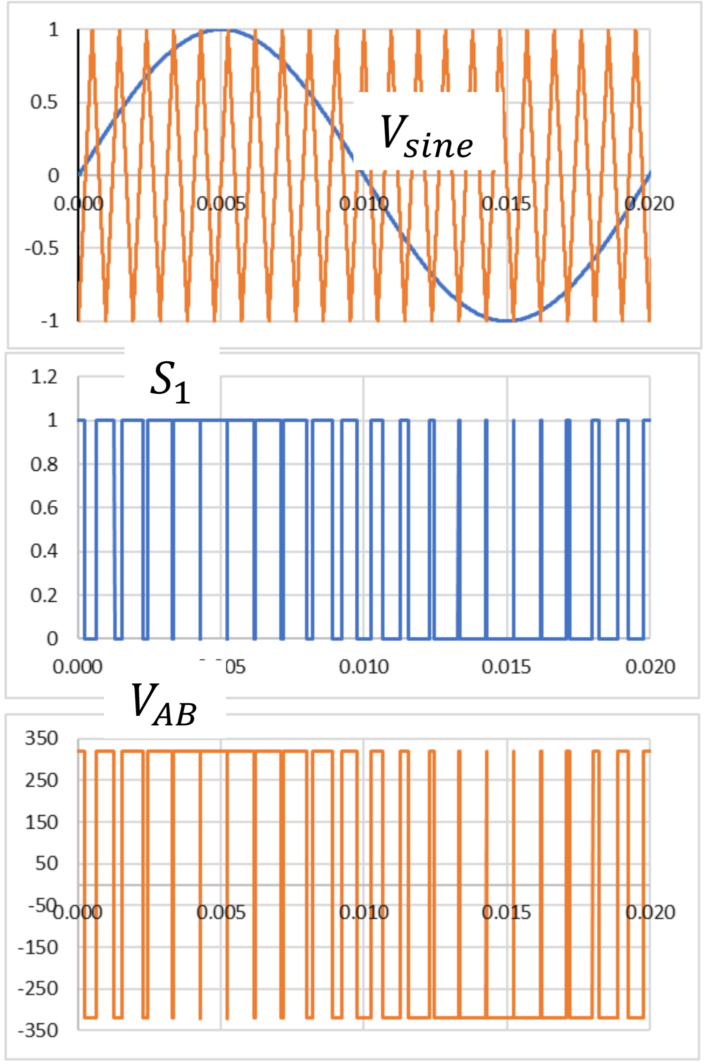
- Instead, keep the DC input to the inverter fixed and vary the duty of the inverter switches
- This scheme is know as Pulse Width Modulation (PWM)

