Chapter 4

DC–AC Converters (OR) Inverters

LEARNING OBJECTIVES

After reading this chapter, you will be able to understand:

- Basic inverter principles and classifications
- Single-phase half-bridge inverter
- Gating sequence
- Single phase full bridge inverter
- Fourier analysis of single phase inverter output voltage
- I-Q half-bridge inverter
- I-Q full-bridge inverter
- Modified Mc Murray half-bridge inverter
- Three-phase bridge inverter
- Three-phase 120° mode V.S.I.
- Series inverter
- Parallel inverter
- PWM techniques

- Inversion is the conversion of DC power to AC power at a desired output voltage or current and frequency, where thyristors are supplied with DC and turned off by forced commutation.
- In most of the inverter circuits, voltage and frequency are controlled.
- The output of the inverter will have more AC power at lower frequencies and capacitors and inductors are used as energy storing elements.
- Phase-controlled converters when operated in inverter mode are called line commutated inverters but they require an existing AC supply at the terminals which will be used for its commutation. The voltage level, frequency and waveform on the AC side of line commutated inverters cannot be changed.
- In forced commutation method the SCR current is decreased to zero either by transferring the load current to a different path or by decreasing load current to zero.

Basic Inverter Principles and Classifications

Based on the output from inverter circuits they are broadly classified as

(a) Voltage-source inverter (VSI)
(b) Current-source inverter (CSI)

A VSI is one in which the DC input voltage is essentially constant and independent of the load current drawn. The inverter specifies the load voltage while the drawn current shape is dictated by the load.

A CSI is one in which the source. Hence the load current is predetermined and the load impedance determines the output voltage.

- VSI has a stiff DC voltage source at its input, it requires forced commutation. Load commutation is possible only, if the load is under damped.
- CSI is fed with stiff DC current source and its output current wave shape is not affected by the load.
- The inverter and its output can be single-phase, three-phase or multi-phase.
- The inverter and its output can be single-phase three-phase or multi-phase.
- Inverter output waveforms either voltage or current are usually rectilinear in nature and as such contain harmonics which may lead to reduced load efficiency and performance load harmonics reduction can be achieved by either filtering selected harmonic reduction chopping (or) pulse width modulation (PWM).
- The quality of inverter output is normally evaluated in terms of its harmonic factor 'ρ' distortion factor μ and total harmonic distortion THD for VSI. The in terms of the output voltage harmonics as

$$\Gamma_n = \left|\frac{V_n}{V_1}\right| = n\mu_n ; n > 1$$

The distortion factor for an individual harmonic is

$$\mu_n = \left|\frac{V_n}{nv_1}\right| = \frac{\Gamma_n}{n}$$

$$\text{THD} = \sqrt{\left[\sum_{n\geq z}^{\infty}\left(\frac{\gamma_n}{n}\right)^2\right]}V_1$$

$$= \sqrt{\sum_{n\geq z}^{\infty}\mu_n^{\ 2}} = \sqrt{\sum_{n\geq z}^{\infty}\left(\frac{\rho_n}{n}\right)^2}$$

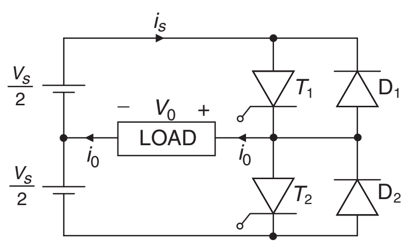
- The factor $\left(\frac{\gamma_n}{n}\right)$ is used since the harmonic currents produced in an inductive load attenuate with frequency.
- The harmonic currents produce unwanted heating and torque oscillations in AC motors, although such harmonic currents are not a drawback to the power delivered to a resistive heating load or incandescent load.

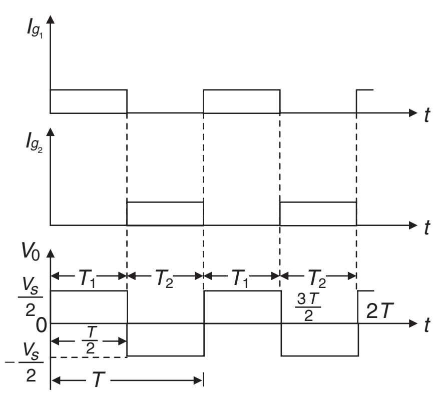
Depending on connection they are.
- Bridge Inverter
- Series Inverter
- Parallel Inverter

Bridge inverters are of two types:

1. Single-phase half-bridge inverters
2. Single-phase full-bridge inverters

Single-phase Half-bridge Inverter





- The inverter circuit consists of two choppers.
- When only T_1 is turned on for a time $\frac{T}{2}$, the instantaneous voltage across the load V_0 is $\frac{V_s}{2}$.
- If transistor T_2 is only turned on for a time $\frac{T}{2}$, $-\frac{V_s}{2}$ appears across the load.
- The logic circuit should be designed such that T_1 and T_2 are not turned on at the same time.
- This inverter requires a three wire DC source and when a transistor is off, its reverse voltage is V_s instead of $\frac{V_s}{2}$. Such an inverter is known as half-bridge inverter.
- For an inductive load current cannot change immediately with the output voltage. If T_1 is turned off at $t = \frac{T}{2}$, the load current would continue to flow through D_2, load and lower half of DC source, until the current flows to zero.
- When T_2 is turned off at $t = \frac{T}{2}$ the load current flows through D_1, load and upper half of the DC source.
- When diodes D_1 and D_2 conducts energy is fed back to the DC source and these diodes are known as feedback diodes.

Gating Sequence

1. Generate a square-wave gating signal V_{g1} at an output frequency f_0 and a 50% duty cycle. The gating signal V_{g2} should be a logic invert of V_{g1}.
2. Signal V_{g1} will drive switch T_1 through a gate isolating circuit, and V_{g2} can drive T_1 without any isolating circuit.

Note:
- An AC output voltage can be obtained by alternatively connecting the positive and negative terminals of the DC source, across the load by turning on and off the switching devices accordingly.
- Feedback diodes are required to transfer the energy stored in the load inductance back to the DC source.
  The output voltage does not depend on the nature of load.
  By Fourier series

$$V_0 = \sum_{n=1,3,5}^{n} \frac{2Vs}{n\pi} \sin n\omega t$$

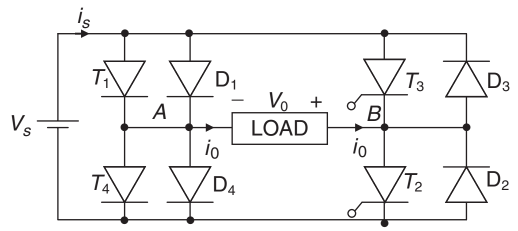
Frequency of output

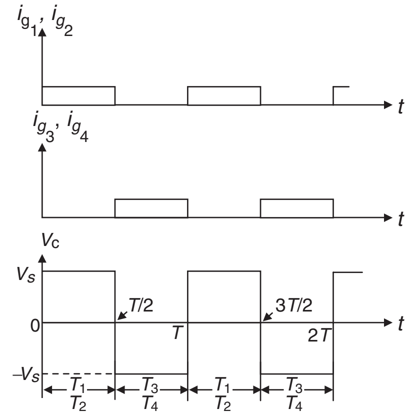
$$f = \frac{1}{T} \text{ voltage}$$

Disadvantages
- Mid-point supply is required
- Output voltage $= \pm\frac{V_s}{2}$

(i.e.) no proper utilization of thyristor rating

Single-phase Full-bridge Inverter





- It consists of four choppers.
- When transistors T_1 and T_2 are turned on simultaneously, the input voltage V_s appears across the load.
- If transistors T_3 and T_4 are turned ON at the same time, voltage across the load is reversed and is $-V_s$.

Switch states for a single-phase full-bridge VSI

State	State no.	Switch State*	v_{ao}	v_{bo}	v_o	Components Conducting
S_1, S_2 are on and S_4, S_3 are off	1	10	$V_s/2$	$-V_s/2$	V_s	S_1 and S_2 if $i_0 > 0$ D_1 and D_2 if $i_0 < 0$
S_4, S_3 are on and S_1, S_2 are off	2	01	$-V_s/2$	$V_s/2$	$-V_s$	D_4 and D_3 if $i_0 > 0$ S_4 and S_3 if $i_0 < 0$
S_1, S_3 are on and S_4, S_2 are off	3	11	$V_s/2$	$V_s/2$	0	S_1 and D_3 if $i_0 > 0$ D_1 and S_3 if $i_0 < 0$
S_4, S_2 are on and S_1, S_3 are off	4	00	$-V_s/2$	$-V_s/2$	0	D_4 and S_2 if $i_0 > 0$ S_4 and D_2 if $i_0 < 0$
S_1, S_2, S_3, and S_4 are all off	5	Off	$-V_s/2$ $V_s/2$	$V_s/2$ $-V_s/2$	$-V_s$ V_s	D_4 and D_3 if $i_0 > 0$ D_4 and D_2 if $i_0 < 0$

* If an upper switch is on and 0 if a lower switch is on.

- The above table shows five switch states.
- T_1 & T_4 acts as the switching devices S_1, S_4, respectively. If two switches one upper and one lower conduct at the same time such that output voltage is $\pm V_s$ the switch state is 1, whereas if these switches are off at the same time, the switch state is 0.

Gating Sequence

1. Generate two square-wave gating signals V_{g_1} and V_{g_2} at an output frequency f_0 and a 50% duty cycle. The gating V_{g_1} and V_{g_3} should be the logic invert of V_{g_2} and V_{g_4}, respectively.
2. Signals V_{g_1} and V_{g_3} drive Q_1 and Q_3, respectively, through gate isolating circuits. V_{g_2} and V_{g_4} can drive T_2 and T_4, respectively, without any isolation circuits.

Note:

- Peak reverse blocking voltage of each transistor and quality of output voltage for half- and full-bridge inverters are the same. However, for full-bridge inverters, the output power is four times higher and the fundamental component is twice that of half-bridge inverters.
- The full-bridge inverter requires four switching devices and four diodes. The output voltage switches between = V_s and $-V_s$. The RMS fundamental component V_1 of the output voltage is 0.9 V_s.
- The design of an inverter requires the determination of the average, RMS, and peak currents of the switching devices.

