Chapter 5

AC Voltage Converters (OR) Controllers and Electric Drives

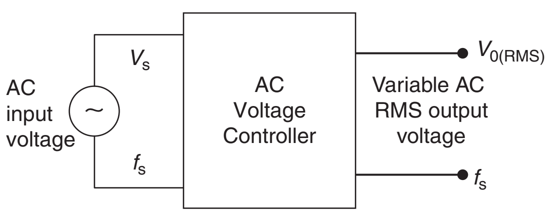
LEARNING OBJECTIVES

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

- AC voltage controllers
- Single-phase half-wave AC voltage controller
- Single-phase full-wave AC voltage controller (AC regulator) or rms voltage controller with resistive load
- Single-phase full-wave AC voltage controller with RL load
- Two-stage sequence control
- Cyclo converters
- Electric drives
- Basic concept of speed control
- Controlling effective rsesistance in the rotor circuit
- Single-phase dual converter drives

AC Voltage Controllers

AC voltage controllers (AC line voltage controller) are employed to vary the RMS value of the alternating voltage applied to a load circuit by introducing thyristors between the load and a constant voltage AC source. The RMS value of alternating voltage applied to a load circuit is controlling the thyristors in the AC voltage controller circuits.



- An AC voltage controller is a type of thyristor power converter which is used to convert a fixed voltage, fixed frequency AC input supply to obtain a variable voltage AC output.

The RMS value of the AC output voltage and the AC power flow to the load is controlled by varying (adjusting) the trigger angle α.

Types of AC Voltage Controllers

They are classified into two types based on the type of input AC supply.

- Single-phase AC voltage controllers.
- Three-phase AC voltage controllers.
- Single-phase AC voltage Controllers operate with single-phase AC supply voltage of 230 V RMS at 50 Hz.
- Three-phase AC voltage controllers operate with three-phase AC supply of 400 V RMS at 50 Hz. Supply frequency. Each type of controller may be subdivided into
  - Unidirectional or half wave AC controller
  - Bidirectional or full wave AC controller

They are commonly used for

- Lightning/illumination control in AC power circuits.
- Induction heating.
- Industrial heating and domestic heating.
- Transformers tap changing (on load transformer tap changing).
- Speed control of induction motor (single-phase and poly-phase conduction).
- AC magnet controls.

AC Voltage Control Techniques

There are two different types of thyristor control used in practice to control the AC power flow.

- Phase angle control
- ON–OFF control

In ON–OFF control technique thyristors are used as switches to connect the load circuit to the AC supply (source) for a few cycles of the input AC supply and then to disconnect if for few input cycles. The thyristors thus act as high speed contactor (or switch).

Phase Control Technique

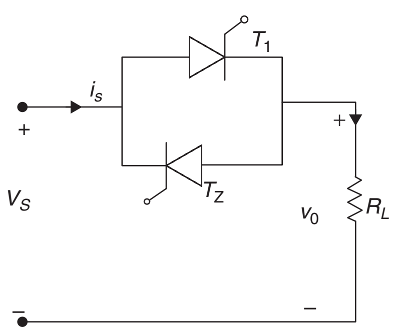
In phase control, the thyristors are used as switches to connect the load circuit to the input AC supply, for a part of every input cycle.

- By controlling the phase angle or the trigger angle α (delay angle), the output RMS voltage across the load can be controlled.
- They use AC line commutation or AC phase commutation.
- Since the input is AC, the commutation is line commutation.
- For applications up to 400 Hz, Triacs are more commonly used.
- Since no commutation circuit, they are more commonly used.
- Since no commutation circuit, they are very simple.

Principle of ON–OFF Control Technique (Integral Cycle Control)

The thyristors switches T_1 and T_2 are turned on by applying appropriate gate trigger pulses to connect the input AC supply to load for n number of input cycle during the time interval t_{ON}.

The thyristor switches T_1 and T_2 are turned off by blocking the gate trigger pulses for 'm' number of input cycles during the time interval t_{OFF}.



n = two input cycles – t_{ON}

m = one input cyclo – t_{OFF}

$$V_s = V_m \sin\omega t$$

$$= \sqrt{2}V_s \sin\omega t$$

V_s = RMS value of input AC supply

$$= \frac{V_m}{\sqrt{2}} = \text{RMS phase supply voltage}$$

$$t_{ON} = n \times T$$

$$t_{OFF} = m \times T$$

$$T = \frac{1}{F}$$

Output RMS voltage $V_{0(RMS)} = V_{i(RMS)} \sqrt{\frac{t_{ON}}{T_0}}$

$V_{i(RMS)}$ = input RMS supply voltage (V_s)

$$\frac{t_{ON}}{T_0} = \frac{t_{ON}}{T_{ON} + T_{OFF}} = \frac{nT}{nT + mT}$$

$$= \frac{n}{n+m} = k = \text{duty cycle}$$

$$V_{0(RMS)} = V_s \sqrt{\frac{n}{(n+m)}} = V_s \sqrt{k}$$

Duty Cycle: $K = \dfrac{n}{m+n}$

RMS load current

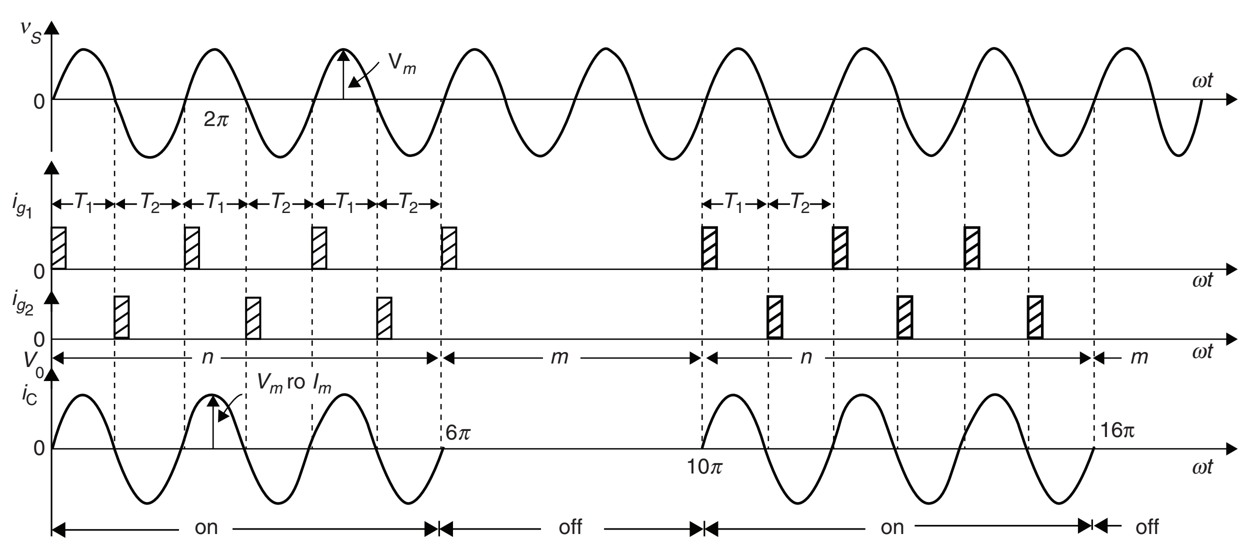
$$I_{0(RMS)} = \frac{V_{0(RMS)}}{Z} = \frac{V_{0(RMS)}}{R_L}$$

Output AC (Load) Power:

$$P_0 = I^2_{0(RMS)} \times R_L$$

Input Power Factor:

$$PF = \frac{P_0}{VA} = \frac{P_0}{V_S I_S}$$



$$\text{P.F.} = \sqrt{K} = \sqrt{\frac{n}{m+n}}$$

The average current of thyristor I_T (avg)

$$I_T = \frac{I_m n}{\pi(m+n)} = \frac{KI_m}{\pi}$$

RMS current of thyristor $I_{T_{RMS}} = \frac{I_m}{Q}\sqrt{k}$

Solved Examples

Example 1: A 1-ϕ AC voltage controller working on ON–OFF control technique has supply voltage of 230 V, RMS 50 Hz load = 50 Ω, The controller is ON for 30 cycles and OFF for 40 cycles. Calculate, ON and OFF time intervals RMS output voltage Input p.f., average and RMS thyristor currents.

Solution: $V_{(RMS)} = 230$ V

$$V_m = \sqrt{2}\times 230$$
$$= 325.269 \text{ V}$$
$$T = \frac{1}{f} = \frac{1}{50\text{ Hz}} = 0.02 \text{ s}$$
$$T = 20 \text{ ms}$$
$$n = 30 \text{ ON}$$
$$M = 40 \text{ OFF}$$
$$t_{ON} = n \times T = 30 \times 20 \text{ ms} = 600 \text{ ms} = 0.6 \text{ s}$$
$$T_{OFF} = m \times T = 40 \times 20 \text{ ms} = 800 \text{ ms} = 0.8 \text{ s}$$

Duty cycle $k = \frac{n}{m+n} = \frac{30}{40+30} = 0.4285$

RMS output voltage

$$V_{0(RMS)} = V_{i\,(RMS)}\sqrt{\frac{n}{n+m}}$$
$$V_{0(RMS)} = 230\text{ V}\sqrt{3/7} = 150.570 \text{ V}$$
$$I_{0(RMS)} = \frac{V_{o_{RMS}}}{z} = \frac{V_{o_{RMS}}}{R_L} = \frac{150.570}{50\ \Omega} = 3.01 \text{ A}$$
$$P_0 = I^2_{0\,(RMS)} \times R_L = (3.0114)^2 \times 50 = 453.426 \text{ W}$$

Input p.f. $= \sqrt{K} = \sqrt{\frac{n}{m+n}} = 0.6546$

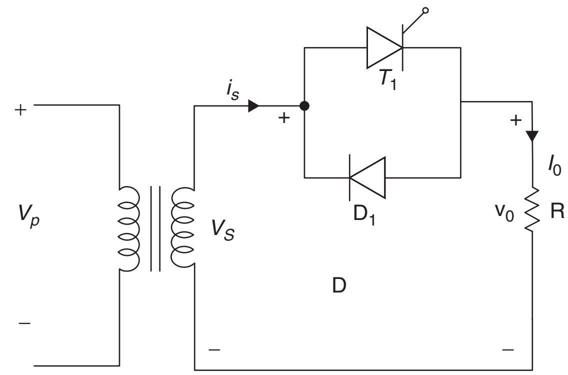
Average thyristor current rating

$$I_{T(Avg)} = \frac{k \times I_m}{\pi} = 0.88745 \text{ A}$$

RMS current rating of Thyristor

$$I_T\,(\text{RMS}) = \frac{I_m}{2} \times \sqrt{k} = 2.12986 \text{ A}$$

Single-phase Half-wave AC Voltage Controller

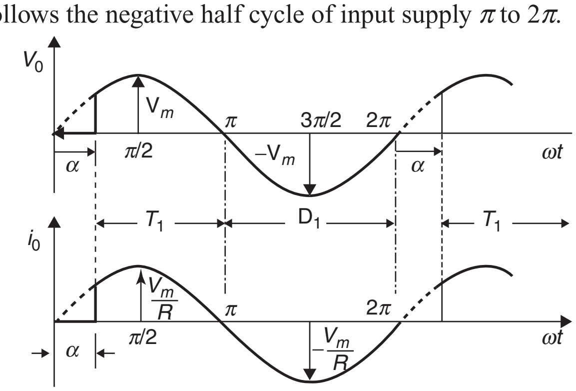


The half wave AC controller uses one thyristor and one diode connected in parallel across each other in opposite direction that is anode of thyristor T_1 is connected to the cathode of diode D_1 and the cathode of T_1 to the anode of D_1.

- The output voltage across the load V resistor 'R' and hence the AC power flow to the load is controlled by varying the trigger angle α.
- The thyristor T_1 is forward biased during the positive half cycle of input AC supply. It can be triggered and made to conduct by applying a suitable gate trigger pulse only during the positive half cycle of input supply. When T_1 is triggered it conducts and the load current flows through the thyristor T_1, the load and through the transformer secondary winding.

When the supply voltage reverses and becomes negative the diode D_1 becomes forward biased and hence turns ON and conducts.

The load current flows in the opposite direction during $\omega t = \pi$ to 2π radians when D_1 is ON and the output voltage follows the negative half cycle of input supply π to 2π.



Equations

Input AC supply voltage across the transformer secondary winding:

$$V_s = V_m \sin\omega t$$
$$V_s = V_{m\,(RMS)} = \frac{V_m}{\sqrt{2}}$$
$$= \text{RMS Value of secondary supply voltage}$$

Output load voltage

$$V_0 = V_L = 0 \text{ for } \omega t = 0 \text{ to } \infty$$
$$V_0 = V_L = V_m \sin\omega t \text{ for } \omega t = \alpha \text{ to } 2\pi$$

Output load current

$$I_0 = i_L = \frac{V_o}{R_L} = \frac{V_m \sin\omega t}{R_L} \quad \text{for } \omega t = \infty \text{ to } 2\pi$$

$$I_0 = i_L = 0 \text{ for } \omega t = 0 \text{ to } \infty$$

the RMS values of the output voltage $V_{0(\text{RMS})}$

$$V_{0(\text{RMS})} = \sqrt{\frac{1}{2\pi}\left[\int_{\alpha}^{2\pi} V_m^2 \sin^2 \omega t d(\omega t)\right]}$$

$$V_{0(\text{RMS})}\ V_s = \sqrt{\frac{1}{2\pi}(2\hat{\lambda} - \alpha) + \frac{\sin 2\alpha}{2}}$$

where $V_{1(\text{RMS})} = V_s = \frac{V_m}{\sqrt{2}} =$ RMS value of input supply voltage (across the transformer secondary winding)

- Half wave AC controller has the drawback of limited range RMS output voltage control.