Sine Pulse Width Modulation: Switch Gate Pulse Generation







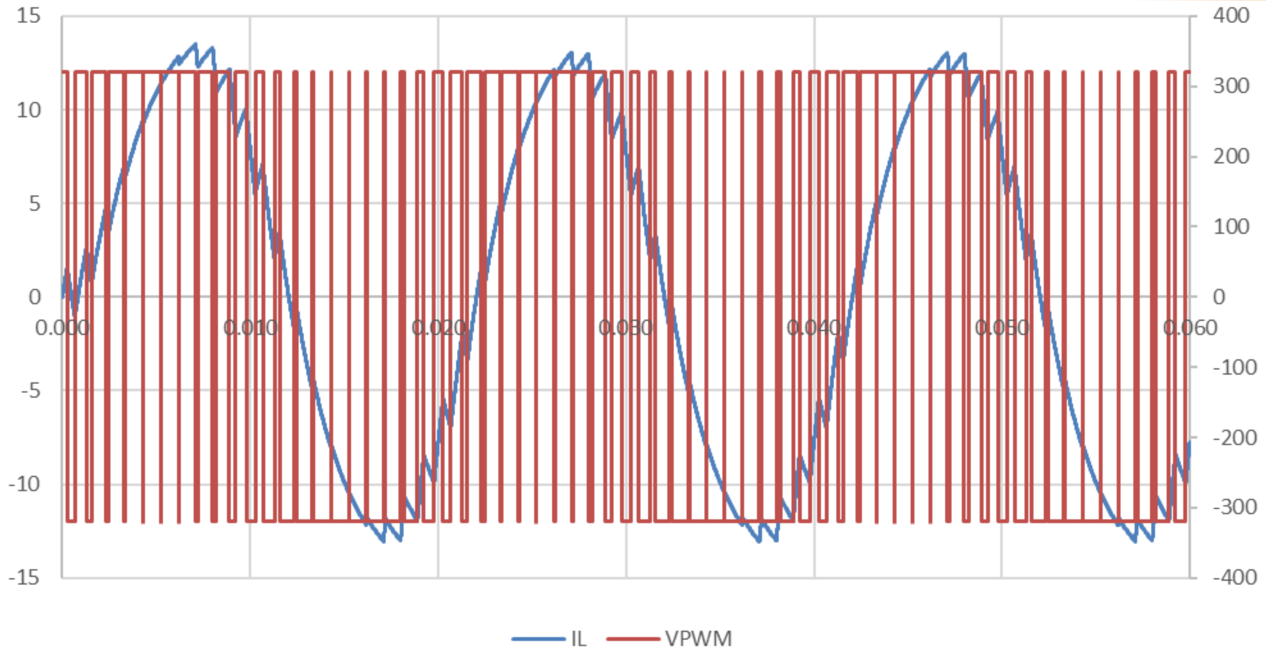


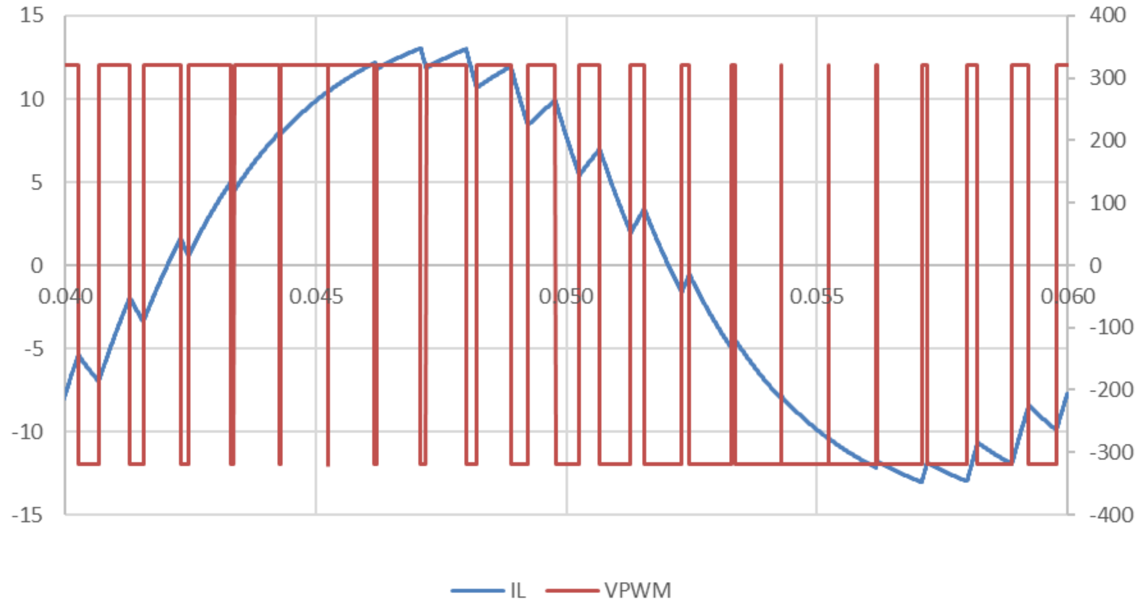
- A sinusoidal voltage (50 Hz) is compared with a triangular wave (High frequency)
- The obtained output is given as gate pulses to the corresponding switch