The output voltage waveforms do not depend on the nature of the load. These waveforms can be represented as follows

- For single-phase, half-bridge inverter

$$V_0 = \sum_{n=1,3,5\ldots}^{\alpha} \frac{2V_s}{n\pi} \sin \omega t \text{ Volt}$$

- For single-phase, full-bridge inverter

$$V_0 = \sum_{n=1,3,5\ldots}^{\alpha} \frac{4V_s}{n\pi} \sin n\omega t \text{ Volt}$$

Here, n is the order of harmonic

$\omega \rightarrow$ Frequency of the output voltage in rad/sec

Load current

$$i_0 = \sum_{n=1,3,5....}^{\alpha} \frac{4V_S}{n\pi|Z_n|}\sin(n\omega t - \phi_n)$$

$$i_0 = \left[R^2 + \left(n\omega L - \frac{1}{n\omega C}\right)^2\right]^{1/2}$$

where Z_n = Load impedance at frequency n.f.

$$\text{Phase angle, } \phi_n = \frac{\tan^{-1}\left(n\omega L - \frac{1}{n\omega C}\right)}{R}$$

If I_{01} is RMS value of fundamental component of load current, the fundamental load power

$$P_{01} = I_{01}^2 R = V_{01} I_{01} \cos\phi_1$$

$V_{01} \rightarrow$ RMS value of fundamental output voltage.

P_{01} does the useful work in most of the applications (e.g.: electric motor drives). The output power associated with harmonic current does no useful work and is dissipated as heat leading to rise in load temperature.

Steady State Analysis of Single-phase Inverter

If $(T/2 - t_1) > t_q$, load commutation takes place No force commutation is necessary.

In the under damped case, if duration $(T_2 - t_1) > t_q$, T_1, T_2 gets commutated naturally and therefore no commutation circuitry will be needed.

Fourier Analysis of Single-phase Inverter Output Voltage

1-Q Half-bridge Inverter

$$V_0 = \sum_{n=1,3}^{\infty} \frac{2V_s}{n\pi}\sin n\omega t$$

$$i_0 = \sum_{n=1,3}^{\infty} \frac{2V_s}{n\pi Z_n}\sin(n\omega t - \phi_n)$$

1-Q Full-bridge Inverter

$$V_0 = \sum_{n=1,3}^{\infty} \frac{4V_s}{n\pi}\sin n\omega t$$

$$i_0 = \sum_{n=1,3}^{\infty} \frac{4V_s}{n\pi Z_n}\sin(n\omega t - \phi_n)$$

Z_n is the impedance offered to n^{th} harmonic

$$z_n = \sqrt{R^2 + \left(n\omega L - \frac{1}{n\omega c}\right)^2}$$

$$Q_n = \tan^{-1}\left[\frac{n\omega L - \frac{1}{n\omega c}}{R}\right]$$

$V_{or} = V_s$ – full-bridge inverter

$V_{or} = \frac{V_s}{2}$ – Half-bridge inverter

Harmonic factor of n^{th} harmonic

$$\text{H.F.n} = \frac{V_n}{V_1}$$

where V_n = RMS value of nth harmonic component

V_1 = fundamental component RMS value

Total harmonic distortion (T.H.D.) – It is a measure of closeness in shape between a waveform and its fundamental component.

$$\text{THD} = \frac{1}{V_1}\left[\sum_{n=2,3}^{\alpha} V_n^2\right]^{\frac{1}{2}}$$

$$= \sqrt{\frac{V_{or}^2 - V_1^2}{V_1}}$$

Distortion of factor of n^{th} harmonic is defined as

$$\text{DFn} = \frac{V_{1\,\text{RMS}}}{V_{or}}$$

Solved Examples

Example 1: When a line commutated converter delivers real power from AC supply.

(A) It works as a rectifier at $\alpha > 90°$.
(B) It operates in the inverter mode at $\alpha < 90°$.
(C) Till $\alpha \le 90°$ it operates as rectifier and beyond 90° it operates as inverter.
(D) Cannot be determined

Solution: (C)

Example 2: The false statement among the following choices regarding the operations below is "6 MOSFETs are connected in a bridge configuration must be operated as a 'voltage source inverter'.

(A) It saturation region MOSFETs can be operated as excellent current sources.
(B) The setup can be operated both as VSI and CSI.
(C) MOSFET's have inherent anti parallel diodes.
(D) MOSFET's are voltage-driven devices.

Solution: (A)

Example 3: A 200 V DC voltage is supplying power to an RCL load through a single-phase full bridge through a $R = 10\ \Omega$, $L = 60$ mH, C = 100 μF.

If the output frequency is 50 Hz, The maximum thyristor current is

(A) 5 A (B) 10 A (C) 15 A (D) 7.32 A

Solution: (B)

Output voltage $V_0 = \frac{4V_s}{\pi}\sin\omega t + \frac{4V_s}{3\pi}\sin 3\omega t + \frac{4V_s}{5\pi}\sin 5\omega t$

$= 254.65 \sin 314t + 84.88 \sin 942t + 50.93 \sin 1570t$

It is of the general form

$$V_0 = V_1 \sin \omega_1 t + V_2 \sin \omega_2 t + V_3 \sin \omega_3 t$$

$$I_{TH} = \sqrt{I_1^2 + I_2^2 + I_3^2}$$

$$= \sqrt{\left(\frac{V_1}{Z_1}\right)^2 + \left(\frac{V_2}{Z_2}\right)^2 + \left(\frac{V_3}{Z_3}\right)^2}$$

$$Z_1 = \sqrt{R^2 + \left(\omega_1 L - \frac{1}{\omega_1 c}\right)^2}$$

$$Z_1 = \sqrt{20^2 + \left(314 \times 60 \times 10^{-3} - \frac{1}{314 \times 100 \times 10^{-6}}\right)^2}$$

$$= 23.86\ \Omega$$

Similarly

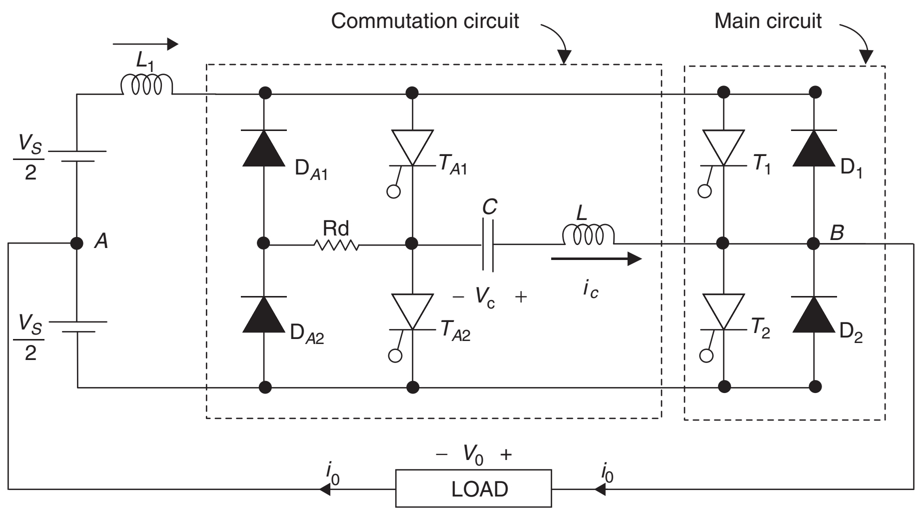
$$Z_2 = 50\ \Omega \qquad Z_3 = 90\ \Omega$$

$$I_{TH} = \sqrt{\left(\frac{254.66}{23.86}\right)^2 + \left(\frac{84.88}{50}\right)^2 + \left(\frac{50.93}{90}\right)^2}$$

$$I_{TH} = 10\ \text{A}$$

Modified McMurray Half-bridge Inverter

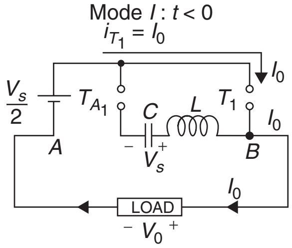
- The power circuit diagram for a single-phase modified Mc Murray half-bridge converter is as given below.



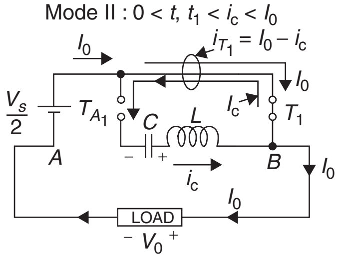
- It consists of a commutation circuit and a main circuit with two Thyristor and two diodes for each circuits.
- It operated in seven different modes which are as follows.

Operating Modes

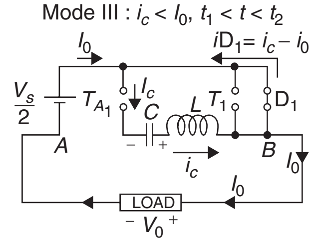
Mode I : $t < 0$



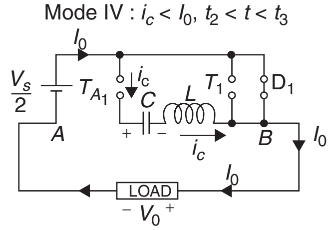
Mode II : $0 < t,\ t_1 < i_c < I_0$



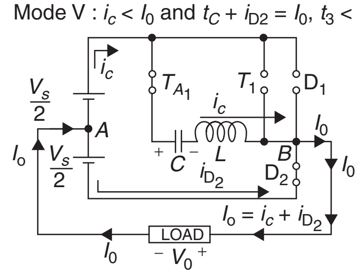
Mode III : $i_c < I_0,\ t_1 < t < t_2$



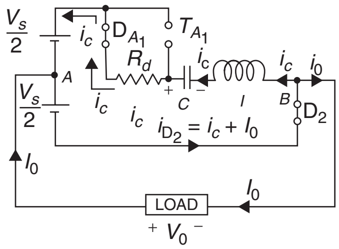
Mode IV : $i_c < I_0,\ t_2 < t < t_3$



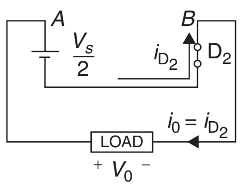
Mode V : $i_c < I_0$ and $t_C + i_{D2} = I_0,\ t_3 < t < t_4$



Mode VI : $i_{D2} > I_0$, $t_4 < t < t_5$

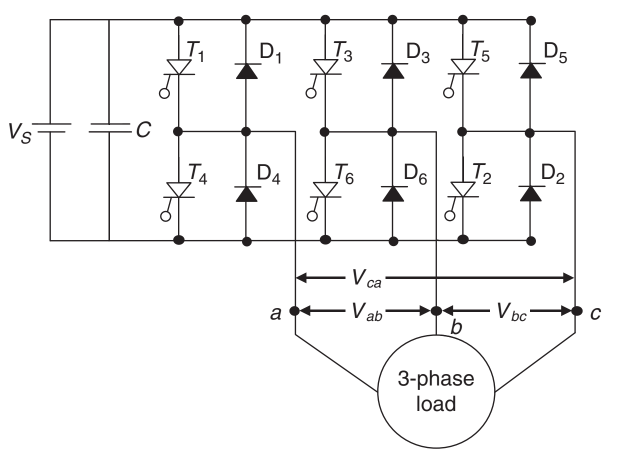


Mode VII : $i_c = 0$, $i_{D_2} = i_0$, $t_5 < t < t_6$



Three-phase, Bridge Inverter

- These are normally used for high power applications.
- Three, single-phase half (or full) -bridge inverters can be connected in parallel to form the configuration of a three-phase inverter.
- The gating signals of singe-phase inverters should be advanced or delayed by 120° with respect to each other to obtain three-phase balanced voltages.
- The transformer primary windings must be isolated from each other whereas secondary windings may be connected in Y or Δ. The transformer secondary is normally connected in Δ to eliminate triplen harmonics appearing in the output voltages and the circuit arrangement is shown as below.