The average value (DC value) of output voltage

$$V_{0(\text{DC})} = \frac{1}{2\pi}\int_{\alpha}^{2\pi} V_m \sin\omega t d(\omega t)$$

$$V_{0(\text{DC})} = \frac{V_m}{2\pi}\int_{\alpha}^{2\pi} \sin\omega t d(\omega t)$$

$$V_{\text{DC}} = \frac{V_m}{2\pi}\left[\cos\alpha - 1\right]$$

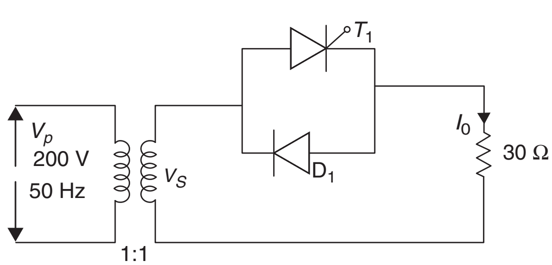
$$V_m = \sqrt{2}V_s$$

$$\therefore \quad V_{\text{DC}} = \frac{\sqrt{2}V_s}{2\pi}(\cos\alpha - 1)$$

When α is varied from o to π, V_{DC} varies from o to $\frac{-V_m}{\pi}$

- The half wave AC voltage controller using a single thyristor and a single diode provides control on the thyristor and a single diode provides control on the thyristor only in one half cycle of the input supply. Hence, AC power flow to the load can be controlled only in one half cycle.

Common Data for Examples 2 and 3:



A single-phase voltage controller has the specifications as shown in the above figure. If T_1 is triggered at $\alpha = 30°$. Then

Example 2: RMS value of output voltage would be

(A) 218.47 V (B) 198 V
(C) 200 V (D) 226.67 V

Solution: (B)

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{1}{1}$$

$$V_s = V_P = 200 \text{ V}$$

$$(V_0)_{\text{RMS}} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi} V_m^{\ 2} \sin^2 \omega t\, d\omega t}$$

$$V_0 = V_m\sqrt{\frac{1}{2\pi}\left[(2\pi - \alpha) + \frac{\sin 2\alpha}{2}\right]}$$

$$= V_m\sqrt{\frac{1}{2\pi}[5.76 + 0.433]}$$

$$= 200 \times 0.99 = 198 \text{ V}$$

Example 3: The input power factor would be

(A) 0.949 (B) 0.75
(C) 0.99 (D) 0.86

Solution: (C)

$$(I_0)_{\text{RMS}} = \frac{(V_0)_{\text{RMS}}}{R_L} = \frac{198}{30} = 6.6 \text{ A} = I_s$$

$$P_0 = \frac{(V_0)^2_{\text{RMS}}}{R_L}\ \frac{198^2}{30} = 1.3068 \text{ kW}$$

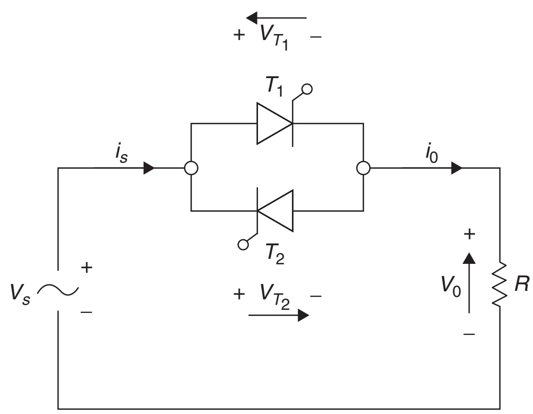
$$\text{Input power factor} = \frac{P_0}{V_S I_S} = \frac{1.3068 \times 10^3}{200 \times 6.6}$$

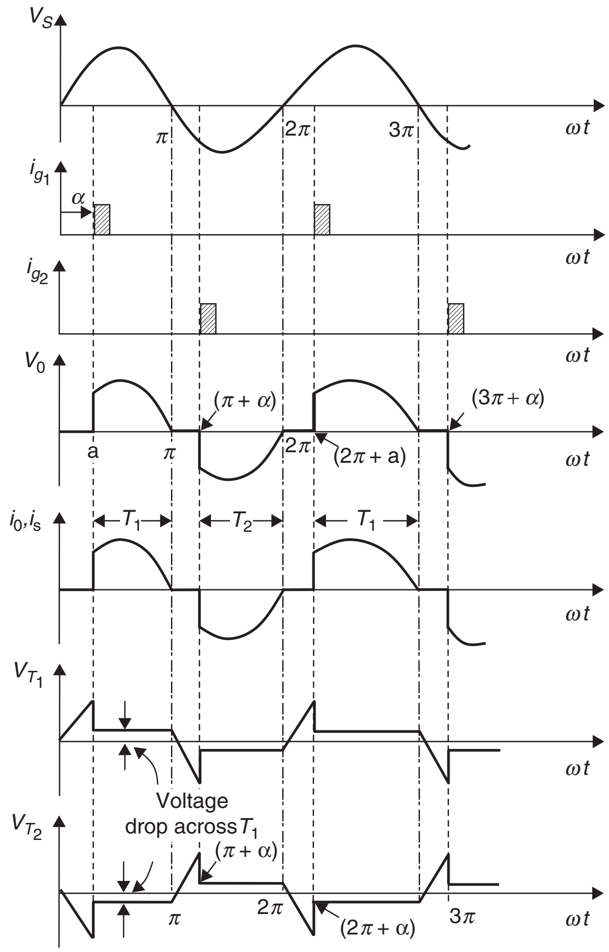
$$= 0.99$$

Single-phase Full-wave AC Voltage Controller (AC Regulator) or RMS Voltage Controller with Resistive Load

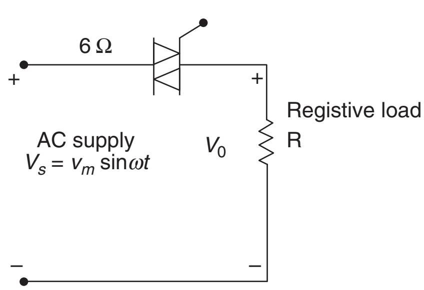
Single-phase full wave AC voltage controller circuit using two SCRs or a single triac is generally used in most of the AC control applications. The AC power flow to the load can be controlled in both the half cycles by varying the triggering angle α The RMS value of load voltage can be varied by varying the trigger angle α.

- There is no DC component of input supply current, because input supply current is alternating in the case of a full wave AC voltage controller and symmetrical in nature. It is also referred to as to a bi directional controller.





Instead of using two SCRs in parallel, a triac can be used for full-wave AC voltage TRIAC.



Circuit turn-off time, $t_c = \dfrac{\pi}{\omega}$ s

RMS output voltage

$$V_{or} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \, d\omega t\right]^{1/2}$$

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

$$I_{or} = \frac{V_{or}}{R} = \text{RMS value of load current}$$

Power delivered to the load

$$P = I_{or}^2 \, . \, R = \frac{V_m^2}{2\pi R}\left[(\pi - \alpha) + \frac{1}{2}\sin 2\alpha\right]$$

$$\text{Power factor P.F.} = \frac{V_s I_1 \cos\phi_1}{V_s I_{RMS}} = \frac{\text{Real power}}{\text{Apparent power}}$$

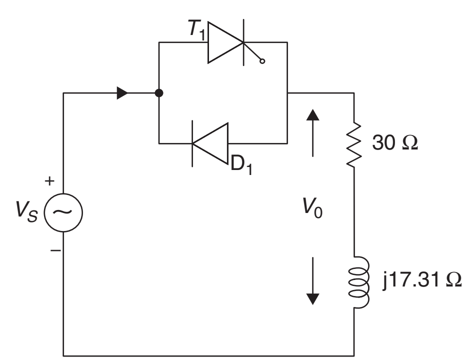
$$\text{P.F.} = \frac{I_1 \cos\phi_1}{I_{RMS}}$$

where ϕ_1 = Phase angle between V_s and I_1

I_1 = RMS value of fundamental component of source current

$$\text{P.F.} = \frac{V_{or}}{V_s} = \left\{\frac{1}{\pi}\left[(\pi - \alpha) + \frac{1}{2}\sin 2\alpha\right]\right\}^{1/2}$$

Example 4: The below figure shows a single-phase voltage controller circuit.



The output voltage V_0 is uncontrollable for firing angle ranging between

(A) $0 < \alpha < 45°$ (B) $0 < \alpha < 30°$
(C) $45° < \alpha < 135°$ (D) $30 < \alpha < 120°$

Solution: (B)

For controlling the load, the minimum value of firing angle α = load phase angle

$$\phi = \tan^{-1}\left[\frac{\omega L}{R}\right] = \tan^{-1}\left[\frac{17.31}{30}\right]$$

$$\phi = 30°$$

Range of firing angle for which output voltage is uncontrollable $0 < \alpha \le \phi$

$$0 < \alpha \le 30°$$

Example 5: A single-phase AC voltage controller feeding a pure resistive load has a load voltage of 150 V (RMS) when fed from a source of 200 V. The input power factor of the controller is

(A) 0.65 (B) 0.7 (C) 0.75 (D) 0.8

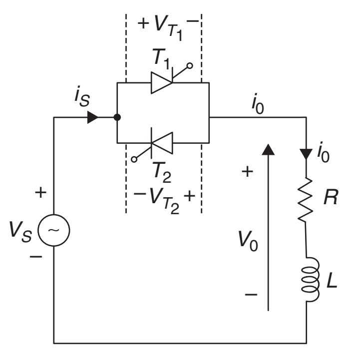
Solution: (C)

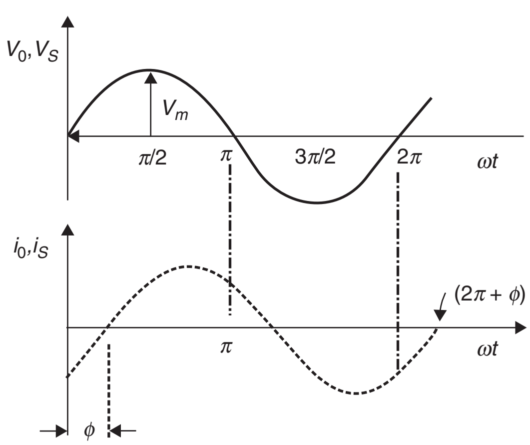
$$\text{P.F.} = \frac{V_0}{V_s} = \frac{150}{200} = 0.75$$

Single-phase Full-wave AC Voltage Controller with RL Load

The RMS Value of the output voltage and the load current may be varied by varying the trigger angle α. The circuit AC RMS voltage across the terminals of an AC motor (induction). It can be used to control the temperature of a furnace by varying the RMS output voltage.

- For very large load inductance 'L' the SCR may fail to commutate, after it is triggered and the load voltage will be a full sine wave as long as the gating signals are applied to the thyristors T_1 and T_2.





Circuit turn-off time, $t_c = \dfrac{\pi}{\omega}$ s

Load current

$$I_0 = \frac{V_m}{Z}\left[\sin(\omega t - \phi) - \sin(\alpha - \phi).\exp\left\{\frac{R}{L}\left(\frac{\alpha}{\omega} - t\right)\right\}\right]$$

At $\omega t = \beta$ (or) $t = \dfrac{\beta}{\omega}$

$$0 = \sin(\beta - \phi) - \sin(\alpha - \phi)\exp\left[\frac{R}{L}\left(\frac{\alpha - \beta}{\omega}\right)\right]$$

$$\sin(\beta - \phi) = \sin(\alpha - \phi)\exp\left[\frac{R}{L}\left(\frac{\alpha - \beta}{\omega}\right)\right]$$

Conduction angle $\gamma = (\beta - \alpha)$

Maximum thyristor

Conduction angle

$$\delta = (\beta - \alpha) = \pi \text{ radians} = 180° \text{ for } \alpha < \phi$$

RMS output voltage

$$V_{0(\text{RMS})} \frac{V_m}{\sqrt{2}} = \sqrt{\frac{1}{\pi}(\beta - \alpha) + \frac{\sin 2\alpha}{2} - \frac{\sin\frac{2\beta}{2}\beta}{2}}$$

The average thyristor current

$$I_{\text{T(Avg)}} = \frac{1}{2\pi}\left[\int_{\infty}^{\beta} i_{T1}\, d(\omega t)\right]$$

Maximum value of $I_{\text{T(Avg)}}$

Occur at $\alpha = 0$

$$\Rightarrow \quad I_{\text{T(Avg)}} = \frac{V_m}{z}$$

RMS Thyristor current $I_{\text{T(RMS)}}$

$$I_{\text{T(RMS)}} = \left[\frac{1}{2\pi}\int_{\infty}^{\beta} i_{T_1^2}(\omega t)\right]$$

Maximum value of $I_{\text{T(RMS)}}$

Occurs at $\alpha = 0$

Thyristors should be rated for maximum.

$$I_{\text{T(RMS)}} = \frac{I_m}{\sqrt{2}}$$

When a TRIAC is used in a single-phase full wave AC Voltage controller with RL load, then I_T (Avg) = 0 and maximum.