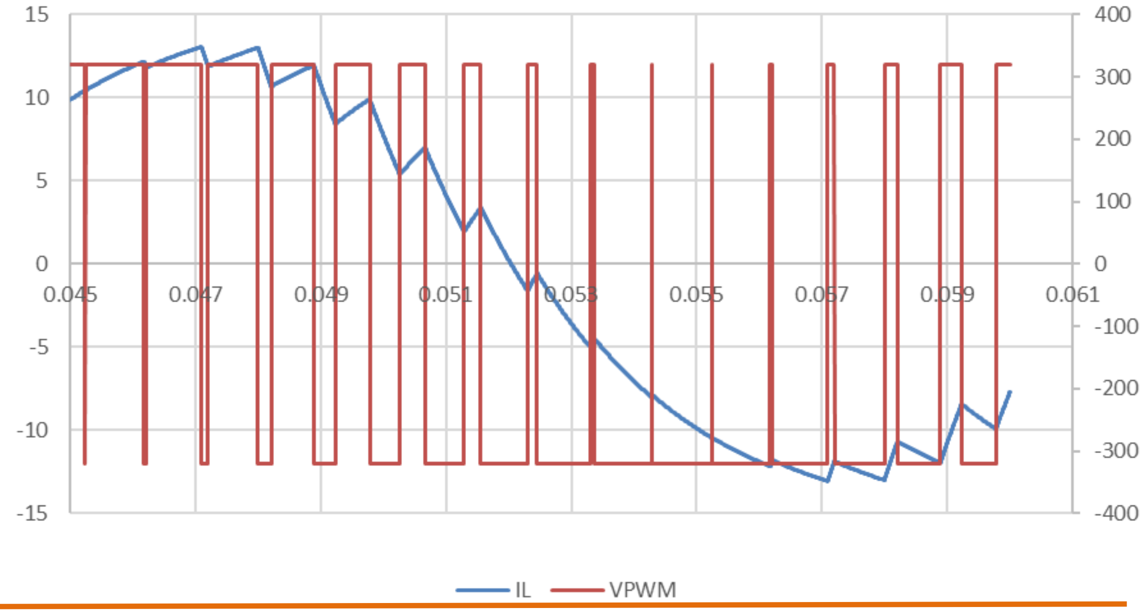
Sine Pulse Width Modulation

VSI feeding an $R - L$ load,
R = 10 ohm, L = 50 mH,
f_s = 1050 Hz

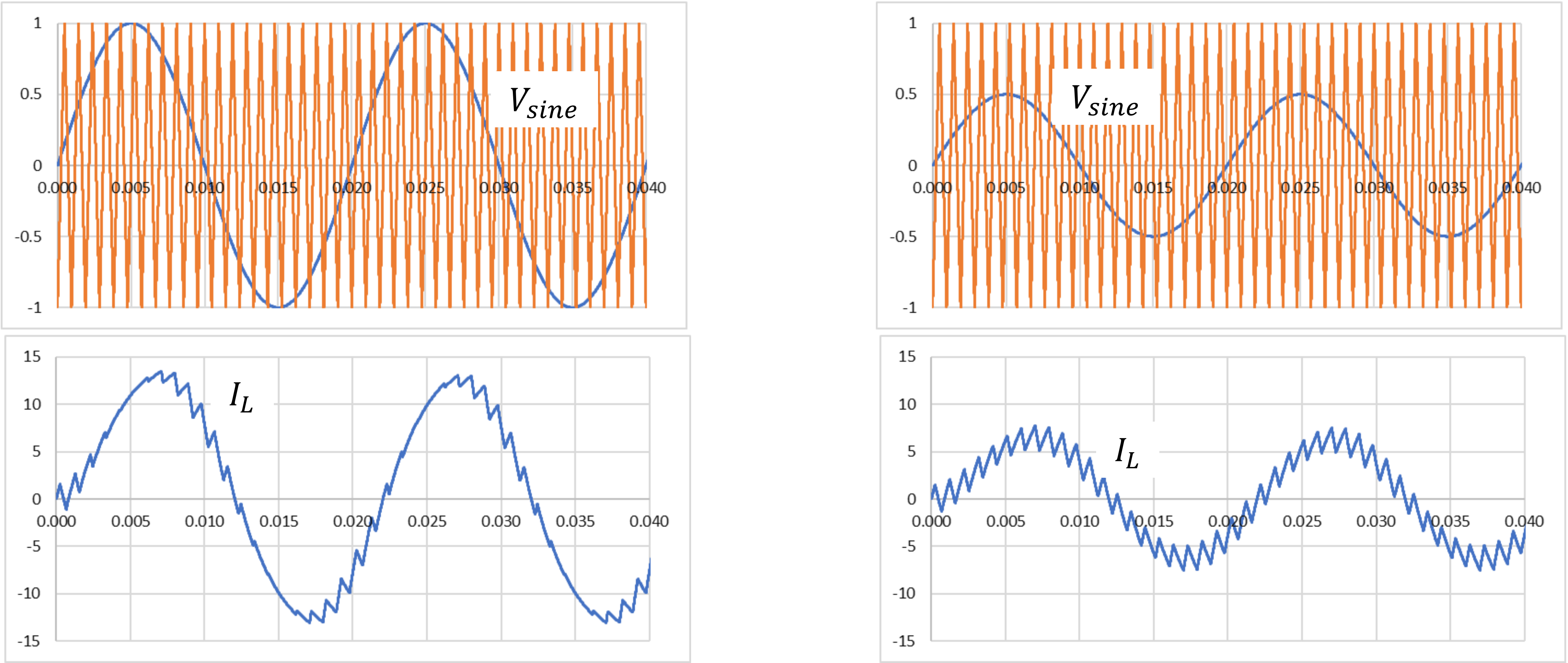
➔ It is possible to obtain sinusoidal current waveform