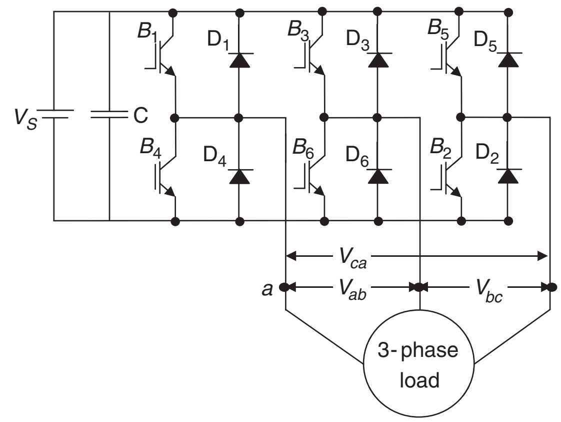
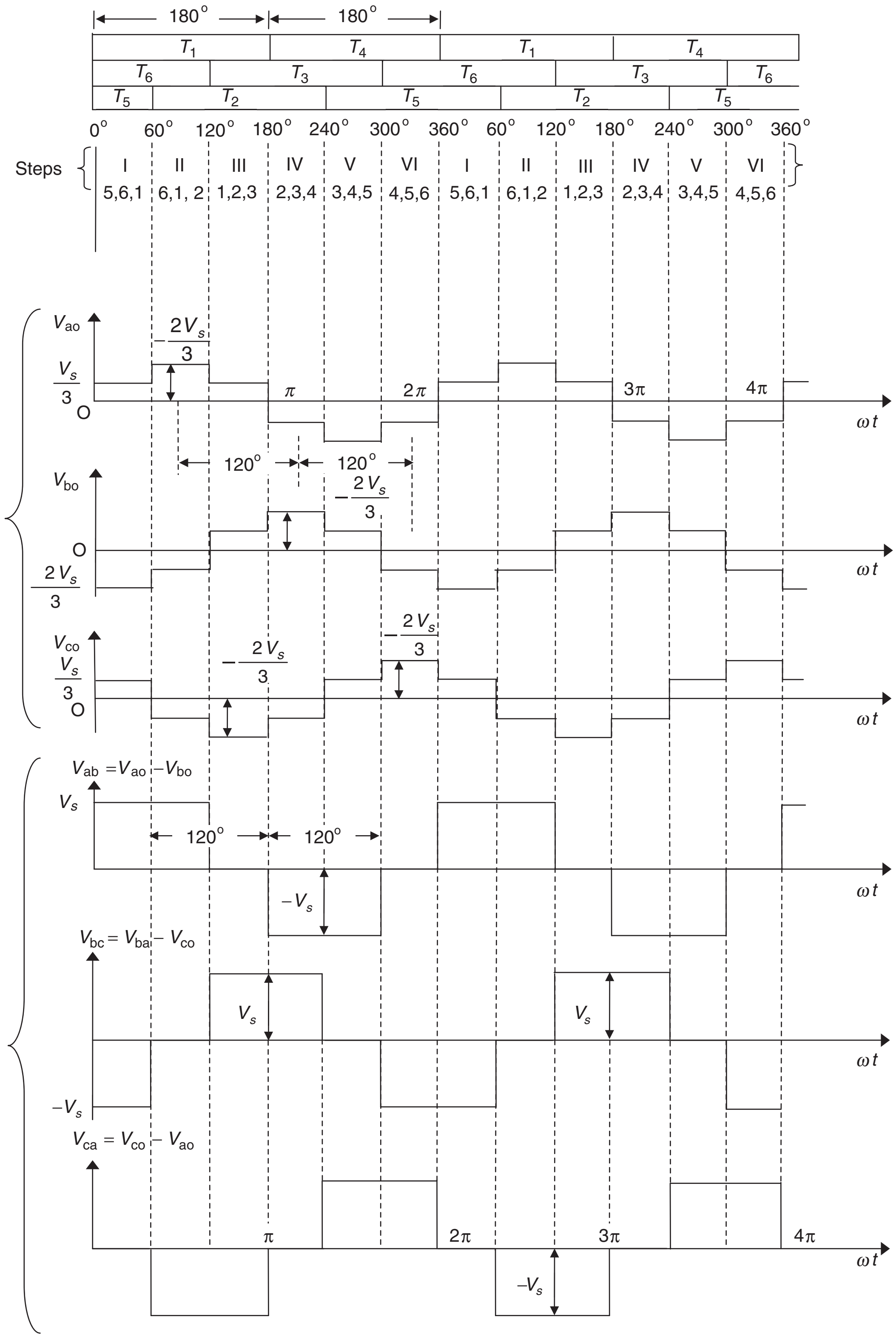


Figure 1 (a) Using thyristors; (b) Using IGBTs

- This arrangement requires three, single-phase transformers, 12 transistors and 12 diodes.
- If the output voltages of single-phase inverters are not perfectly balanced in magnitude and phases, the three-phase output voltages are unbalanced.
- Two types of control signals can be applied to the transistors to obtain 180° conduction or 120° conduction.
- The 180° conduction has better utilization of the switches and is the preferred method.

Three-phase, 180° Mode VSI

- Each transistor conducts for 180°. Three transistors remain on at any instant of time.
- When T_1 is switched ON, a is connected to the positive terminal of a DC input voltage. When T_4 is switched on, terminal a is brought to the negative terminal of DC source. There are six modes of operation in a cycle and the duration of each mode is 60°.
- The transistors are numbered in the sequence of gating as (123, 234, 345, 456, and 612).
- The gating signals are shifted from each other by 60° to obtain three-phase balance voltages.
- The switches of any leg of the inverter (S_1 and S_4, S_3 and S_6, S_5 and S_2) cannot be switched ON simultaneously. This would result in a short circuit across the DC link voltage supply.
- To avoid undefined states and thus undefined AC output line voltages the switches of any legs of the inverter cannot be switched of simultaneously. This can result in voltages that depend on the respective line current polarity.


180°
180°
T1 T4 T1 T4
T6 T3 T6 T3 T6
T5 T2 T5 T2 T5
0° 60° 120° 180° 240° 300° 360° 60° 120° 180° 240° 300° 360°
Steps
I II III IV V VI I II III IV V VI
5,6,1 6,1, 2 1,2,3 2,3,4 3,4,5 4,5,6 5,6,1 6,1,2 1,2,3 2,3,4 3,4,5 4,5,6
Vao
2Vs/3
Vs/3
O
π 2π 3π 4π
ωt
120° 120°
Vbo
2Vs/3
O
2Vs/3
ωt
Vco
Vs/3
O
2Vs/3
2Vs/3
ωt
Vab = Vao − Vbo
Vs
120° 120°
−Vs
ωt
Vbc = Vbo − Vco
Vs
Vs
−Vs
ωt
Vca = Vco − Vao
π 2π 3π 4π
−Vs
ωt

The line output voltages

$$V_{ab} = \sum_{n=1,3,5\ldots}^{\alpha} \frac{4V_s}{n\pi} \cos\frac{n\pi}{6} \sin n\left(\omega t + \frac{\pi}{6}\right)$$

$$V_{bc} = \sum_{n=1,3,5\ldots}^{\alpha} \frac{4V_s}{n\pi} \cos\frac{n\pi}{6} \sin n\left(\omega t - \frac{\pi}{2}\right)$$

$$V_{ca} = \sum_{n=1,3,5\ldots}^{\alpha} \frac{4V_s}{n\pi} \cos\frac{n\pi}{6} \sin n\left(\omega t + \frac{5\pi}{6}\right)$$

RMS value of n^{th} component of the line voltage,

$$V_{\text{IN}} = \frac{4V_s}{\sqrt{2}\cdot n\pi} \cos\frac{n\pi}{6}.$$

RMS value of fundamental line voltage

$$V_{L1} = \frac{4V_s}{\sqrt{2}\pi} \frac{\cos n\pi}{6} = 0.7797 V_s$$

From line voltage waveform V_{ab}

Line voltage is V_s from 0° to 120°

$$V_L = \left[\frac{1}{\pi}\int_0^{2\pi/3} V_s^2\, d(\omega t)\right]^{1/2} = \sqrt{\frac{2}{3}} V_s = 0.8165\, V_s$$