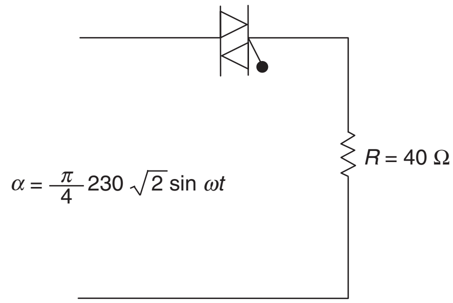
$$T_T\,(\text{RMS}) = \frac{I_m}{\sqrt{2}}$$

Example 6: A single-phase AC voltage controller is controlling current in a purely inductive load. If the firing angle of the S.C.R. is α, then the conduction angle will be

(A) 2π (B) $2\pi - \alpha$
(C) π (D) $\pi - \alpha$

Solution: (D)

Example 7: The triac circuit shown in figure controls the AC output power to the resistive load. The peak power dissipation in the load is



(A) 3968 W (B) 5290 W
(C) 7935 W (D) 10,580 W

Solution: (D)

For resistive load, peak power = $\frac{V_m^{\ 2}}{R}$

$$V_m = 230 \times \sqrt{2} \ = \frac{\left(230 \times \sqrt{2}\right)}{10}$$

$$= 10{,}580 \text{ W}$$

Two-stage Sequence Control

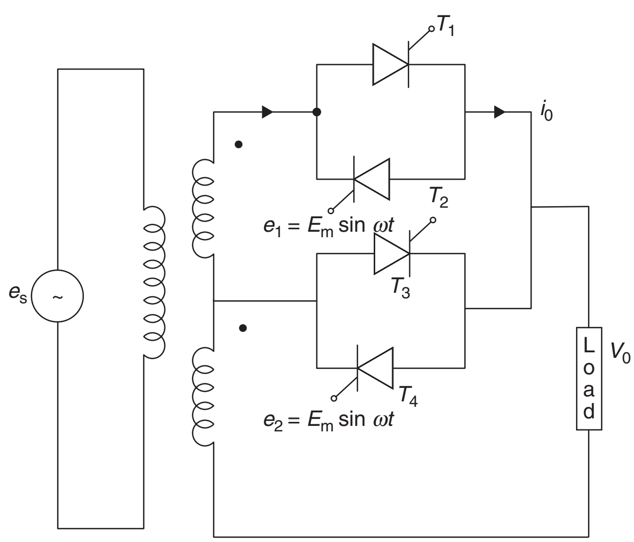
Two-stage sequence control of AC regulator employs two stages in parallel. The turn ratio from primary to each secondary is taken as unity.

For source voltage

$$e_s = E_m \sin\omega t.$$

$e_1 = e_2 = E_m \sin\omega t$ and the sum of two secondary voltages is $2E_m \sin\omega t$ for both R and RL loads, for obtaining output voltage control from zero to RMS value E, only thyristor pairs T_3, T_4 are used.

For zero output voltage, α is 18° for T_3 and T_4 and for E, α is zero for output voltage control from E to $2E$, α for thyristor pair T_3 and T_4 is always zero and for thyristor pair T_1, T_2 it is varied from zero to 180°.



Multistage Sequence Control of AC Regulators

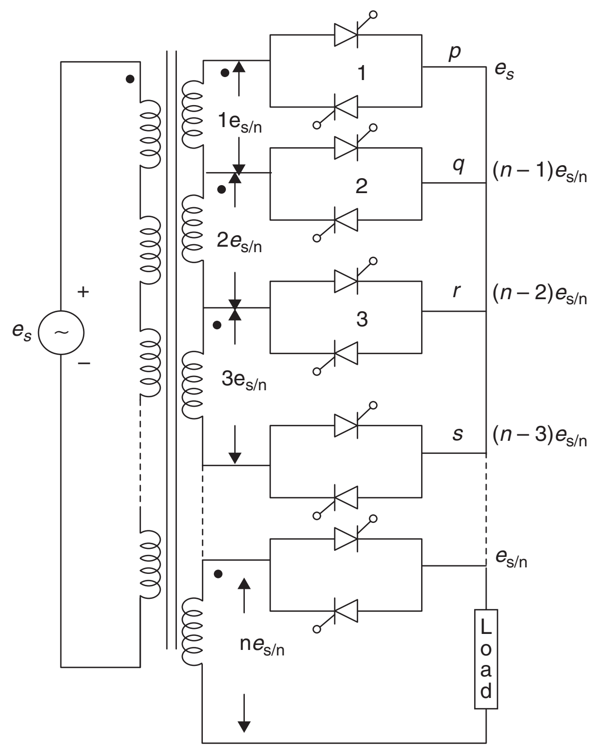
By using more than two stages of sequence control, is possible to have further improvement in power factor and reduction in harmonics than that in a two stage sequence control.

The transformer has n secondary windings. Each secondary is rated for $e_{s/n}$, where e_s is the source voltage.

The voltage node P with respect to K is e_s.

Voltage of terminal q is $(n - 1)\, e_{s/n}$ and so on. If voltage control from $e_{sk} = (n - 3)\, e_{s/n}$ to $e_{rk} = (n - 2)\, e_{s/n}$ is required then thyristor pair 4 is triggered at $\alpha = 0°$ and the firing angle of thyristor pair 3 is controlled from $\alpha = 0°$to 180°, whereas e_s all other thyristor pairs are kept OFF.

The load voltage can be controlled from $e_{s/n}$ to e_s by an appropriate control of triggering the adjacent thyristor pairs.



The presence of harmonics in the output voltage depends upon the magnitude of voltage variation. If this voltage variation is a small fraction of the total output voltage the harmonic content in the output voltage is small. Multistage sequence control of AC regulators.

Example 8: AC voltage regulators are widely used in
(A) Traction drives
(B) Fan drives
(C) Synchronous motor drives
(D) Slip power recovery scheme of slip ring induction motor.

Solution: (B)

Cyclo Converters

A cyclo converter is an AC to AC converter that directly converts AC power at input frequency to an output AC power at a different frequency without employing an intermediate DC stage. It is therefore, a single stage frequency converter. They are of two types.

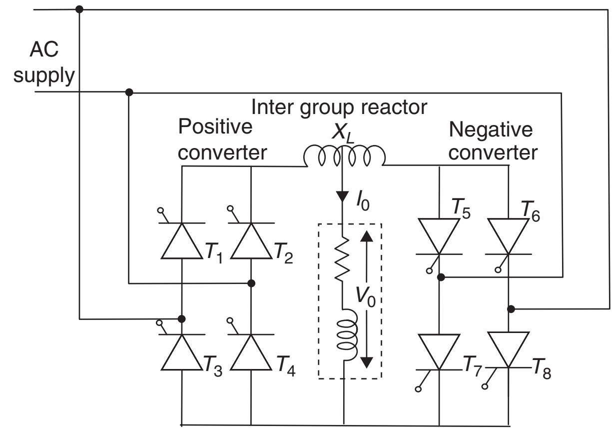
1. Step-down cyclo converter in which like a step-down transformer gives reduced voltage as output), provides an AC output whose frequency is less than that of the input, that is $f_0 < f_i$.
2. Step-up cyclo converter in which the output frequency is greater than the input frequency as in a step-up transformer whose output voltage is greater than the input voltage, $f_0 > f_i$.
   - A step-down cyclo converter uses thyristors as power switches. The maximum output frequency is limited to a fraction of supply frequency below 20 Hz in the case of 50 Hz input converter.
   - The thyristor are line commutated, there is no need for separate commutation circuits.
   - But a step-up cyclo converter needs forced commutation of thyristors, which makes the cyclo converter of this type relatively complex.
   - A frequency changer cyclo converter finds application in the following areas:
     — Speed control of high power AC drives
     — Induction heating
     — For converting variable frequency voltage from a variable speed alternator to a constant frequency voltage
   - The majority of cyclo converters are step-down type.

The step-down cyclo converter circuits, namely:

1. Single-phase to single-phase cyclo converter
2. Three-phase to single-phase cyclo converter and
3. Three-phase to three-phase cyclo converter

- A step-down cyclo converter is essentially a wave synthesizer.
- In addition to frequency cyclo converter, output voltage can be varied by the application of phase control principle.
- Cyclo converter can be used to provide either variable frequency output from fixed frequency input or vice versa.
- A cyclo converter can also handle loads of lagging as well as leading power factor in addition to unity power factor loads.
- This is because cyclo converter permits power flow in either direction.
- The output voltage wave is a distorted sine wave the associated harmonic components can be filtered out if necessary the distortion is low for low frequency outputs but increases with output frequencies.

(a) Single-phase to Single-phase Cyclo Converter Feeding RL Load



Two single-phase fully controlled converters are connected in anti-parallel, as in dual converter. Converter 1 produces positive load current and when converter 2 conducts, the load current reverses.

- Two converters should not conduct together as their will produce a short circuit on the input.

The firing angles of SCRs in the two converters are kept the same so that the output load voltage is symmetrical for resistive loads,

- With R-load, they undergo natural commutation and produce discontinuous current operation.
- With inductive loads, line commutation taken place and the load current is continuous.
- The instantaneous value of output voltage will become negative because for inductive load, SCR conduct for duration more than $(\pi - \alpha)$ in each half cycle of the input.
- If only one converter conducts at a time, then it is known as non-circulating current scheme.
- In non-circulating current scheme, there is a dead time during the changeover of current.

Example 9: The quality of output AC voltage of a cyclo converter is improved with

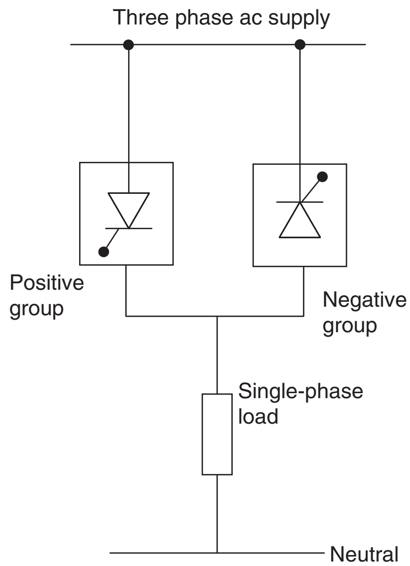
(A) Increase in output voltage with increased frequency.
(B) Decrease in output voltage with increased frequency.
(C) Increase in output voltage at reduced frequency.
(D) Decrease in output voltage at reduced frequency.

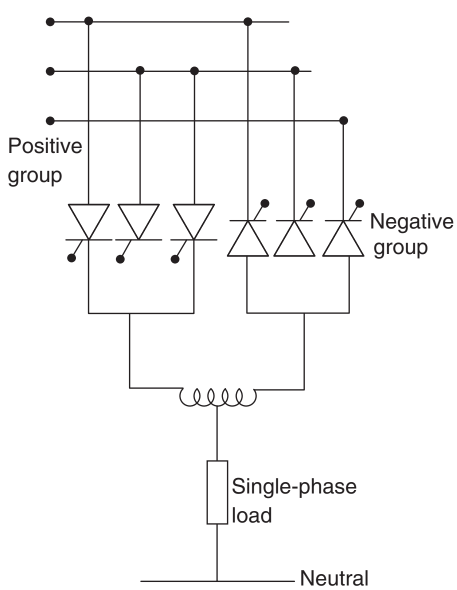
Solution: (A)

(b) Three-phase to Single-phase Cyclo Converter

- Many industrial AC voltages as input single phase to single, phase cyclo converter are seldom used in single-phase induction motor control because it can supply only non-sinusoidal output voltage.

- A very nearly sinusoidal output voltage can be fabricated from three-phase input voltage waves by means of three-phase to single-phase cyclo converters.





The positive group converter P is a three-phase half-wave-controlled rectifier that can conduct load current that flows downward towards the neutral.

- Negative group converter N is also a three-phase half-wave controlled rectifier which conducts the load current in the reverse.
- The inter group reactor is sometimes necessarily used to limit the circulating current common to P and N converters.
- The low frequency load voltage is fabricated by P and N converters making use of three-phase input supply by varying the firing angle of three thyristors of a three-phase half-wave circuit.

The average direct voltage output is given by

$$V_d = V_{do} \cos \alpha$$

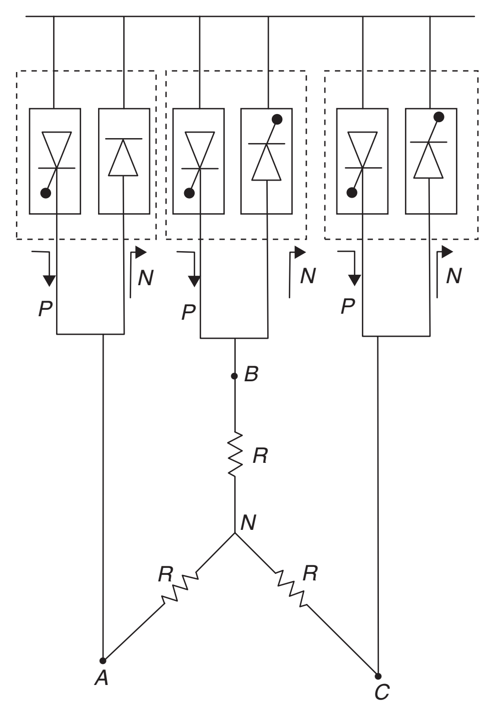
α = firing angle

V_{do} = maximum output voltage with zero firing delay.