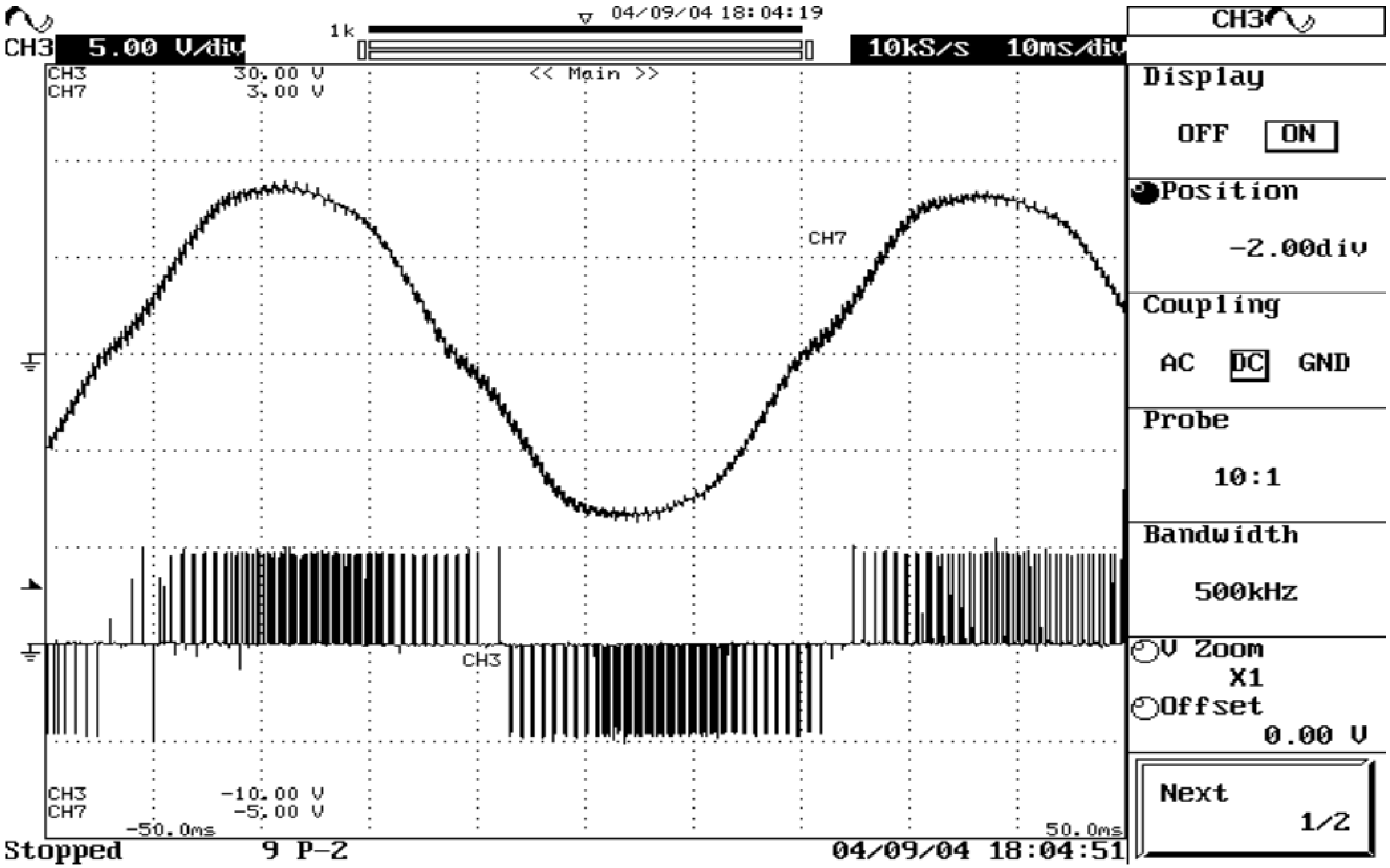




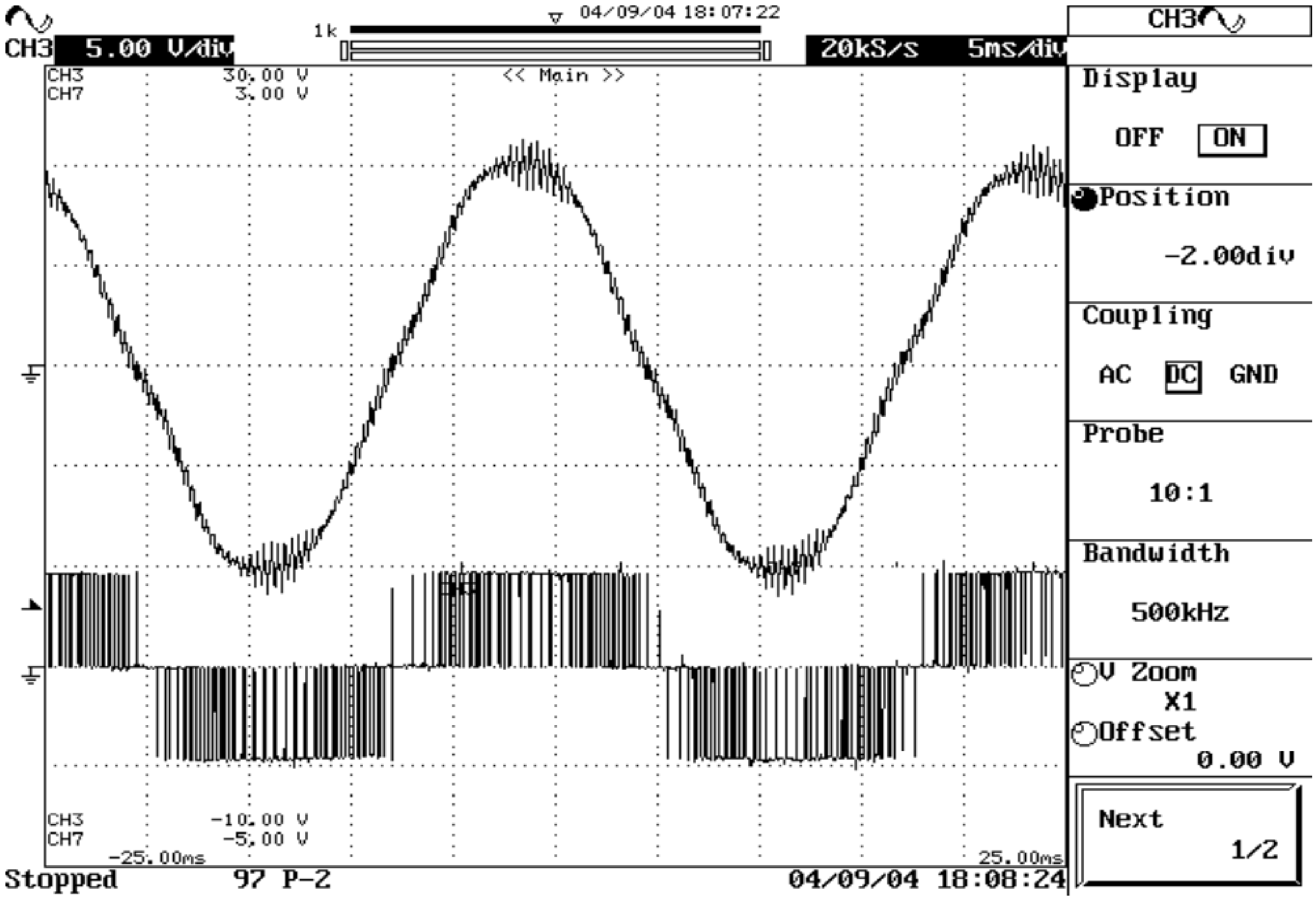
Sine Pulse Width Modulation: Variation of Load current with reference sine



Line-Line voltage & line current waveform of PWM inverted fed IM at 15Hz



Line-Line voltage & line current waveform of PWM inverted fed IM at 40 Hz



Line-Line voltage & line current waveform of PWM inverted fed IM at 40 Hz