RMS value of phase voltage

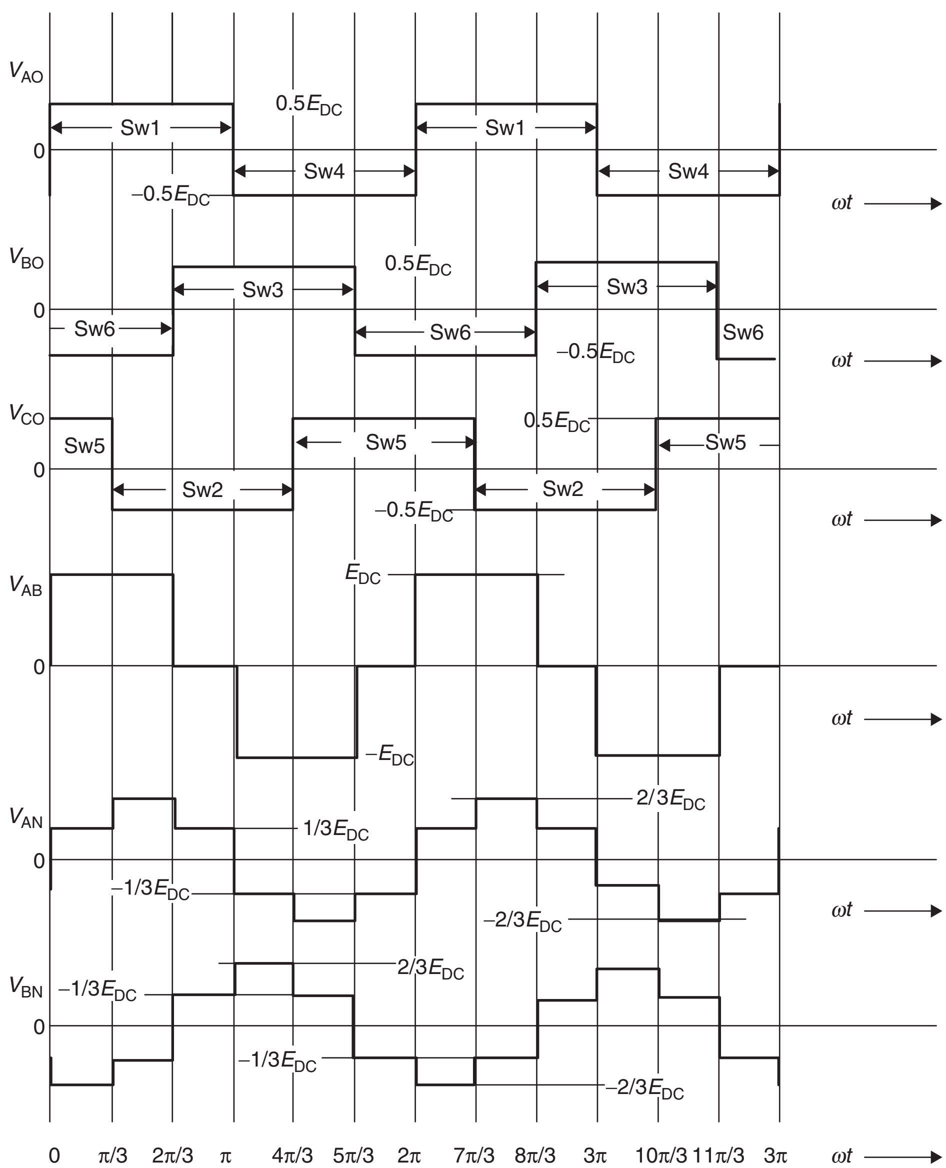
$$V_p = \frac{V_L}{\sqrt{3}} = \frac{\sqrt{2}V_s}{3} = 0.4714 V_s$$

RMS value of fundamental phase voltage

$$V_{p1} = \frac{\sqrt{2}V_s}{\sqrt{2}\pi} = 0.4502\, V_s = \frac{V_{L1}}{\sqrt{3}}$$

Three-phase 120° Mode V.S.I.

- For this mode, each thyristor conducts for 120° of a cycle. Like 180° conduction mode inverter also requires 6 steps, each of 60° duration for completing one cycle of the AC output voltage.
- The sequence of firing of six thyristors and voltage waveforms is as shown below.



Phase voltage waveforms are expressed as

$$V_{a0} = \sum_{n=1,3,5\ldots}^{\alpha} \frac{2V_s}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t + \frac{\pi}{6}\right)$$

$$V_{b0} = \sum_{n=1,3,5\ldots}^{\alpha} \frac{2V_s}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t - \frac{\pi}{2}\right)$$

$$V_{c0} = \sum_{n=1,3,5\ldots}^{\alpha} \frac{2V_s}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t + \frac{5\pi}{6}\right)$$

Line voltage

$$V_{ab} = \sum_{n=6K+1}^{\alpha} \frac{3V_s}{n\pi}\sin n\left(\omega t + \frac{\pi}{3}\right)$$

where $K = 0, 1, 2, \ldots\ldots\ldots..$

V_{bc}, V_{ca} can be obtained in a similar manner.

RMS value of fundamental phase voltages

$$V_{p1} = \frac{2V_s}{\sqrt{2}\pi}\cos\pi/6 = 0.3898V_s$$

RMS value of phase voltage

$$V_{\text{ph}} = \left[\frac{1}{\pi}\int_0^{2\pi/3}\left(\frac{V_s}{2}\right)^2 d\omega t\right]^{1/2}$$

$$= \sqrt{\frac{2}{3}}\frac{V_s}{2} = \frac{V_s}{\sqrt{6}} = 0.4082V_s$$

RMS value of fundamental line voltage

$$V_{L1} = \frac{3V_s}{\sqrt{2}\pi} = 0.6752V_s + = \sqrt{3}\ V_{p1}$$

RMS value of line voltage

$$V_L = \sqrt{3}V_{ph} = \frac{V_s}{\sqrt{2}} = 0.7071V_s$$

Example 4: A thyristor bridge converter (three-phase, fully controlled) is uses as a line commuted inverter to feed 30 kW power at 220 V to a 3-∅, 215v (l – l), 50 Hz AC mains. The RMS value of thyristor current is (assume DC link current as constant)

(A) 39.68 A (B) 119.05 A
(C) 68.7 A (D) 78.73 A

Solution: (D)

$$P = V_0 I_0$$

$$I_0 = \frac{P}{V_0} = \frac{30\times10^3}{220} = 136.3$$

RMS value of thyristor current $(I_{\text{TH}})_{\text{RMS}} = I_0/\sqrt{3}$

$$(I_{\text{TH}})_{\text{RMS}} = \frac{136.36}{\sqrt{3}} = 78.73 \text{ A}$$

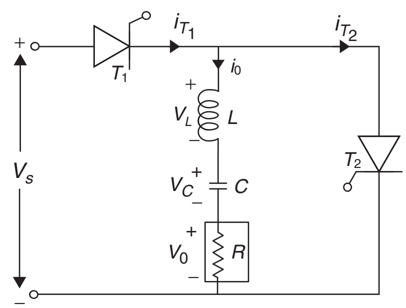
Example 5: Which among the following statement is TRUE regarding a three-phase VSI operated in 180° conduction mode?

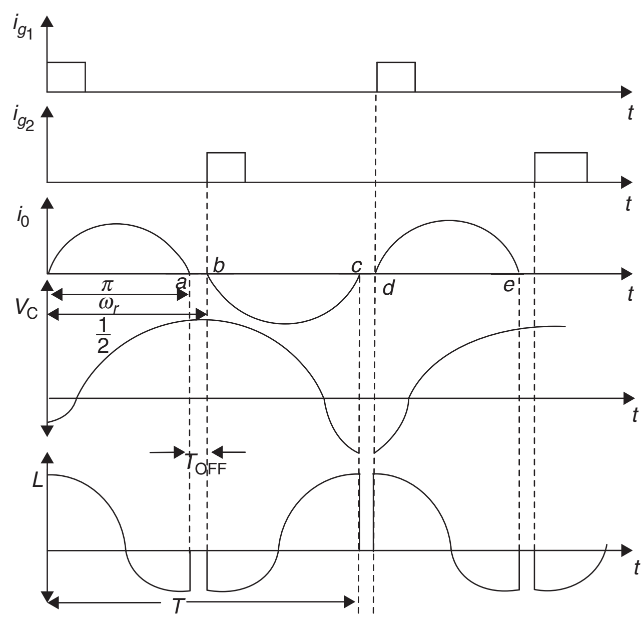
(A) Third harmonic component will not be present in line voltage but absent in phase voltage.
(B) Third harmonic component will not be present in phase voltage but absent in line voltage.
(C) Third harmonic component will be absent both in line and phase voltages.
(D) Both phase and line voltage will contain third harmonic component.

Solution: (C)

Series Inverter

- The time interval between the instant T_1 is turned off and instant T_2 is turned on is indicated by $T_{\text{OFF}} = ab$, where $T_{\text{OFF}} > t_{q,\min}$.





- After thyristor T_1 has commutated, upper plate of the capacitor attains positive polarity. Now when T_2 is turned on at instant b, capacitor begins to discharge and load current in the reverse direction builds up to some peak negative value and then decays to zero at instant C.
- After this time $T_{\text{OFF}} = cd$ must elapsed for T_2 to recover.
- At d, T_1 is again turned on and the process repeats. In this manner DC is converted to AC with the help of series inverter. $T_{\text{OFF}} = ab$ (or) cd is called the circuit turn-off time or dead zone time.
- The capacitor stores charge during one half cycle and releases the same amount of charge during the next half

cycle. Hence, the positive half cycle of current is identical with the negative half cycle of load current.

- In a practical series inverter, positive and negative half cycles may not be sine waves.

$$i(t) = \frac{V_S + V_\alpha}{\omega_r \cdot L} - e^{-\xi t} \sin \omega_r t$$

$\xi = \dfrac{R}{2L}$ is called damping factor

$\omega_0 = \dfrac{1}{\sqrt{LC}}$ is resonant frequency is rad/sec

ω_r = circuit-ringing frequency in rad/sec

ω = operating (or) output frequency in rad/sec

Time period of oscillation $T_{\text{osc}} = \dfrac{\pi}{\omega_r}$

$$T_{\text{osc}} = \frac{\pi}{\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}}$$

Output frequency

$$f = \frac{\frac{1}{2\pi}}{\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2} + 2T_{\text{OFF}}}$$

Circuit-ringing frequency

$$f_r = \frac{1}{2\pi\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}} \text{ Hz i.e. } f < f_r$$

Voltage across inductor L

$$V_L = (V_s + V_{co}) . \frac{\omega_0}{\omega_r} . e^{\theta t} \cos(\omega_r t + \psi)$$

where ω_0 = resonant frequency

$$\omega_0 = \sqrt{\omega_r^2 + \varepsilon^2}$$

$$\psi = \tan^{-1}\left(\frac{\xi}{\omega_r}\right)$$

- Series inverter produces an approximately sinusoidal waveform at high output frequency which is in the range of 200 Hz–100 kHz.

Parallel Inverter

- The basic inverter circuit for a single-phase parallel inverter, utilizing capacitor for its commutation is shown in Figure 1.
- It consists of two thyristors T_1 and T_2 and inductor L, an output transformer and a commutating capacitor C.
- Transformer turns ratio from each primary half to secondary winding is assumed unity. The output voltage and current are V_0 and i_0, respectively, L makes the source current constant at I_0.

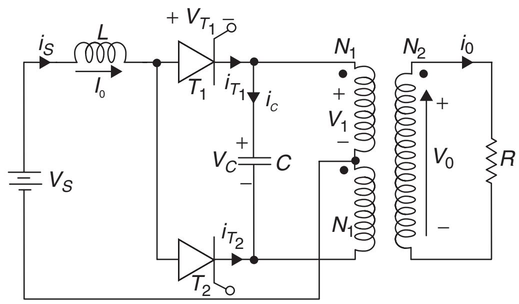


Figure 2

- During the working of this inverter C, comes in parallel with the load via the transformer and hence it is called parallel inverter.