(c) Three-phase to Three-phase Cycloconverter

A three-phase output can be obtained by a phase displacement of 120° from three similar three-phase to single-phase cyclo converters.

- It requires six thyristors per phase and 18 thyristors in all.
- If each phase consists of a three-phase bridge then 36 thyristors are required.
- The average value of the output voltage can be varied by varying the delay angle of the thyristors, whereas the frequency of the output voltage can be varied by changing the sequence of thyristor triggering.
- With a balanced load, the neutral connection is no longer necessary and can be omitted.



- Three-phase cyclo converters can handle large amounts of current and produce a smoother output waveform.
- It is a highly efficient, variable speed of drive because the large number of thyristor increases the pulse number, which causes a small amplitude ripple content in the load voltage waveform.

Example 10: In the construction of a three-phase cyclo converter, the number of switches required is

(A) 12 (B) 18 (C) 3 (D) 6

Solution: (B)

Example 11: Among the following, a cyclo converter fed induction motor drive is most suitable for
(A) Machine tool drive
(B) Compressor drive
(C) Paper mill drive
(D) Cement mill drive

Solution: (A)

Electric Drives

An electric drive is an electromechanical system that employs an electric motor as the prime mover instead of a diesel engine, steam or gas turbines, hydraulics, etc., to control the motion and processes of different machines and mechanisms. Typical applications of electric drives include fans, ventilators compressor pumps, hoists, cranes, conveyors, excavators, escalators, electric locomotives and cars.

- Drives that use electric motors as the prime movers are known as electric drives.
- It consists of a motor, micro controller, feedback circuit and a power electronic circuit Motor is a subset of drive.

(Output of converter = Input of motor); output voltage of converter acts as terminal voltage of motor.

Application of Choppers and Inverters

(a) Choppers

1. Speed control of DC series motor
2. Switch mode power supplies

(b) Inverters

1. Speed control of AC series motors
2. Induction heating
3. Air craft power supplies
4. Uninterruptable power supplies

Speed Control of Motors

Speed Control of DC Motors

Phase Control

When supply is AC the current is controlled to flow from supply to the motor for a fraction of each positive half cycle, this is repeated cyclically.

- It can be applied for all motor ratings.

Integral Cycle Control

- This method is useful for small fractional kW size motors.
- From AC supply, the current is made to flow for a number of complete cycles and quenched for a further number of cycles and the sequence of operation is repeated.
- 'ON' and 'OFF' duration ratio is adjusted by control.

Chopper Control

A DC voltage can be switched ON and OFF rapidly and repeatedly by means of a thyristor to a DC motor.

- The average DC voltage is controlled by varying ON/OFF time ratio.
- This type of control is used for traction motors.

Basic Concept of Speed Control

Speed of a DC motor, $\omega = \dfrac{E}{K_c \phi}$

So, speed of a DC machine can be controlled either by varying flux ϕ (or) by controlling supply voltage V, which is done by the following two methods.

1. Field flux control (Constant power drive)
2. Armature voltage control (Constant torque drive)

Speed Control of AC Motors

Speed of induction motor can be varied by varying its terminal voltage and motor resistance.

Speed Control Schemes

Speed of induction motor can be controlled by using suitable power electronic converter.

1. Stator voltage control
2. Stator frequency control
3. Stator voltage and frequency control
4. Stator current control
5. Static rotor resistance control
6. Slip energy recovery control

Stator Voltage Control

By controlling firing angle of the thyristors, the RMS value of the stator voltage can be regulated or controlled. Hence motor torque and speed can be controlled.

Stator Voltage and Frequency Control

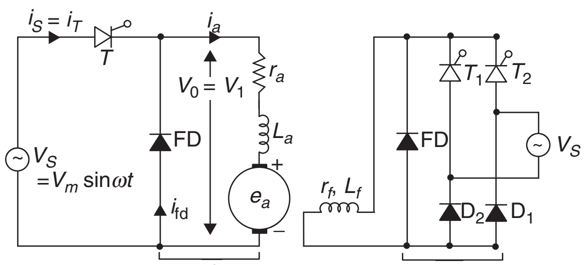
- In this V/f ratio is kept constant, so that air-gap flux, ϕ will remain constant.
- Control of stator voltage and frequency can be implemented by using three-phase inverters or cyclo converters.
- Generally voltage source inverter and PWM inverter are used for voltage and frequency control.

Stator Current Control ($T \propto I^2{}_l$)

- By controlling stator current I_1, we can control torque, hence we can control speed.
- Stator current control method is employed using current source inverters.

Controlling Effective Resistance in the Rotor Circuit

1. **Phase-Controlled Rectifier:** Scheme: In this scheme firing circuit is synchronized with rotor frequency.
2. **Chopper-Controlled Resistance Scheme:** It does not require synchronization with rotor frequency

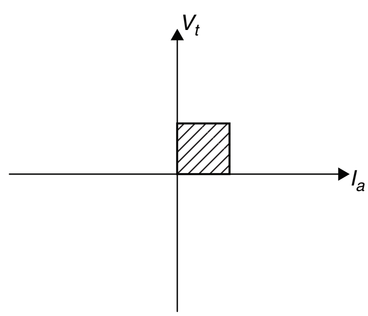


(a)

Single-phase Converter Drives

Single-phase Half-wave Converter Drives

- The diagram below is a separately excited DC motor, fed through single-phase, half-wave converter.



(b)

Average output voltage of converter (Single-phase, half-wave)

$$V_0 = V_t = \frac{V_m}{2\pi}(1+\cos\alpha), \text{ where } 0 < \alpha < \pi.$$

For single-phase semi-converter in the field circuit, the average output voltage

$$V_t = \frac{V_m}{2\pi}(1+\cos\alpha), \text{ where } 0 < \alpha < \pi.$$

RMS value of armature current $I_{ar} = I_a$.

RMS value of thyristor current

$$I_{sr} = I_a\left(\frac{\pi-\alpha}{2\pi}\right)^{1/2}$$

RMS value of free-wheeling diode current

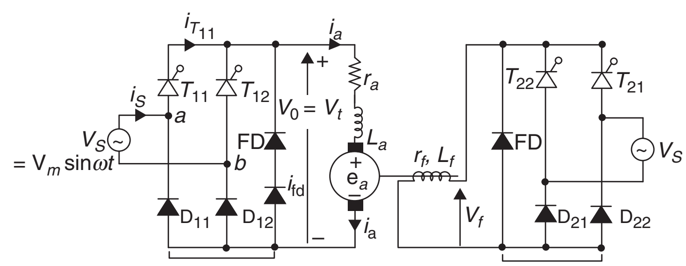
$$I_{fdr} = \sqrt{I_a^2\left(\frac{\pi+d}{2\pi}\right)} = I_a\left(\frac{\pi+d}{2\pi}\right)^{1/2}$$

Apparent input power = (RMS source voltage) (RMS source current) = $V_s I_{sr}$

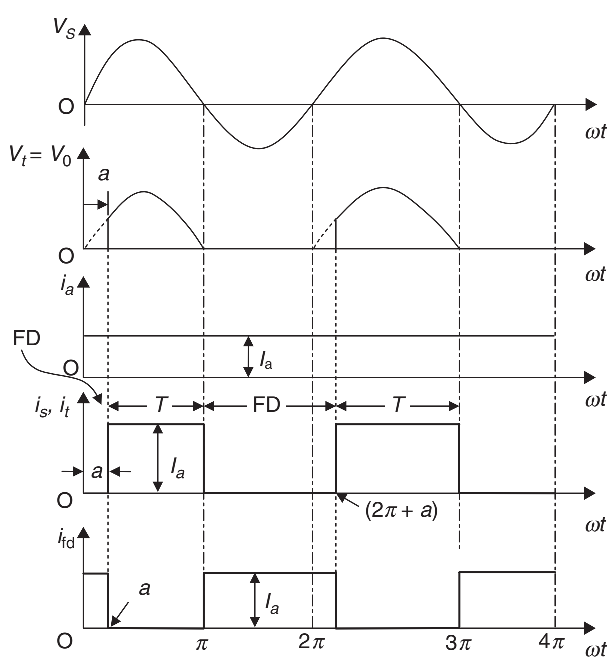
Power delivered to the motor

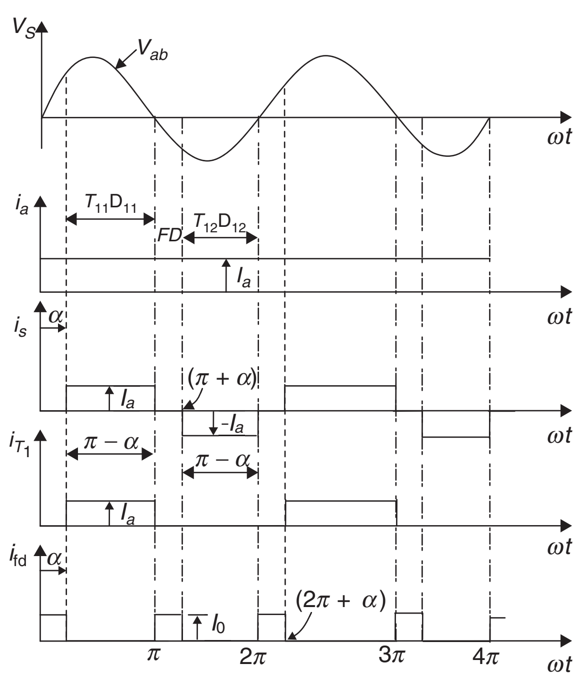
$$= E_a I_a + I_a^2 r_a = V_t I_a = (E_a + I_a r_a)\cdot I_a$$

Input supply of P.F. $= \dfrac{V_t I_a}{V_s I_{sr}}$



(a)





For single-phase semi-converter, average output voltage

$$V_0 = V_t = \frac{V_m}{\pi}(1+\cos\alpha)$$

For field circuit $V_f = \dfrac{V_m}{\pi}(1+\cos\alpha_1)$

RMS value of source current, $I_{sr} = I_a\left[\dfrac{\pi-\alpha}{\pi}\right]^{1/2}$

RMS value of free-wheeling diode current, $I_{fdr} = I_a\left[\dfrac{\alpha}{\pi}\right]^{1/2}$

RMS value of thyristor current, $I_{tr} = I_a\left[\dfrac{\pi-\alpha}{2\pi}\right]^{1/2}$

Input PF $= \dfrac{V_t \cdot I_a}{V_s \cdot I_{sr}}$

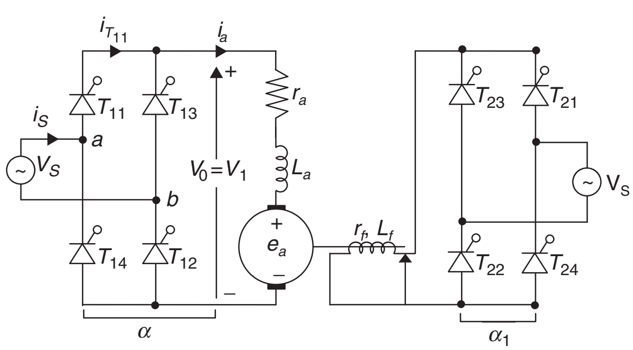
Example 12: A separately excited DC motor is required to be controlled from a three-ϕ source for operation in the first quadrant only the most preferred converter would be

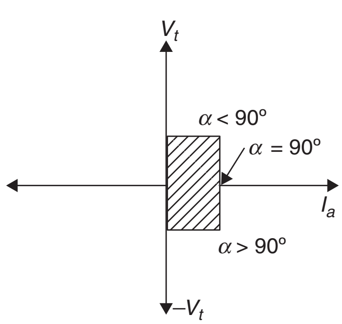
(A) Fully controlled converter
(B) Fully controlled converter with free-wheeling diode
(C) Half controller converter
(D) Sequence control of two series connected fully controlled converters

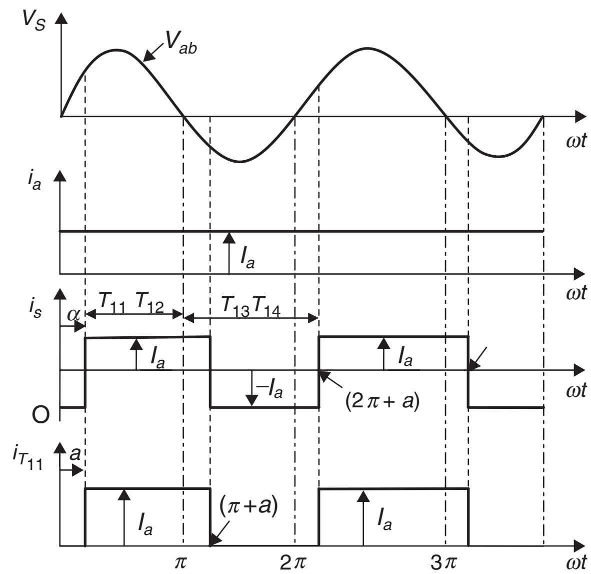
Solution: (C)

Single-phase Full Converter Drives

- A single-phase, full converter drive feeding a separately excited DC motor is in the figure below.







For armature converter 1

$$V_0 = V_t = \frac{2V_m}{\pi}\cos\alpha \text{ for } 0 < \alpha < \pi$$

For field converter 2

$$V_f = \frac{2V_m}{\pi}\cos\alpha_1 \text{ for } 0 < \alpha_1 < \pi$$

From the waveforms drawn,

RMS value for thyristor current

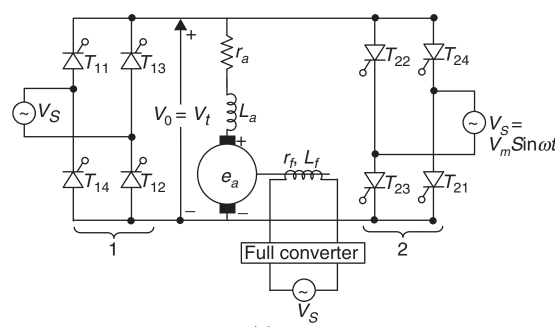
$$I_{tr} = \left(I_a^2\frac{\pi}{2\pi}\right)^{1/2} = \frac{I_a}{\sqrt{2}}$$

$$\text{Input supply p.f.} = \frac{V_t \cdot I_a}{V_s \cdot I_{sr}} = \frac{2V_m}{\pi}\cos\alpha\,\frac{I_a\sqrt{2}}{V_m \cdot I_a}$$

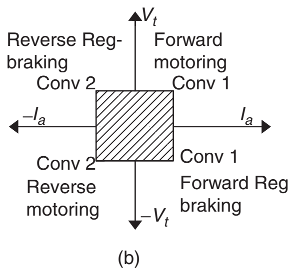
$$= \frac{2\sqrt{2}}{\pi}\cos\alpha$$

Single-phase Dual Converter Drives

- The figure shown below is a single-phase dual converter obtained by connecting two, full converters in anti-parallel.



(a)



(b)

Figure 1

- It is a four-quadrant converter.
- For working in first and fourth quadrants, converter 1 is in operation.
- For operation in second and third quadrants, converter 2 is energized.
- Four-quadrant operation demands the field winding of the motor to be energized from a single-phase or a three-phase full converter.
- When $V_t = \frac{2V_m}{\pi}\cos\alpha_1$ for $0 < \alpha_1 < \pi$ converter 1 operates.
- When $V_t = \frac{2V_m}{\pi}\cos\alpha_2$ for $0 < \alpha_2 < \pi$ converter 2 operates.
- Converter 1 with $\alpha_1 < 90°$ operates the motor in forward motoring mode in quadrant 1.
- Converter 1 with $\alpha_1 > 90°$ and with field excitation reversed operates the motor in forward regenerative braking mode in quadrant 4.
- Converter 2 with $\alpha_2 < 90°$ operates the motor in reverse motoring mode in quadrant 3.
- Converter 2 with $\alpha_2 > 90°$ and with field excitation reversed operates the motor in reverse regenerative braking mode in quadrant 2.

Example 13: The speed–torque characteristics of a DC motor and control methods suitable for the same are given in List I and II, respectively. The correct match would be

List I	List II
(P) Above base speed	(1) Field control
(Q) Above rated torque	(2) Armature control
(R) Below base speed	
(S) Below rated torque	

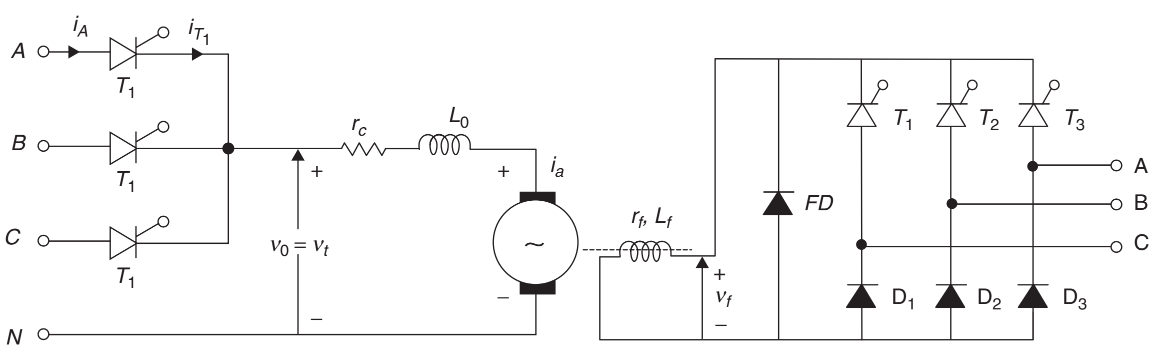
(A) P-1 Q-2 (B) P-2 Q-1
(C) P-1 R-2 (D) Q-2 S-1

Solution: (A)

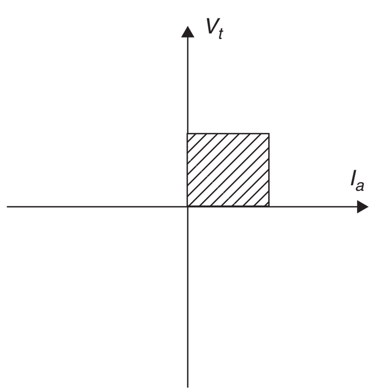
Three-phase Converter Drives

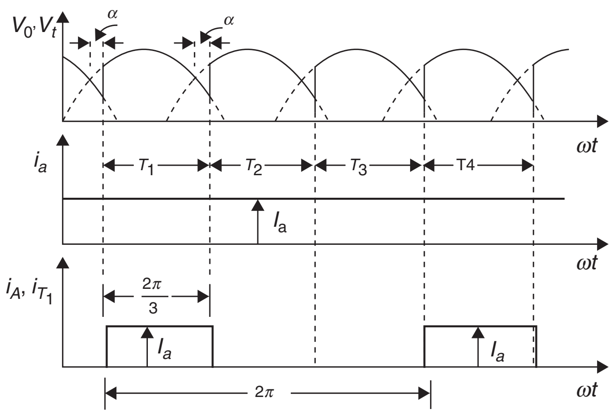
Three-phase, Half-wave Converter Drives

- Figure below shows a three-phase, half wave converter drive consisting of two converters and a separately excited DC motor.



(a) Circuit diagram





- The armature circuit of the DC motor is fed through a three-phase half-wave converter whereas the field is energized through a three-phase semi-converter.
- This converter offers one quadrant operation.
- Two-quadrant operation can be obtained from a three-phase, half-wave converter drive, in case motor field windings are energized from single-phase or three-phase full-converter.

Average value of output voltage

$$V_0 = V_t = \frac{3V_{ml}}{\pi}\cos\alpha \quad \text{for } 0 \le \alpha < \pi$$

(for continuous armature current)

V_{ml} = maximum line voltage

For three-phase semi-converter, average value of field voltage

$$V_f = \frac{3V_{ml}}{2\pi}(1 + \cos\alpha_1) \text{ for } 0 \le \alpha_1 < \pi.$$

RMS value of armature current

$$I_{ar} = I_a$$

RMS value of phase or line current

$$I_{sr} = \sqrt{I_a^2 \frac{2\pi}{3} \cdot \frac{1}{2\pi}} = \frac{I_a}{\sqrt{3}}$$

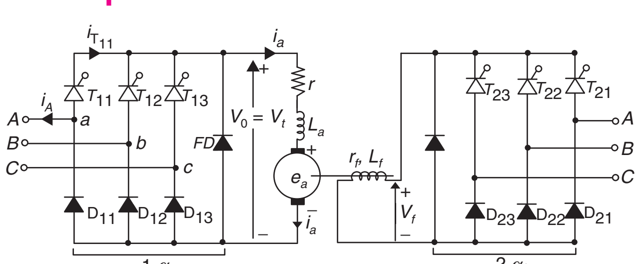
Average thyristor current

$$I_{TA} = I_a \cdot \frac{2\pi}{3} \cdot \frac{1}{2\pi} = \left(\frac{I_a}{3}\right)$$

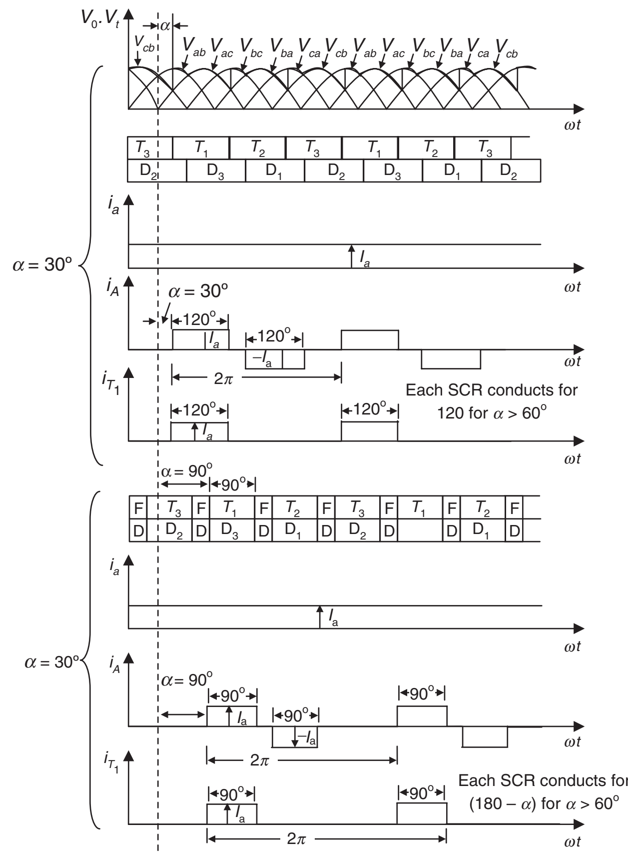
RMS value of thyristor current

$$I_{tr} = I_{sr} = \left(\frac{I_a}{\sqrt{3}}\right)$$

Three-phase Semi-converter Drives



(a)



For $\alpha < 60°$ RMS value of supply line current I_a is given by

$$I_{sr} = I_a\sqrt{\frac{2}{3}}$$

$$I_{tr} = \frac{I_a}{\sqrt{3}}$$

For $60 < \alpha < 180$ $I_{sr} = I_a\sqrt{\frac{180 - \alpha}{180}}$

$$I_{tr} = I_a\sqrt{\frac{180 - \alpha}{360}}$$

Average thyristor current = $\frac{I_a}{3}$ for $\alpha < 60°$.

For $60 < \alpha < 180$, $\frac{(180 - \alpha)}{360}$

For $60 < \alpha < 180°$

$$I_{f.da} = I_a\left(\frac{\alpha - 60}{120}\right)$$

$$I_{f.dr} = I_a\sqrt{\frac{\alpha - 60}{120}}$$

For converter 1, $V_0 = V_t = \frac{3\,V_{ml}}{\pi}(1 + \cos\alpha)$ for $0 < \alpha < \pi$

For converter 2, $V_f = \frac{3\,V_{ml}}{\pi}(1 + \cos\alpha_1)$ for $0 < \alpha_1 < \pi$

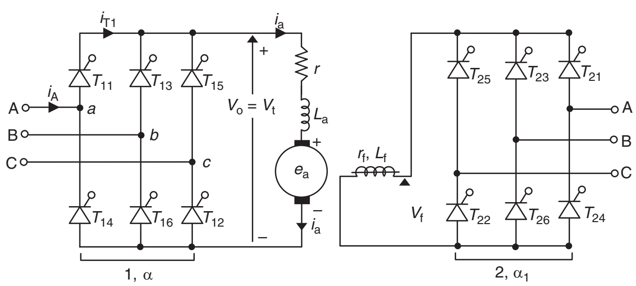
Example 14: A separately excited DC motor supplying a non-zero torque for steady-state operation, if fed from a three-phase semi-converter. The motor armature current is found to drop to zero at certain instances.