Operating Modes

Mode I

In this mode thyristor T_1 is conducting and current flows in the upper half of primary winding thyristor T_2 is off.

- This current establishes magnetic flux that links both the halves of primary winding. As a result an emf, V_s is induced across upper as well as lower half of primary winding. In other words total voltage across primary winding is $2V_s$.
- This voltage charges the commutating capacitor C to a voltage of $2V_s$ with upper plate positive.
- Thyristor T_2 is forward biased through T_1 by the capacitor voltage $2V_s$. Eventually a steady state current I_o flows through V_s, L, T_1 and upper half of primary winding.

Mode 2

- At time $t = 0$, thyristor T_2 is turned on by applying a triggering pulse to its gate. At this time $t = 0$ capacitor voltage $2V_s$, appears as reverse bias across T_1, it is therefore turned off. A current I_o begins to flow through T_2, lower half of primary windings, V_s and L as shown.

  At the same time capacitor voltage $2V_s$ is applied across the total transformer primary and a capacitor current $-i_C$ is established. Negative sign before i_c means that current i_C flows opposite to its positive direction assumed initially.
- Before T_2 is on, i.e. at $t = 0^-$ mmf in the upper primary winding is I_0N_1 and zero in the lower primary winding. Soon after T_2 is on, i.e. at $t = 0^+$, mmfs linking both upper and lower halves cannot change suddenly. Therefore at $t = 0^+$, $-i_C = I_o$ such that mmf in the lower half remains zero and mmf in the upper half is equal to mmf at $t = 0^-$. After $t = 0^+$, capacitor C discharges and current I_C is such that it supplies load current i_0 and balances the primary and secondary ampere turns of the transformer.

  Capacitor current continues flowing till capacitor has charged from $+2V_s$ to $-2V_s$ at time $t = t_1$.
- Load voltage changes from V_s at $t = 0$ to $-V_s$ at $t = t_1$.

Mode 3

When capacitor has charged to $-2V_s$ with upper plate negative and lower plate positive, SCR T_1 may be turned on at any time. T_1 is triggered at $t = T/2$.

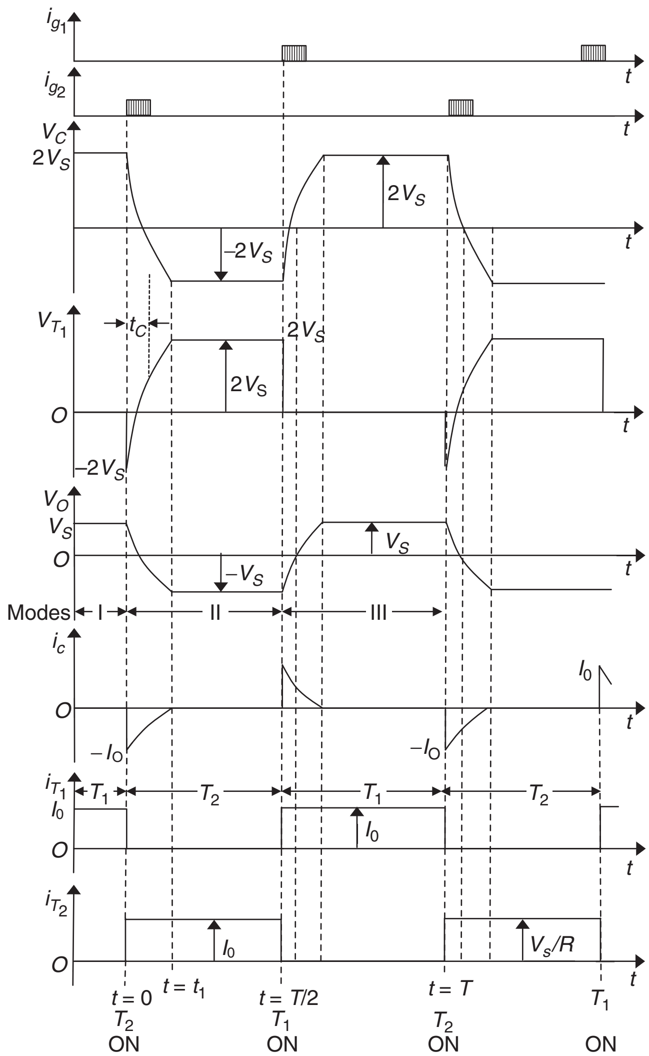
- Capacitor voltage $2V_s$ applies a reverse bias across T_2, it is therefore turned OFF. After T_2 is OFF, capacitor starts discharging current i_c is now positive. mmfs in the upper and lower halves remain unchanged from their valves just before $T/2$.

Current and Voltage Waveforms

When i_C decays to zero,

$$V_c = +2V_s,\ V_o = V_s,$$

$$i_{T1} = I_o = V_s/R.$$



At $t = 0+$ when T_2 is turned ON; $V_{T1} = -2V_s$, $i_C = -I_0$, $i_{T1} = 0$ and $i_{T2} = I_0$. As the turns ratio from whole primary to secondary winding is 2, the load voltage has half the amplitude of capacitor voltage. However, load voltage has the same waveform as the capacitor voltage.

$$V_c = 2V_s\left[2\exp\left(\frac{-n^2 t}{4RC}\right) - 1\right]$$

Circuit turn-off time, $t_c = \dfrac{4RC\ I_n 2}{n^2}$

Commutating capacitance, $C = \dfrac{n^2\, t_C}{4R.\ln 2}$

- Parallel inverter produces square and rectangular waveforms.

INVERTER CONTROL METHODS AND TECHNIQUES

Voltage Control in Single-phase Inverters

Inverter output voltage can be controlled by controlling the gain of the inverter.

- Inverter gain is defined as the ratio of output voltage to input DC voltage.
- The various methods for control of output voltage of inverters are listed as follows.
  1. External control of the AC output voltage
  2. External control of the DC input voltage
  3. Internal control of the inverter output voltage
- In the first two methods, extra circuits for the control of either DC input or AC output become necessary.

External Control of the AC Output Voltage

There are two possible methods to externally control the AC output voltage obtained from inverter output voltage terminal.

- The AC voltage control and
- The series inverter control

AC Voltage Control

In this method, an AC voltage controller is inserted between the output terminals of inverter and the input terminals of the load.

The load voltage is regulated through this voltage controller.

- This method gives rise to higher harmonic content in the output voltage, particularly when the output voltage from the AC voltage controller is a low level.
- This method is rarely employed except in the low power applications.

Series Inverter Control

This method of voltage control involves the use of two or more inverters in series.

- The series connection of inverters called multiple converter control does not augment the harmonic content even at low output voltage levels.

External Control of the DC Input Voltage through Variable DC Link

- In this method, the input DC voltage may be altered to vary the RMS voltage of the AC output.
- This can be achieved easily by using a phase-controlled thyristor bridge converter or a DC chopper.
- An LC filter is essential in between the variable DC source and the inverter.
- In this case, output voltage waveform and its harmonic content are not affected appreciably as the inverter output voltage is controlled through the adjustment of DC input voltage to the inverter.

Internal Control of the Inverter Voltage

The output voltage from an inverter can also be adjusted by incorporating a control mechanism within the inverter itself.

The most efficient method is by PWM Control.

PWM control

In this method, a fixed DC input voltage is given to the inverter and a controlled AC output voltage is obtained by adjusting the on and off periods of the inverter components.

The advantages are:

- Output voltage control can be obtained without any additional components.
- Lower-order harmonic can be eliminated or minimized along with their output voltage control.

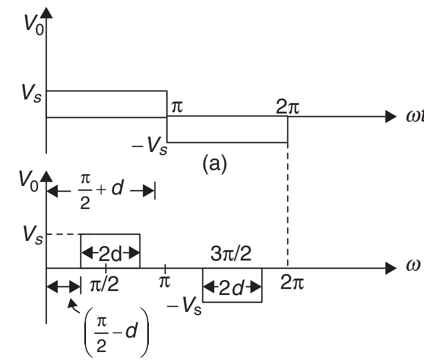
  As the higher-order harmonics can be filtered easily, the filtering requirements are minimized.
- These types of inverters are gradually taking over other types of inverters in industrial applications.
- PWM techniques are characterized by constant amplitude pulses. The width of these pulses is however modulated to obtain inverter output voltage control and to reduce its harmonic content.

PWM Techniques

- Forced commutation is essential.
- PWM differs from each other in the harmonic content in their respective output voltages.
- Thus, choice of a particular PWM technique depends upon the permissible harmonic content in the inverter output voltage.

Single-pulse Modulation

- The output voltage from single-phase full-bridge inverter is shown below.



- When this waveform is modulated, the output voltage is of the form shown in fig II.
- It consists of a pulse of width $2d$ located symmetrically located about $\pi/2$. The range of pulse width $2d$, varies from $0 < 2d < \pi$.
- The output voltage is controlled by varying the pulse width $2d$.
- The shape of output voltage wave shown is called quasi-square wave.

By Fourier analysis of waveform, we have

$$b_n = \frac{2}{\pi}\int_{(\pi/2-d)}^{(\pi/2+d)} V_s \sin\, n\omega t.\, d\omega t$$

$$b_n = \frac{4V_s}{\pi}\left[\sin\frac{n\pi}{2}\sin nd\right], a_n = 0$$

$$V_0 = \sum_{n=1,35\ldots}^{\alpha} \frac{4V_s}{\pi}\sin\frac{n\pi}{2}\sin nd \sin\left(n\,\omega t\right)$$

$$V_0 = \frac{4V_s}{\pi}\left[\sin d\sin\omega t - \frac{1}{3}\sin 3d\sin\omega t + \frac{1}{5}\sin 5d\sin 5\omega t\right]$$

Maximum value of fundamental component of output voltage

$$V_{o1m} = \frac{4V_s}{\pi}\Big|_{d=\pi/2}$$

For pulse width other than $2d = \pi$ rad, peak value of fundamental component $= \frac{4V_s}{\pi}\sin d$

To eliminate n^{th} harmonic from the inverter output voltage pulse width $2d = \frac{2\pi}{n}$

Peak value of n^{th} harmonic

$$V_{onm} = \frac{4V_s}{\pi}\sin nd$$

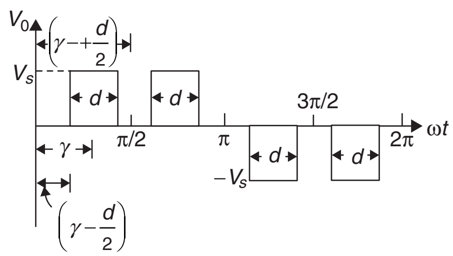
$$\frac{V_{onm}}{V_{o1m}} = \frac{\sin nd}{n}$$

RMS value of output voltage

$$V_{or} = \left[\frac{V_s^2 2d}{\pi}\right]^{1/2} = V_s\left[\frac{2d}{\pi}\right]^{1/2}$$

Multiple-pulse Modulation

- Multiple-pulse modulation (MPM) is an extension of single-pulse modulation.
- In MPM, several equidistant pulses per half cycle are used. For simplicity the effect of using two symmetrically spaced pulses per half cycle is investigated as shown in the waveform below.