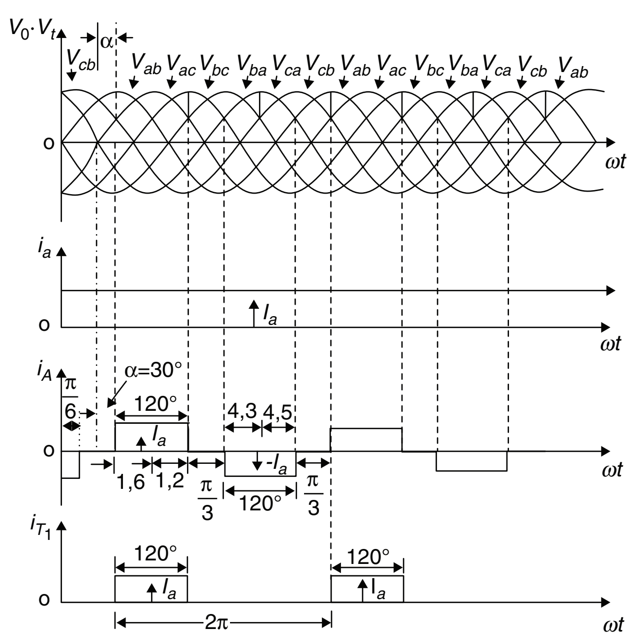
The assumed value of voltage is

(A) Zero
(B) Arbitrary
(C) Equal to instantaneous value of the AC phase voltage
(D) Equal to instantaneous value of the motor back emf

Solution: (D)

Three-phase Full Converter Drives





Average output voltage in armature circuit for converter 1

$$V_0 = V_t = \frac{3V_{ml}}{\pi}\cos\alpha$$

For field circuit $V_f = \dfrac{3V_{ml}}{\pi}\cos\alpha_1$

RMS value of source current

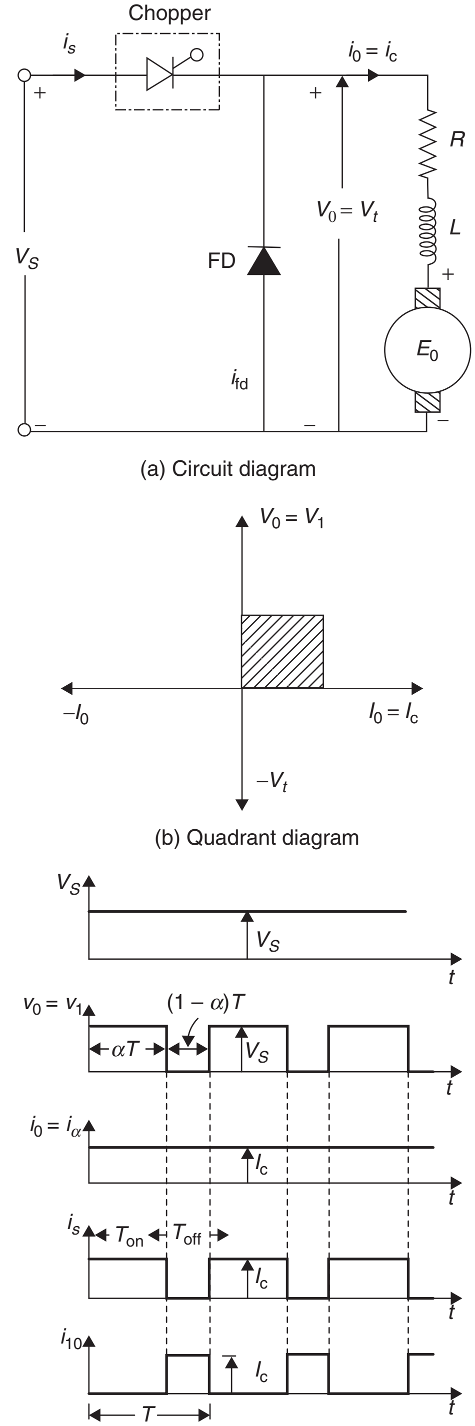
$$I_{sr} = I_a\sqrt{\frac{2}{3}}$$

$$I_{tr} = \frac{I_a}{\sqrt{3}}$$

$$I_{TA} = \frac{I_a}{3}$$

Chopper-controlled Drives

Power Control (or) Motoring Control



(a) Circuit diagram

(b) Quadrant diagram

(c) Waveforms

Figure 2

Average motor voltage

$$V_0 = V_t = \left(\frac{T_{ON}}{T}\right).V_s = \alpha V_s$$

$$V_0 = f\,T_{ON}\,V_s$$

where $\alpha = \dfrac{T_{ON}}{T}$ (duty cycle)

$$f = \text{chopping frequency} = \frac{1}{T}$$

Power delivered to motor

= (Average motor voltage) × (Average motor current)

$= V_t \,.\, I_a$

$= \alpha V_s \cdot I_a$

Input power to chopper

= (Average input voltage) (Average source current)

$= V_s \cdot \alpha I_a$

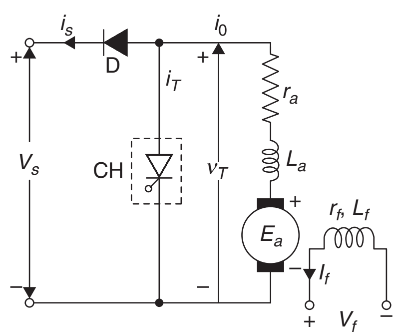
For the motor armature circuit

$$V_t = \alpha V_s = E_a + I_a\,(r_a + r_s)$$

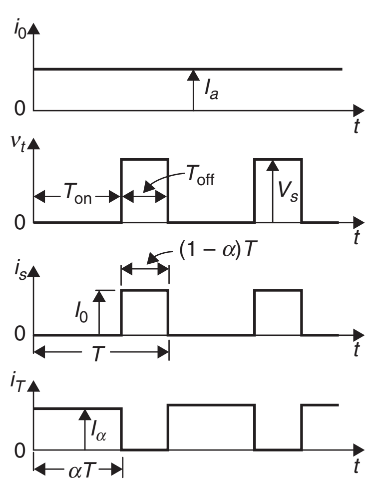
$$= K_m \cdot \omega_m + I_a\,(r_a + r_s)$$

$$\omega_m = \frac{\alpha V_s - I_a(r_a + r_s)}{K_m}$$

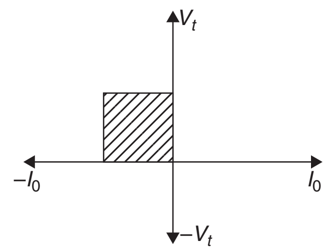
Regenerative Braking Control



(a) Circuit diagram



(b) Waveforms



(c) Quadrant diagram

Figure 3

$$V_{t\,avg} = (1 - \alpha)V_s$$

Power generated by motor

$$= V_t \,.\, I_a = (1 - \alpha)V_s .\, I_a$$

Motor emf generated

$$E_a = K_m\,\omega_m = V_t + I_a r_a$$

$$E_a = (1 - \alpha)V_s + I_a r_a$$

Motor speed during regenerative braking

$$\omega_m = \frac{(1-\alpha)V_s + I_a r_a}{K_m}$$

Conditions for controlling power during regenerative braking

$$0 \le (E_a - I_a r_a) \ge V_s$$

Min braking speed $\omega_{mn} = \dfrac{I_a r_a}{K_m}$

Max braking speed $\omega_{mx} = \dfrac{V_s + I_a r_a}{K_m}$

Therefore regenerative braking control is effective only when motor speed is less than ω_{mx} and more than ω_{mn}.

$$\omega_{mn} < \omega_m < \omega_{mx}$$

- Speed range for regenerative braking

$$= \frac{V_s + I_a r_a}{K_m} : \frac{I_a r_a}{K_m} = (V_s + I_a r_a) : I_a r_a$$

AC Drives

AC motors exhibit highly coupled, nonlinear and multi-variable structures as opposed to much simpler decoupled structures of separately excited DC motors.

They require control of frequency, voltage and current for variable speed applications. The power converters, inverters and AC voltage controllers can control the frequency, voltage or current to meet the drive requirements.

They are two types of AC drives:

- Induction motor drives
- Synchronous motor drives

AC drives are replacing DC drives and are used in many industrial and domestic applications.

The speed and torque of induction motors can be controlled by

- Stator voltage control
- Rotor voltage control
- Frequency control
- Stator voltage and frequency control
- Stator current control

To meet the torque–speed duty cycle of a drive, the voltage, current and frequency control are normally used stator voltage control.

Stator Voltage Control

The stator voltage can be varied by three-phase

- AC voltage controllers
- Voltage = fed variable DC link inverters, or
- Pulse width modulation (PWM) inverters.

However, due to limited speed range requirements the AC voltage controllers are normally used to provide the voltage control.

- The AC voltage controllers are very simple.
- However, the harmonic contents are high and the input PF of the controllers is low.
- They are used mainly in low-power applications such as fans, flowers, and centrifugal pumps, where the starting torque is low.
- They are also used for starting high power induction motors to limit the in – rush current.

Rotor Voltage Control

In a wound rotor motor an external three-phase resistors may be connected to its slip rings.

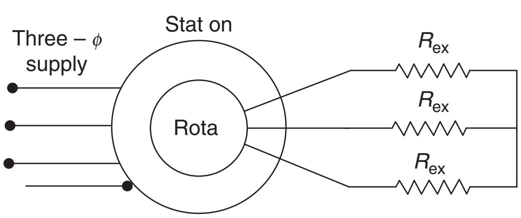
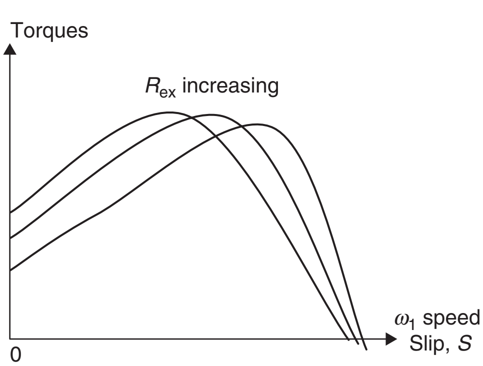


Figure 4 Rotor resistance

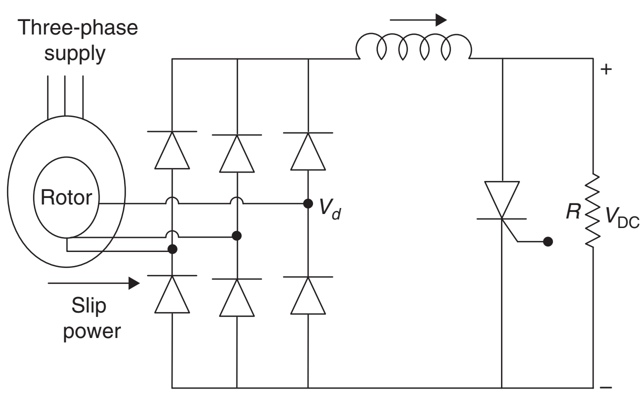


- The developed torque may be varied by varying the resistance R_{ex}.

Rotor Voltage Control

- This method increases the starting torque while limiting the starting current.
- However, this is an inefficient method and there would be imbalances in voltages and currents if the resistances in the rotor circuit are not equal.
- A wound rotor induction motor is designed to have a low-rotor resistance so that the running efficiency is high- and the full-load slip is low.
- The increase in the rotor resistance does not affect the value of maximum torque but increases the slip at maximum torque.
- The wound rotor motors are widely used in applications requiring frequent starting and braking with large motor torques (crane hoists).
- Because of the availability of rotor windings for changing the rotor resistance, the wound rotor offers greater flexibility for control.
- But cost and maintenance increases due to slip rings and brushes.
- Therefore wound rotor motor is less widely used as compared with the squirrel – cage motor.

The three-phase resistor may be replaced by a three-phase diode rectifier and a DC converter. Where the GTO or an IGBT operates as a DC converter switch.



The inductor L_d acts as a current source I_d and the DC converter varies the effective resistance which is given as $R_{ex} = R(1 - K)$.

where K = duty cycle of the DC converter motor speed can be controlled can be controlled by varying the duty cycle.

The portion of the air-gap power, which is not converted into mechanical power is called slip power which is dissipated in R.

Frequency Control

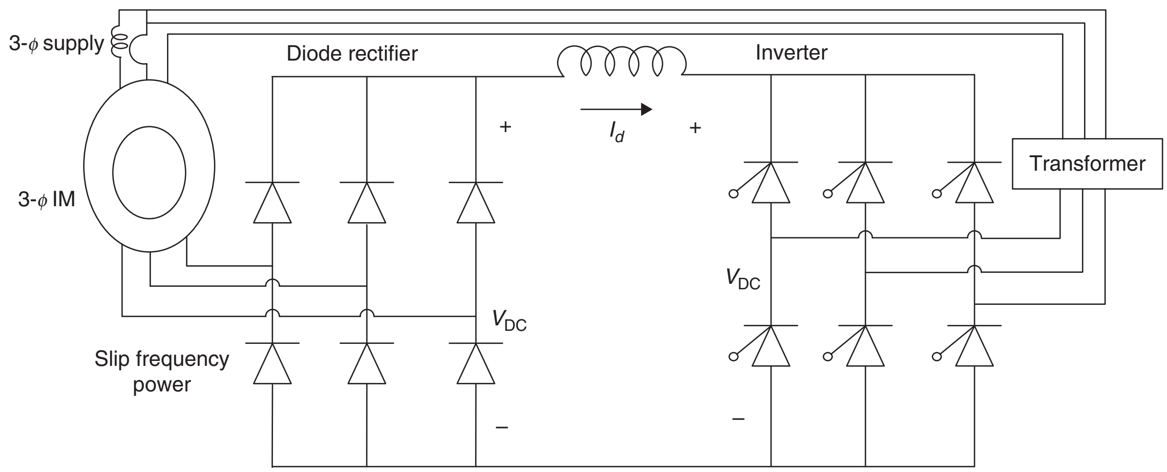
- The torque and speed of induction motors can be controlled by changing the supply frequency.
- If the voltage is maintained fixed at its rated value when the frequency is reduced below its rated value, the flux increases.

- This would cause saturation of the air-gap flux, and the motor parameters would not be valid in determining the torque–speed characteristics.
- At low frequency, the reactances decrease and the motor current may be too high. Therefore this type of frequency control is not normally used.

Slip Power Recovery Scheme

In chopper method of speed control, for slip ring induction motor, the slip power is wasted in the external resistance and it leads to poor efficiency of the drive. Two important slip power recovery schemes are listed as follows.

1. Static Kramers drive (sub synchronous speed)
2. Static Scherbius drive (super synchronous speed)



- Speed is sub-synchronous.
- The slip power can flow in only one direction, due to which

Static Kramers drive can offer speed below synchronous speed.

- The slip power from the rotor circuit is converted to DC voltages which is then converter to line frequency and pumped to the AC source.
- It will work as a constant torque drive.

Applications

Large power pumps compressor type loads where speed control is within narrow range and below synchronous speed.