By Fourier analysis of waveform,

$$b_n = \frac{2}{\pi}\int_0^{\pi} V_o \sin n\omega t \; d(\omega t)$$

$$= \frac{2}{\pi}\int_{(\gamma - d/2)}^{(\gamma + d/2)} V_s \sin n\omega t \; d(\omega t)\cdot 2$$

$$= \frac{4V_s}{\pi}\left[\cos n\omega t\right]_{\gamma - d/2}^{\gamma + d/2} = \frac{8V_s}{n\pi}\sin n\gamma \sin nd/2$$

$$V_0 = \sum_{n=1,3,4}^{\alpha} \frac{8V_s}{n\pi}\sin n\gamma \sin nd/2 \sin n\omega t$$

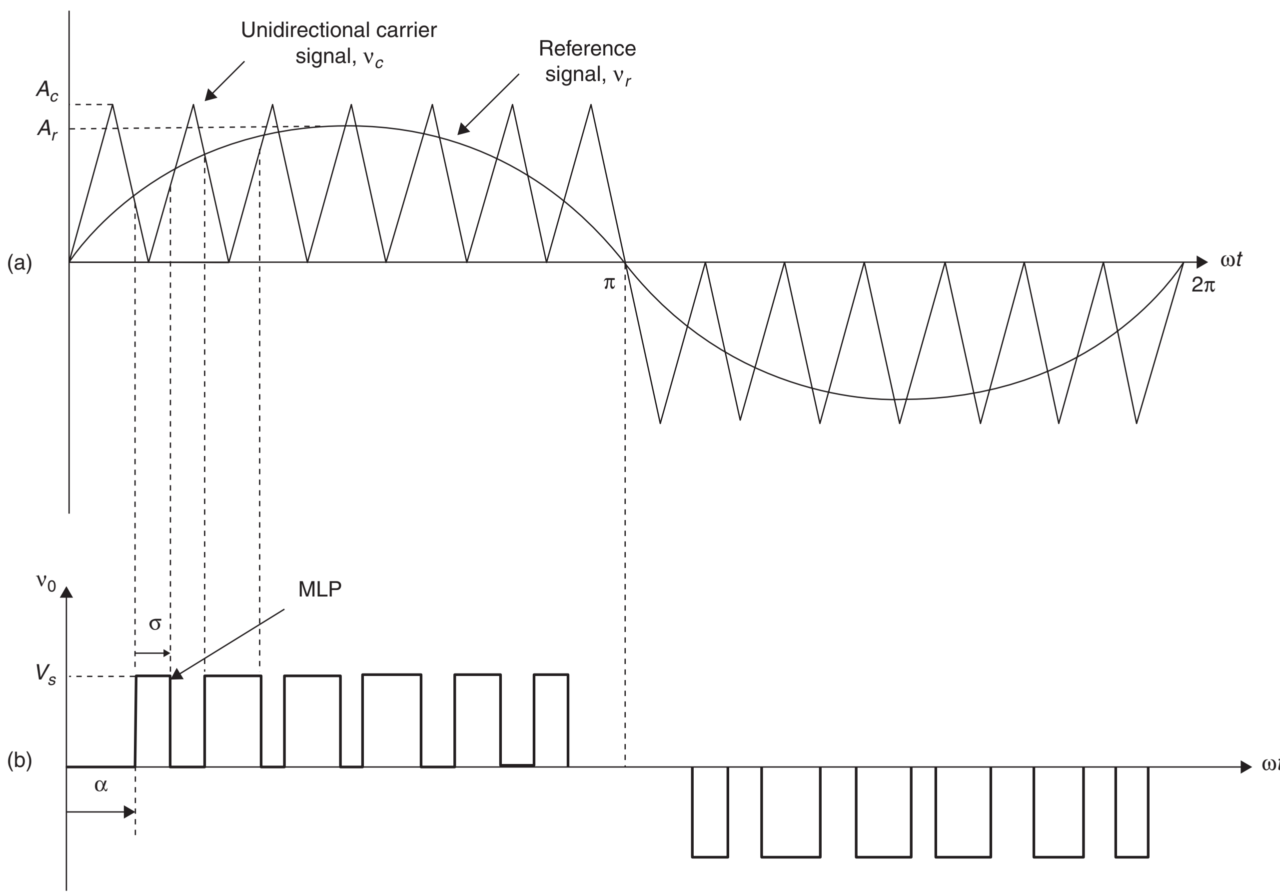
For n^{th} harmonic

$$V_n = \frac{8V_s}{n\pi}\sin n\,\gamma \sin\frac{nd}{2}$$

This equation shows that magnitude of V_n depends upon γ and d. This equation shows that when $\gamma = \pi/n$ (or) $d = 2\pi/n$, n^{th} harmonic can be eliminated from the output voltage. But this has the effect of reducing the fundamental component of output voltage.

Sinusoidal PWM

In this method of modulation, several pulses per half cycle are used as in case of MPM. In MPM, the pulse width is equal for all the pulses. But in SPWM, the pulse width is a sinusoidal function of the angular position of the pulse in a cycle as shown below.



- For realizing SPWM, a high-frequency triangular carrier wave V_c is compared with a sinusoidal reference. Wave V_r of the desired frequency. The intersection of V_c and V_r wave determines the switching instants and commutation of the modulated pulse. In the waveform figure, V_c is the peak value of triangular carrier wave and V_r that of the reference or modulating signal.

- When triangular carrier wave has its peak coincident with zero of the reference sinusoid, there are $N = \frac{f_c}{2f}$ pulses per half cycle.
- In case, zero of the triangular wave coincides with zero of the reference sinusoid there are $(N-1)$ pulses per half cycle.
- The ratio V_r/V_c is called modulation index (MI) and it controls the harmonic content of the output voltage waveform.
- The magnitude of fundamental component of output voltages is proportional to MI but MI can never be more than unity.
- Thus output voltage is controlled by varying MI.

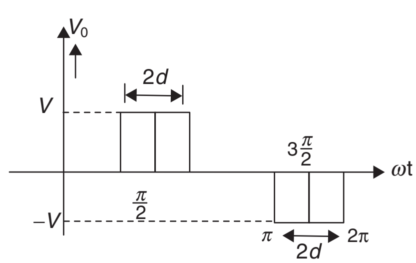
Example 6: A three-phase inverter employs a PWM switching scheme to
(A) Increase the high-order harmonics and minimize the low-order harmonics.
(B) Reduce the DC side load.
(C) Minimize the total harmonic distortion with modes filtering.
(D) Increase the battery life.

Solution: (A)

Example 7: When a triangular PWM control is applied to a three-phase BJJ base VSI
(A) DC side would have low-order harmonic voltages
(B) DC side would contain high-order harmonic voltages
(C) AC side would contain high-order harmonic voltages
(D) AC side would contain low-order harmonic voltages

Solution: (B)

Example 8: The figure shown below represents a single pulse of width $2d$, generated by a single-phase inverter generated in PWM mode. For a pulse width of 130° it was observed that the output voltage is free from 5th harmonic. The percentage of third harmonic that is present in the output voltage would be



(A) 24% (B) 19%
(C) 34.5% (D) 12.33%

Solution: (C)

Given $2d = 130° \Rightarrow d = 60°$

When $2d = \pi$

$$(V_0)_{max} = \frac{4V_s}{\pi}$$

when $2d \neq \pi$

Peak value of fundamental waveform

$$(V_0)_1 = \frac{4V_s}{\pi} \sin d \sin(\pi/2)$$

Peak value of nth harmonic

$$(V_0)_n = \frac{4V_s}{n\pi} \sin(nd)\sin(n\pi/2)$$

Peak value of third harmonic

$$(V_0)_3 = \frac{4V_s}{3\pi} \sin(3d)\sin(3\pi/2) \text{ at } 2d = \pi$$

$$\left(\frac{V_{03}}{V_{01}}\right) = \frac{\frac{4V_s}{3\pi}\sin(3\times 65)^\circ \sin 3\pi/2}{\frac{4V_s}{\pi}}$$

$$= \frac{4\sin(195)\sin 270}{3} = 0.345$$

$$= 34.5\%$$

Example 9: A single-phase VSI is operated in a single PWM mode with a width of 140° in each half cycle. The total harmonic distortion of the AC voltage waveform is
(A) 31.83% (B) 48.42%
(C) 65.65% (D) 28.63%

Solution: (D)

$$2d = 140°$$
$$d = 70°$$

Peak value of fundamental component

$$V_1 = \frac{4V_s}{\pi}\sin d \sin\pi/2$$

RMS value of fundamental component

$$(V_1)_{RMS} = \frac{V_1}{\sqrt{2}} = \frac{\frac{4V_s}{\pi}\sin 70 \sin\pi/2}{\sqrt{2}}$$

$$(V_1)_{RMS} = 0.846\, V_s$$

RMS value of output voltage

$$(V_0)_{RMS} = V_s \frac{2d}{\pi}$$

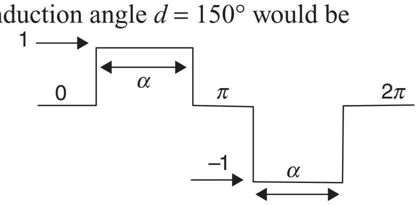
$$= V_s\sqrt{\left[\frac{140}{\pi}\times\frac{\pi}{180}\right]} = 0.88V_s$$

$$\text{T.H.D.} = \sqrt{\frac{(V_0)^2_{RMS} - (V_1)^2_{RMS}}{(V_1)^2_{RMS}}}$$

$$= \sqrt{\frac{(0.88V_s)^2 - (0.846V_s)^2}{(0.846V_s)^2}} = 0.2863$$

$$= 28.63\%$$

Example 10: The output waveform of a periodic output voltage of an inverter is as shown in the figure. The RMS value of fundamental component of the output voltage, when conduction angle $d = 150°$ would be



(A) 0.87 V (B) 0.78 V (C) 1.10 V (D) 0.90 V

Solution: (A)

$$V_{ON} = \frac{4Vs}{n\pi} \sin nd \sin n\pi/2$$

RMS value of fundamental component

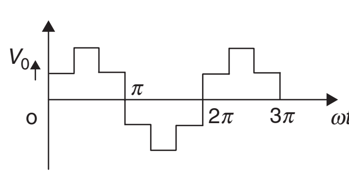
$$(V_0)_{RMS} = \frac{V_{01}}{\sqrt{2}} = \frac{\frac{4\times 1}{\pi}\sin 75 \sin 90}{\sqrt{2}}$$

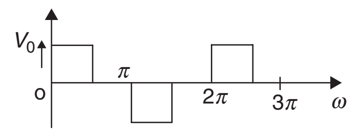
$= 0.87$ V

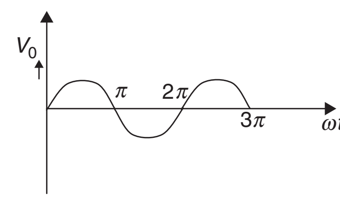
Exercises

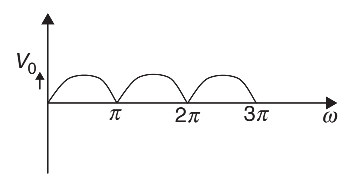
Practice Problems I

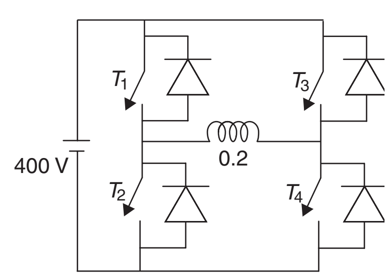
Directions for questions 1 to 15: Select the correct alternative from the given choices.

1. A single-phase half-bridge inverter with supply voltage of 80 V feeds a resistive load of 305 Ω. The fundamental component of output voltage will have an RMS of
   (A) $\frac{160}{\sqrt{2}\pi}V$ (B) $\frac{80}{\sqrt{2}\pi}V$
   (C) $\frac{320}{\sqrt{2}\pi}V$ (D) 40 V
2. A single-phase half-bridge inverter feeds a resistive load. The percentage of 7th harmonic component with respect to fundamental component is
   (A) 20% (B) $28\frac{2}{7}\%$
   (C) $14\frac{2}{7}\%$ (D) 10%
3. If the RMS of output voltage at fundamental frequency of a single-phase full-bridge inverter is $\frac{72}{\sqrt{2}\pi}V$, the supply voltage at input is
   (A) 36 V (B) 72 V
   (C) 9 V (D) 18 V
4. The ratio of output powers of a single-phase full-bridge inverter to that of a half-bridge inverter for the same supply voltage and load current when purely resistive load is employed is
   (A) 2:1 (B) 4:1
   (C) 8:1 (D) 1:4
5. The phase voltage of a three-phase VSI operating in 180° conduction mode is of the nature.
   (A)
   

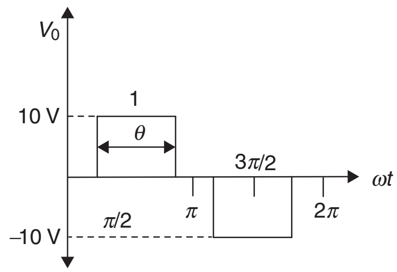
   (B)
   

   (C)
   

   (D)
   

6. The figure shows a single-phase full-bridge inverter operating in square-wave mode at 100 Hz feeding a purely inductive load. The peak value of inductor current amounts to:
   

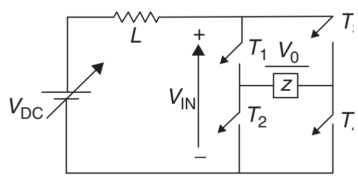
   (A) 20 A
   (B) 2.5 A
   (C) 5 A
   (D) 10 A
7. A single-phase inverter with supply voltage 10 V operating on single-pulse modulation has the output voltage waveform shown in figure.
   The RMS of fundamental component of output voltage when $\theta = 140°$ is



(A) 8.46 V
(B) 5.16 V
(C) 5.78 V
(D) 3.07 V

8. The seventh harmonic component can be eliminated from the output of a single-phase inverter operated with single-pulse modulation if pulse width amounts to:
(A) 103°
(B) 72°
(C) 120°
(D) 90°

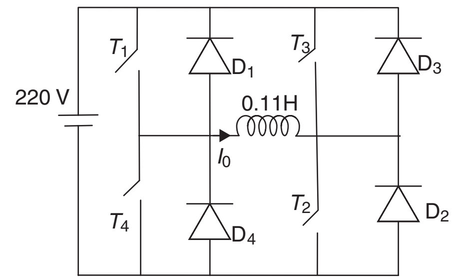
9. For a CSI feeding a capacitive load, the frequency of output voltage V_0 is F. The frequency of voltage V_{IN} will be



(A) F
(B) 2 F
(C) $\frac{F}{2}$
(D) 4 F

10. If a single-phase CSI feeds a capacitive load, the waveforms of output voltage and output current, respectively, are:
(A) Square; square
(B) Triangular; square
(C) Square; triangular
(D) Triangular; sine

11. The figure below shows a single-phase VSI inverter operated at 60 Hz in 180° square-wave mode and is feeding a purely inductive load. Assuming that the load current does not have any DC components, the peak value of inductor current will be



(A) 32 A
(B) 16 A
(C) 8 A
(D) 6.23 A

12. A three-phase VSI feeds an induction motor at the base speed and rated voltage. In order to reduce the motor speed by regenerative braking, which of the following actions should be taken?
(A) Reduce the inverter output frequency.
(B) Increase the output voltage.
(C) Reduce the inverter output voltage.
(D) Increase the inverter output frequency.

13. Given a three-phase, 4 pole 600 V, 60 Hz synchronous motor fed by a three-phase VSI. In order to operate the motor at 1200 rpm under constant torque region, values of stator voltage and frequency, respectively, are:
(A) 600 V; 40 Hz
(B) 400 V; 40 Hz
(C) 600 V; 60 Hz
(D) 400 V; 60 Hz

14. A three-phase VSI feeds a 500 V, 50 Hz, 4-pole synchronous motor drive. The motor drives a fan load of 400 Nm at synchronous speed. The load torque at 1200 rpm will be:
(A) 320 Nm
(B) 200 Nm
(C) 256 Nm
(D) 400 Nm

15. Which of the following inverter control schemes allows simultaneous control of output voltage and output frequency in three-phase VSI?
(A) Sinusoidal PWM scheme
(B) 180° conduction mode
(C) 120°conduction mode
(D) All of the above

Practice Problems 2

Directions for questions 1 to 15: Select the correct alternative from the given choices.

1. A single-phase bridge inverter using thyristor switches feeds a resistive load. For this operation,
(A) Forced commutation is employed.
(B) Natural commutation of thyristors occurs.
(C) The feedback diodes conduct.
(D) Commutation method will depend on magnitude of load current.

2. The output line voltage of a three-phase VSI operating under 180° conduction mode is free from:
(A) Even harmonics
(B) Odd harmonics
(C) Even and triplen harmonics
(D) Third-order harmonics

3. For a three-phase VSI.
(A) Shoot through problem is inherent in the 120° conduction mode.
(B) No shoot through problem is likely to occur in 120° conduction mode.
(C) Shoot through problem never occurs in 180° conduction mode.
(D) Sufficient dead band is inherently present in 180° conduction mode to prevent shoot through fault.

4. The ratio of RMS of third harmonic component to the fundamental component in the line voltage of a three-phase VSI in 180° conduction mode is:
(A) 1:0.33 (B) 0.33:1
(C) 0.9:1 (D) Zero

5. The advantages of using PWM switching scheme in VSI is
(A) Regulation of output voltage and frequency easily.
(B) Reduction in size of filter
(C) Reduction in harmonics
(D) All of the above

6. Which among the following is true?
(A) Feedback diodes are essential for VSI operation.
(B) CSI requires feedback diodes for proper operation.
(C) MOSFETs cannot be used in a VSI.
(D) None of the above

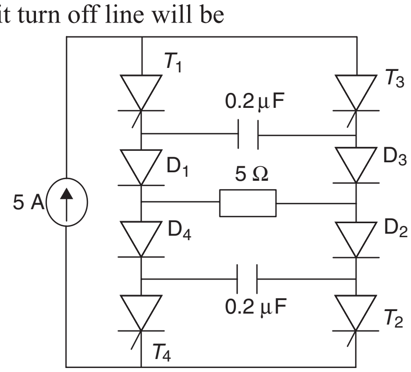
7. On operating a single-phase inverter under single-pulse modulation with a pulse width of 144°.
(A) 7th harmonic will be eliminated.
(B) third harmonic will be eliminated.
(C) 5th harmonic will be eliminated.
(D) 11th harmonic will be eliminated.

8. A single-phase inverter operates with single pulse PWM with supply voltage 10 V and pulse width 120°. What will be the ratio of fifth harmonic component to the fundamental component?
(A) 0.2 (B) 0.4
(C) 0.33 (D) 0.9

9. Which of the following statements is true?
(A) CSI has inherent protection against short circuit current.
(B) CSI needs feedback diodes.
(C) CSI is not suitable for regenerative braking of a drive.
(D) None of the above.

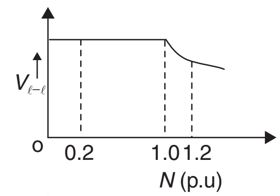
10. Load commutation can be employed in a CSI if the load power factor is
(A) Leading
(B) Lagging
(C) Unity
(D) Does not depend on load power factor

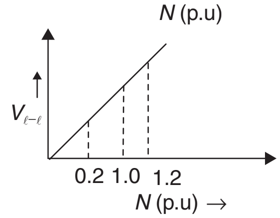
11. The figure shows a CSI feeding a resistive load. The circuit turn off line will be

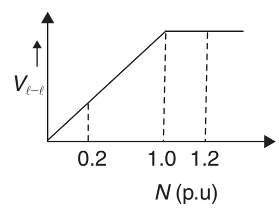


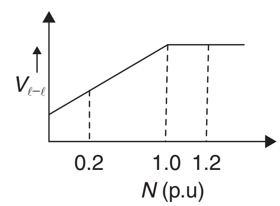
(A) 1.386 μs
(B) 0.693 μs
(C) 2.8 μs
(D) 0.347 μs

12. To control the speed of a three-phase induction motor fed by a three-phase VSI in constant torque region from 0.2 to 1.2 lines base speed, the variation of line to line voltage of VSI with speed will be of the nature.