Static Scherbius Drive

- Speed control below and above synchronous speeds can be obtained.

(a) DC link scherbius drive

- It consists of two-phase-controlled bridges smoothing inductor and transformer.
- For sub synchronous speed control, bridge works as a rectifier and bridge 2 acts as a line commutated inverter.
- Power flows from rotor circuit to supply.
- For super synchronous speed control, bridge 1 acts as a line commutated inverter and bridge 2 works as a rectifier.

(b) Cyclo converter scherbius drive

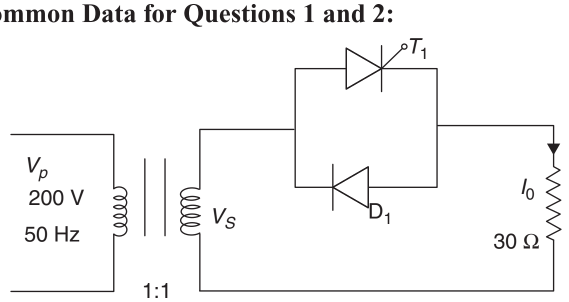
It allows the slip power to flow in either directions and machine can be controlled in both sub synchronous and super synchronous ranges motoring and regeneration features.

Exercises

Practice Problems I

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

Common Data for Questions 1 and 2:



A single-phase voltage controller has the specifications as shown in the above figure. If T_1 is triggered at $\alpha = 30°$. Then

1. The average value of thyristor current would be
(A) 1.55 A
(B) 2 A
(C) 2.23 A
(D) 2.8 A

2. The RMS value of thyristor current would be
(A) 2.65 A
(B) 3.56 A
(C) 4.65 A
(D) 5.56 A

3. The power factor for single-phase AC voltage controller feeding a resistive load is

(A) Unity for all values of firing angle

(B) $\left[\frac{1}{\pi}\left[(\pi-\alpha)-\frac{\sin 2\alpha}{2}\right]\right]^{1/2}$

(C) $\left[\frac{1}{\pi}\left[(\pi+\alpha)+\frac{\sin 2\alpha}{2}\right]\right]^{1/2}$

(D) $\left[\frac{1}{\pi}\left[(\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]\right]^{1/2}$

4. The power factor of a single-phase AC regulator feeding a resistive load is

(A) $(\text{p.u. power})^2$

(B) $\sqrt{\text{p.u. power}}$

(C) $\frac{(\text{p.u. power})^2}{\sqrt{2}}$

(D) $\frac{\sqrt{\text{p.u. power}}}{2}$

5. An AC voltage regulator using back to back connected SCRs is feeding an RL load. The SCR firing angle $\alpha < \theta$. The output load voltage waveform, if the SCRs are fired using short duration gate pulses will be

(A) Half-wave rectified
(B) Sinusoidal
(C) Full-wave rectified
(D) Triangular

6 A thyristor-controlled reactor is used to get

(A) Variable resistance
(B) Variable capacitance
(C) Variable inductance
(D) Improved reactor power factor

7. In a single-phase cyclo-converter circuit an intergroup reactor is used to

(A) Limit circuiting current
(B) Reduce voltage ripples
(C) Limit $\frac{di}{dt}$ in semiconductor switch
(D) Reduce current ripples.

8. It is required to drive a DC shunt motor at different speeds in both directions (forward and reverse) and also to brake it in both the directions. Which one of the following would you use?

(A) A full-controlled thyristor bridge
(B) A full-controlled thyristor bridge
(C) A dual converter
(D) A diode bridge

9. In AC voltage regulator, TRIACS cannot be used for a

(A) Back emf load
(B) Resistive load
(C) R–L Load
(D) Inductive load

10 A separately excited DC motor with a back emf constant 0.25 V/rpm, armature resistance of 4 and drawing an armature current of 10 A is driven by a single-phase half-controlled rectifier. The converter is working from a 230 V single-phase AC source with a firing angle of 45°. Under these operating conditions, the speed of the motor will be

(A) 273.5 rpm (B) 339 rpm
(C) 547 rpm (D) 457 rpm

11. In a self-controlled synchronous motor fed from a variable frequency inverter

(A) Stability problems exists
(B) The rotor speed is decided by the stator frequency.
(C) The stator frequency is decided by the rotor speed.
(D) Rotor poles invariably have damper windings.

12. A 3-φ, 380 V, 50 Hz, AC mains-fed thyristor bridge is feeding a 380 V DC, 12 kW, 1500 rpm, separately excited DC motor with a ripple free continuous current in the DC link. Under all operating conditions, neglecting the losses, the power factor of the AC mains at $(1/4)^{\text{th}}$ the rated speed is

(A) 0.2 (B) 0.3
(C) 0.6 (D) 0.8

13. Which among the following is best employed for the PWM inverter control for an AC motor?

(A) Cycle converter
(B) Controlled rectifier
(C) AC regulator
(D) Uncontrolled rectifier

14. A DC link is used in converter method of speed control of induction motor. The DC link is used to

(A) Vary the slip
(B) Trigger the thyristor of the inverter
(C) Provide a constant peak flux density to the gap and core saturation.
(D) Provide necessary DC voltage to the inverter

15. For the speed control of a 3-φ squirrel cage motor, the most suitable solid state converter used is

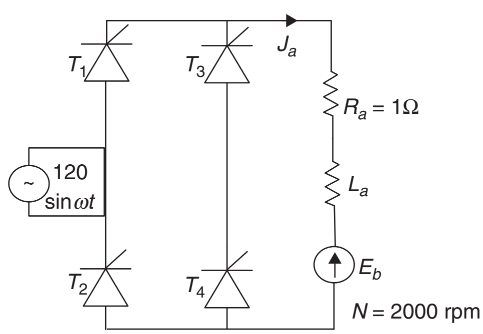
(A) Load-commutated inverter
(B) Cyclo converter
(C) Current source inverter
(D) Voltage source inverter

Practice Problems 2

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

1. For a single-phase to single-phase cycloconverter,
(A) Natural commutation is employed in step-up converter.
(B) Forced commutation is employed in step-down converter.
(C) Natural commutation is employed in step-down converter.
(D) Forced commutation is employed in both step-up and step-down cyclo converter.

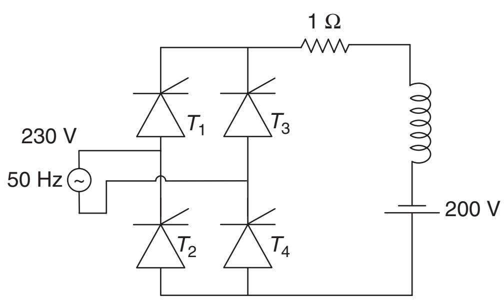
2. A single-phase fully controlled rectifier feeds a separately excited DC motor as shown in figure. If the back emf constant of the motor is 0.03 V/rpm and armature resistance is 1 Ω, calculate the armature current for a firing angle of 30°, assuming continuous conduction.



(A) 6.2 A (B) 12.4 A
(C) 5 A (D) 0.62 A

3. A single-phase half-controlled bridge feeds a separately excited DC motor. The average output voltage of the converter is 100 V at a firing angle of 0°. The firing angle at an average voltage of 75 V will be (assuming continuous conduction)
(A) 30° (B) 45°
(C) 60° (D) 90°

4. Regenerative braking of a separately excited DC motor fed by a single-phase fully controlled rectifier is shown in figure. If the firing angle is set at 160°, then the armature current (assuming a constant DC current in the armature) will be:



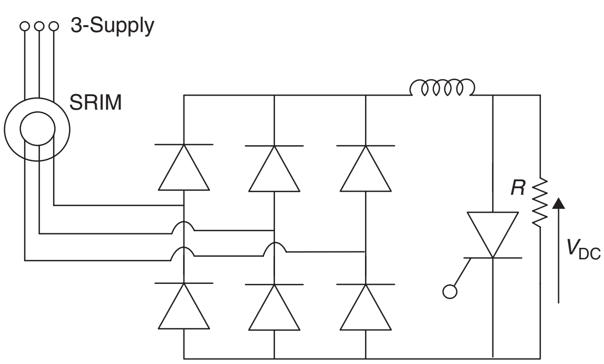
(A) 10 A (B) 15.6 A
(C) 1.2 A (D) 5.62 A

5. Which among the following converters is suitable for operation of a DC drive in forward motoring and forward regenerating mode?
(A) Single-phase half-controlled rectifier
(B) Three-phase half-controlled rectifier
(C) Single-phase fully-controlled rectifier
(D) None of the above

6. A single-phase half-controlled converter feeds a separately excited DC motor. At no load, the armature current becomes discontinuous. The instantaneous output voltage of the converter when current drops to zero amounts to:
(A) Instantaneous supply voltage
(B) Instantaneous back emf of motor
(C) Sudden spike in armature voltage
(D) Cannot be predicted

7. In a self-controlled permanent magnet synchronous motor drive,
(A) The stator supply frequency tracks the rotor speed.
(B) The stator has permanent magnets.
(C) The stator frequency is independently controlled.
(D) The damper windings in rotor are used for damping rotor oscillations.

8. The speed of a three-phase 600 V, 6 pole, 50 Hz slip-ring induction motor drive is controlled by employing a GTO chopper in the rotor circuit. The effective stator to rotor turns ratio is 1:0.6. The speed of the motor is maintained at 960 rpm. The rectified DC voltage in the rotor circuit is



(A) 19.5 V (B) 38 V
(C) 50 V (D) 28.6 V

9. Slip power recovery scheme can be used to control the speed of an induction motor drive
(A) Above synchronous speed only.
(B) Below synchronous speed only.
(C) Both above and below synchronous speed
(D) Above twice synchronous speed

10. Integral cycle control in a single-phase AC voltage controller
(A) Is suitable for application with small mechanical and thermal time constants.

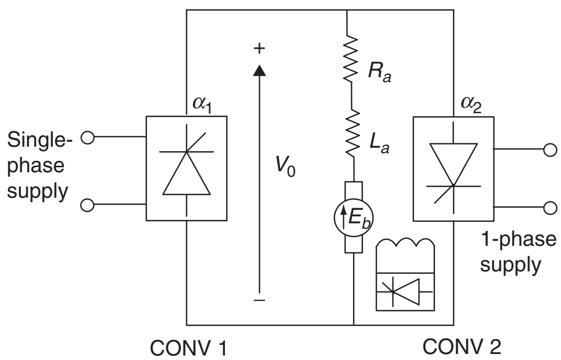
(B) Is suitable for applications with large mechanical and thermal time constants.
(C) Provides a sinusoidal output voltage.
(D) Only (a) and (c) are true.

11. A single-phase voltage controller feeds a resistive load of 20 Ω with an input voltage of 110 V, 50 Hz. The load is connected to supply for 8 cycles and disconnected for 4 cycles. The RMS of the output voltage will be:

(A) $\frac{110}{\sqrt{2}}$ V (B) 90 V

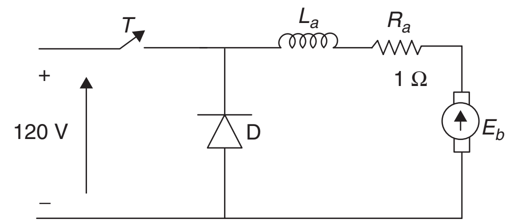
(C) $90\sqrt{2}$ V (D) 73 V

12. The figure shows a single-phase dual converter feeding a separately excited DC motor. For the motor to operate in forward motoring mode in circulating current mode,



(A) Converter 1 firing angle $\alpha_1 > 90°$; converter 2 firing angle $\alpha_2 < 90$ field reversed.
(B) Converter 1 firing angle $\alpha_1 < 90°$; converter 2 $\alpha_2 > 90°$; field correct polarity.
(C) Converter 1 firing angle $\alpha_1 < 90°$; field reversed.
(D) None of the above.