(A)


(B)


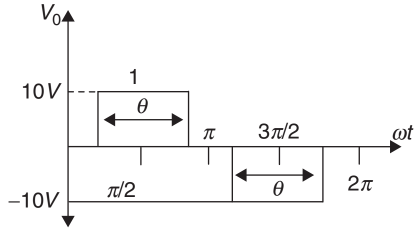
(C)


(D)


13. In order to operate a three-phase induction motor fed by a three-phase VSI in constant torque mode up to base speed,
(A) The air gap flux in the machine should be kept constant.
(B) The air gap flux should be increased with increase in speed.
(C) The air gap flux should be reduced with reduction in speed.
(D) Air gap flux has no bearing on this method of speed control.

14. If a three-phase VSI is operating in 180° conduction mode the output voltage will be controlled by:
(A) Varying switching frequency
(B) Varying input voltage and switching frequency together
(C) Varying input DC voltage alone
(D) Varying both output voltage and frequency

15. The figure shows the output voltage of a single-phase inverter. If $\theta = 150°$, the RMS of the output voltage is



(A) 2.362 V
(B) 5.625 V
(C) $\frac{10}{\sqrt{2V}}$
(D) 9.128 V

PREVIOUS YEARS' QUESTIONS

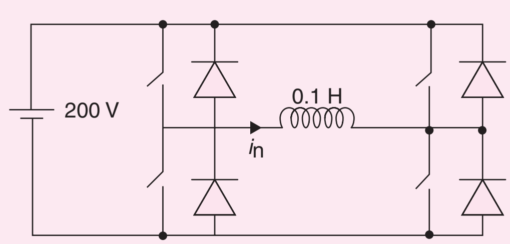
1. A VSI is used to control the speed of a three-phase, 50 Hz, squirrel cage induction motor. Its slip for rated torque is 4%. The flux is maintained at rated value. If the stator resistance and rotational losses are neglected, then the frequency of the impressed voltage to obtain twice the rated torque at starting should be **[2007]**

(A) 10 Hz (B) 5 Hz
(C) 4 Hz (D) 2 Hz

2. A 3-phase VSI is operated in 180° conduction mode. Which one of the following statements is true? **[2008]**

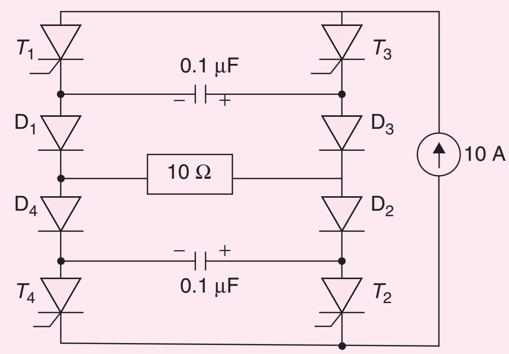
(A) Both pole voltage and line voltage will have third harmonic components.
(B) Pole voltage will have third harmonic component but line voltage will be free from third harmonic.
(C) Line voltage will have third harmonic component but pole voltage will be free from third harmonic.
(D) Both pole voltage and line voltage will be free from third harmonic components.

3. A single-phase VSI is feeding a purely inductive load as shown in the figure. The inverter is operated at 50 Hz in 180° square-wave mode. Assume that the load current does not have any DC component. The peak value of the inductor current i_0 will be **[2008]**



(A) 6.37 A (B) 10 A
(C) 20 A (D) 40 A

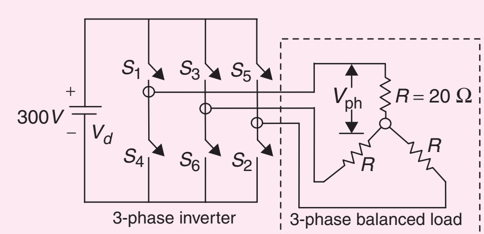
4. The CSI, shown in figure, is operated by alternately turning on thyristor pairs (T_1, T_2) and (T_3, T_4). If the load is purely resistive, the theoretical maximum output frequency obtainable will be **[2009]**



(A) 125 kHz (B) 250 kHz
(C) 500 kHz (D) 50 kHz

Common Data for Questions 5 and 6

In the 3-phase inverter circuit shown, the load is balanced and the gating scheme is 180°-conduction mode. All the switching devices are ideal.



5. The RMS value of load phase voltage is **[2012]**

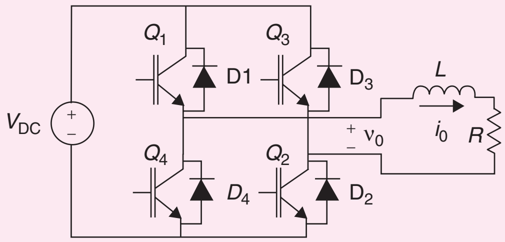
(A) 106.1 V (B) 141.4 V
(C) 212.2 V (D) 282.8 V

6. If the DC bus voltage $V_d = 300$, the power consumed by 3-phase load is **[2012]**

(A) 1.5 kW (B) 2.0 kW
(C) 2.5 kW (D) 3.0 kW

Common Data for Questions 7 and 8

The VSI shown in the figure below is switched to provide a 50 Hz, square-wave AC output voltage (V_0) across and R–L load. Reference polarity of V_0 and reference direction of the output current i_0 are indicated in the figure. It is given that $R = 3\ \Omega$, $L = 9.55$ mH.



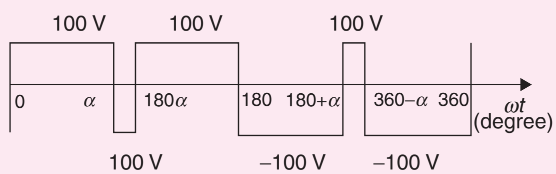
7. In the interval when $v_0 < 0$ and $i_0 > 0$, the pair of devices which conducts the load current is **[2013]**

(A) Q_1, Q_2 (B) Q_3, Q_4
(C) D_1, D_2 (D) D_3, D_4

8. Appropriate transition, i.e., zero voltage switching (ZVS)/zero current switching (ZCS) of the IGBTs during turn-on/turn-OFF is **[2013]**

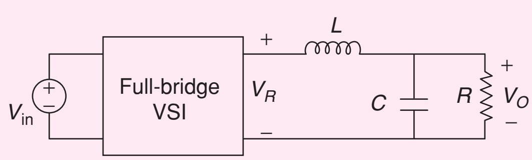
(A) ZVS during turn-OFF
(B) ZVS during turn-ON
(C) ZCS during turn-OFF
(D) ZCS during turn-ON

9. The figure shows one period of the output voltage of an inverter. α should be chosen such that $60° < \alpha < 90°$. If RMS value of the fundamental component is 50 V, then α in degree is ________ **[2014]**



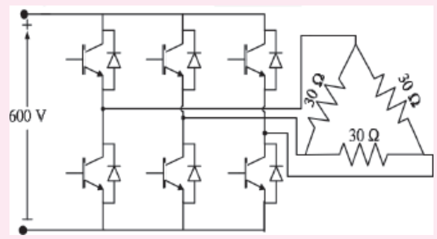
10. The single-phase full-bridge voltage source inverter (VSI), shown in figure, has an output frequency of 50 Hz. It uses unipolar pulse width modulation with switching frequency of 50 kHz and modulation index of 0.7. For V_{in} = 100 V DC, L = 9.55 mH, C = 63.66 μF, and R = 5 |, the amplitude of the fundamental component in the output voltage V_o (in Volts) under steady – state is ___________. **[2015]**

11. A 3-phase 50 Hz square wave (6-step) VSI

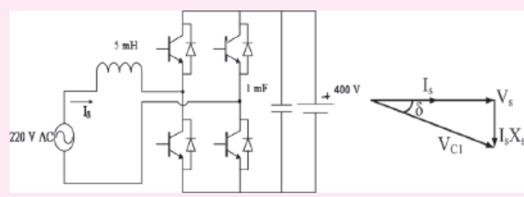


feeds a 3-phase, 4 pole induction motor. The VSI line voltage has a dominant 5th harmonic component. If the operating slip of the motor with respect to fundamental component voltage is 0.04, the slip of the motor with respect to 5th harmonic component of voltage is ______. **[2015]**

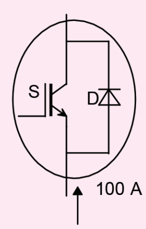
12. A three-phase Voltage Source Inverter (VSI) as shown in the figure is feeding a delta connected resistive load of 30Ω/phase. If it is fed from a 600V battery, with 180° conduction of solid-state devices, the power consumed by the load, in kW, is ________. **[2016]**



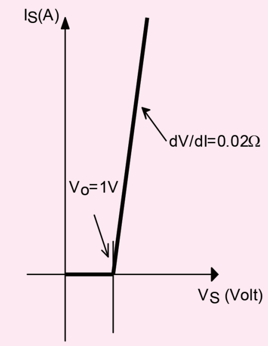
13. A single-phase bi-directional voltage source converter (VSC) is shown in the figure below. All devices are ideal. It is used to charge a battery at 400V with power of 5kW from a source V_s = 220 V(rms), 50HZ sinusoidal AC mains at unity p.f. If its AC side interfacing inductor is 5mH and the switches are operated at 20KHz, then the phase shift (δ) between AC mains voltage (V_s) and fundamental AC rms VSC voltage (V_{c1}), in degree, is ________. **[2016]**



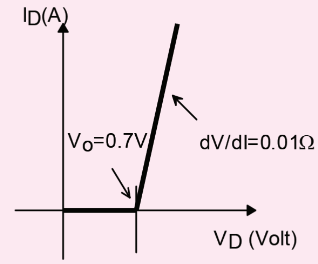
14. A steady dc current of 100 A is flowing through a power module (S, D) as shown in Figure (a). The V-I characteristics of the IGBT (S) and the diode (D) are shown in Figures (b) and (c), respectively y. The conduction power loss in the power module (S, D), in watts, is ____________. **[2016]**



(a)



V-I characteristic of IGBT
(b)



V-I characteristic of diode
(C)

Answer Keys

Exercises

Practice Problems 1

1. A **2.** C **3.** D **4.** A **5.** A **6.** C **7.** A **8.** A **9.** B **10.** B
11. C **12.** A **13.** B **14.** C **15.** A

Practice Problems 2

1. A **2.** C **3.** B **4.** D **5.** D **6.** A **7.** C **8.** A **9.** A **10.** A
11. B **12.** D **13.** A **14.** C **15.** D

Previous Years' Questions

1. C **2.** D **3.** B **4.** B **5.** B **6.** D **7.** D **8.** D **9.** 77.15
10. 63.05 **11.** 1.2 **12.** 24 **13.** 9.21 **14.** 170 W