13. The figure shows a chopper circuit feeding a separately excited de motor with a back emf constant of k_b = 0.21 V/rpm at a speed of 276 rpm. The duty ratio of chopper is 0.5. Assuming continuous conduction, the armature current will be



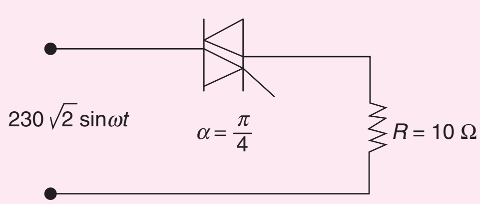
(A) 1 A
(B) 3 A
(C) 5 A
(D) 2 A

14. In a salient-pole synchronous motor, if the field winding is disconnected from exciting voltage, the motor continues to rotate at synchronous speed. This is due to
(A) Rotor inertia
(B) Reluctance torque
(C) Electromagnetic torque
(D) Permanent magnet in rotor

15. Rotor resistance control in a three-phase induction motor drive using a chopper in rotor circuit is used to control the drive.
(A) Above synchronous speed alone
(B) Below synchronous speed alone
(C) Both above and below synchronous speed
(D) Up to 0.2 times the base speed from standstill

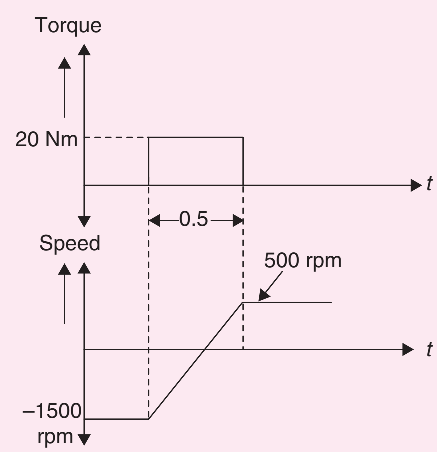
Previous Years' Questions

1. The triac circuit shown in figure controls the AC output power to the resistive load. The peak power dissipation in the load is **[2004]**



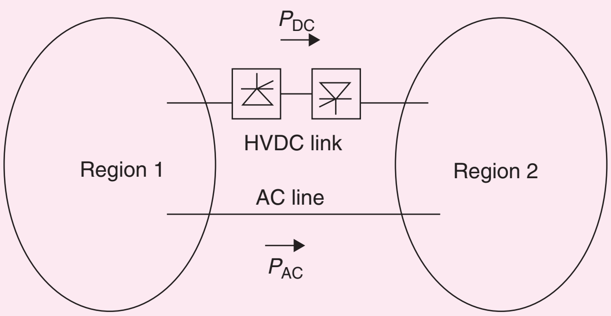
(A) 3968 W
(B) 5290 W
(C) 7935 W
(D) 10,580 W

2. A variable speed drive rated for 1500 rpm, 40 Nm is reversing under no load. Figure shows the reversing torque and the speed during the transient. The moment of inertia of the drive is **[2004]**



(A) 0.048 kgm^2
(B) 0.064 kgm^2
(C) 0.096 kgm^2
(D) 0.128 kgm^2

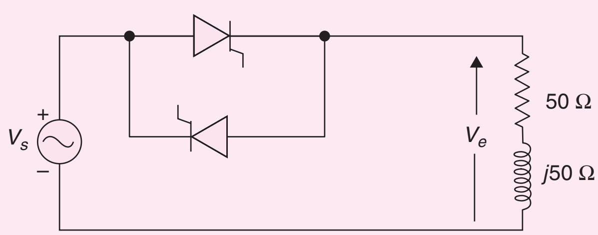
3. Two regional systems, each having several synchronous generators and loads are interconnected by an AC line and a HVDC link as shown in the figure. Which of the following statements is true in the steady state? **[2007]**



(A) Both regions need not have the same frequency.
(B) The total power flow between the regions ($P_{AC} + P_{DC}$) can be changed by controlling the HVDC converters alone.
(C) The power sharing between the AC line and the HVDC link can be changed by controlling the HVDC converters alone.
(D) The direction of power flow in the HVDC link (P_{DC}) cannot be reversed.

4. A three-phase, 440 V, 50 Hz AC mains-fed thyristor bridge is feeding a 440 V DC, 15 kW. 1500 rpm separately excited DC motor with a ripple-free continuous current in the DC link under all operating conditions. Neglecting the losses, the power factor of the AC mains at half the rated speed is **[2007]**
(A) 0.354 (B) 0.372
(C) 0.90 (D) 0.955

5. In the single-phase voltage controller circuit shown in the figure, for what range of triggering angle (α), the output voltage (V_0) is not controllable? **[2008]**

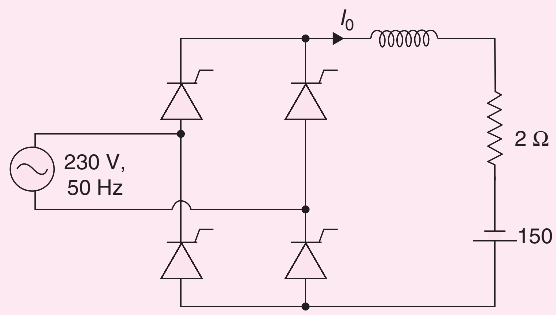


(A) $0° < \alpha < 45°$ (B) $45° < \alpha < 135°$
(C) $90° < \alpha < 180°$ (D) $135° < \alpha < 180°$

6. A 220 V, 20 A, 1000 rpm, separately excited DC motor has an armature resistance of 2.5 Ω. The motor is controlled by a step-down chopper with a frequency of 1 kHz. The input DC voltage to the chopper is 250 V. The duty cycle of the chopper for the motor to operate at a speed of 600 rpm delivering the rated torque will be **[2008]**
(A) 0.518 (B) 0.608
(C) 0.852 (D) 0.902

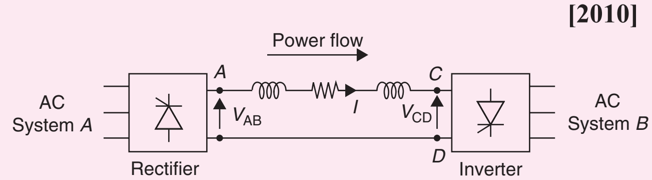
7. A 220 V. 1400 rpm, 40 A separately excited DC motor has an armature resistance of 0.4 Ω. The motor is fed from a single-phase circulating current dual converter with an input AC line voltage of 220 V (RMS). The approximate firing angles of the dual converter for motoring operation at 50% of rated torque and 1000 rpm will be **[2008]**
(A) 43°, 137° (B) 43°, 47°
(C) 39°, 141° (D) 39°, 51°

8. A single-phase fully controlled converter bridge is issued for electrical braking of a separately excited DC motor. The DC motor load is represented by an equivalent circuit as shown in the following figure. Assume that the load inductance is sufficient to ensure continuous and ripple free load current. The firing angle of the bridge for a load current of I_0 = 10 A will be **[2008]**



(A) 44° (B) 51°
(C) 129° (D) 136°

9. Power is transferred from system A to system B by an HVDC link as shown in the figure. If the voltages V_{AB} and V_{CD} are as indicated in the figure, and $I > 0$, then **[2010]**



(A) $V_{AB} < 0, V_{CD} < 0, V_{AB} > V_{CD}$
(B) $V_{AB} > 0, V_{CD} > 0, V_{AB} < V_{CD}$
(C) $V_{AB} > 0, V_{CD} > 0, V_{AB} > V_{CD}$
(D) $V_{AB} > 0, V_{CD} < 0$

10. In a constant V/f control of induction motor, the ratio V/f if maintained constant from 0 to base frequency, where V is the voltage applied to the motor at fundamental frequency f. Which of the following statements relating to low-frequency operation of the motor is TRUE? **[2014]**
(A) At low frequency, the stator flux increases from its rated value.
(B) At low frequency, the stator flux decreases from its rated value.
(C) At low frequency, the motor saturates.
(D) At low frequency, the stator flux remains unchanged at its rated value.

11. A single-phase SCR-based AC regulator is feeding power to a load consisting of 5 Ω resistance and 16 mH inductance. The input supply is 230 V, 50 Hz AC. The maximum firing angle, at which the voltage across the device becomes zero all throughout, and the RMS value of current through SCR, under this operating condition, respectively, are **[2014]**

(A) 30° and 46 A (B) 30° and 23 A
(C) 45° and 23 A (D) 45° and 32 A

Answer Keys

Exercises

Practice Problems 1

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

Practice Problems 2

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

Previous Years' Questions

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

Test
Power Electronics and Drives

Time: 60 min.

Directions for questions 1 to 25: Select the correct alternative from the given choices.

1. Commutation overlap in the phase-controlled AC to DC converter is due to
(A) Load inductance
(B) Harmonic content of load current
(C) Switching operation in the inverter
(D) Non linearity in the device characteristics.

2. Figure 1 shows a composite switch consisting of a power transistor in series with a diode. Assuming that the transistor switch and diode are ideal, I–V characteristic of the composite switch is

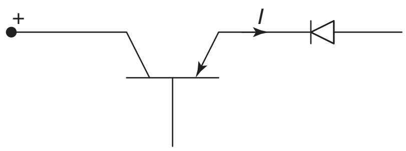
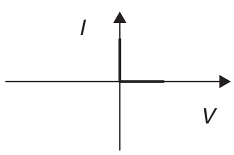
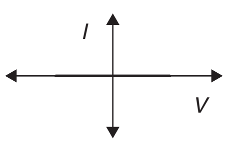


Figure 1

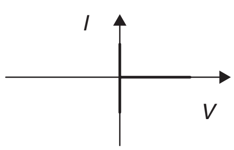
(A)



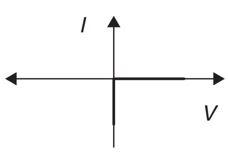
(B)



(C)



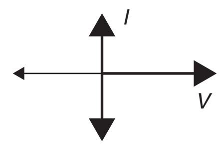
(D)



3. Analysis of voltage wave form of a single phase bridge converter shows that it contains $x\%$ of 6th harmonic. The 6th harmonic content of the voltage waveform of a 3-phase bridge converter would be _______
(A) Less than $x\%$ due to an increase in the number of pulses
(B) Equal to $x\%$, the same as that of the single-phase converter
(C) Greater than $x\%$ due to changes in the input and output voltages of the converter
(D) Difficult to predict as the analysis of converters is not governed by any generalized theory

4. In a three phase controlled bridge rectifier, with an increase of overlap angle, the output dc voltage
(A) Decreases
(B) Increases
(C) Does not change
(D) Depends on load inductance

5. The wave form of the power electronic device shown is related to



(A) SCR (B) IGCT
(C) IGBT (D) FET

6. If an AC chopper is supplying power to an inductive load, then firing pulse to the SCR, it
(A) May have a width equal to turn-on time of the SCR.
(B) Should be a single pulse of long duration.
(C) Should be a series of pulses of short duration.
(D) Should be train of pulses duration equal to the conduction period of the SCR.

7. In a single phase full wave SCR circuit with R–L load
(A) Power is delivered to the source for delay angles less than 90°
(B) The SCR changes from converter to inverter at $\alpha = 90°$
(C) The negative dc voltage maximum is at $\alpha = 180°$
(D) To turn off the thyristor, maximum delay angle must be less than 360°

8. Consider a DC to dc converter (Chopper) having a load resistance of 10 Ω and an input voltage of 232 V. if the voltage drop across the converter during ON time is 2 V and the frequency, of operation is 1 kHZ at a duty cycle of 0.4, then the average output voltage of the converter will be
(A) 94.0 V
(B) 92.8 V
(C) 92.0 V
(D) 90.8 V

9. The correct sequence of the following devices in the increasing order of turn-off times is
(A) MOSFET, IGBT, BJT, Thyristor
(B) IGBT, MOSFET, BJT, Thyristor
(C) Thyristor, BJT, MOSFET, IGBT
(D) MOSFET, BJT, IGBT, Thyristor

10. Figure 2 shows a 3-ϕ inverter fed by constant voltage source V_{DC} and connected to a balanced resistive load at the output. Each switching device may conduct for 120° or for 180°. The waveform shown in Figure 3 is the

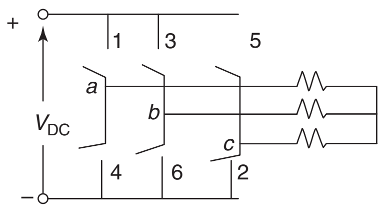


Figure 2

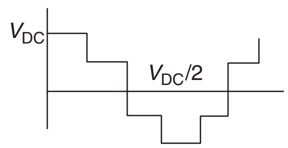
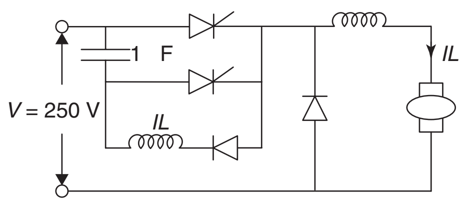


Figure 3

(A) Line voltage with 120° firing
(B) Load phase voltage with 120° firing
(C) Line voltage with 180° firing
(D) Load phase voltage with 180° firing

11. A voltage commutated chopper operating at 1 KHz is used to control the speed of the DC motor. The load current is assumed to be constant at 12 A



The minimum time for which SCR M should be ON.
(A) 140 μs (B) 70 μs (C) 210 μs (D) 280 μs

12. In the Figure 4, the ideal switch S is switched ON and OFF with a switching frequency $f = 20$ kHz. The circuit is operated in steady state at the boundary of continuous and discontinuous conduction so that the inductor current i is as shown in fig. The ON time of the switch and the peak value of current I_p is

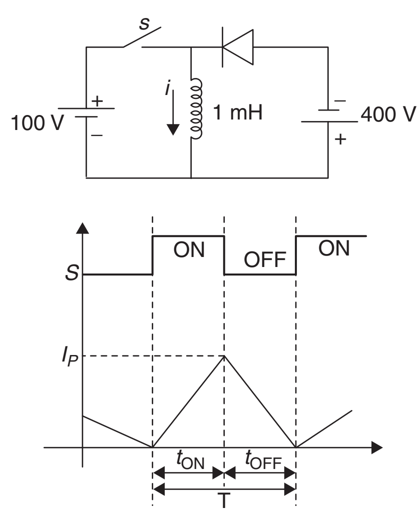


Figure 4

(A) 40 μs, 4 A
(B) 30 μs, 3 A
(C) 33.33 μs, 8 A
(D) 16.67 μs, 4 A

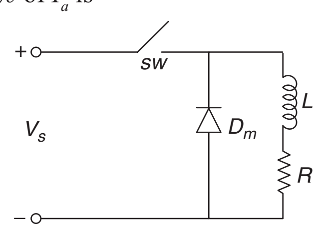
13. Match List–I with List–II and select the correct answer using the codes given below the lists

	List–I		List–II
a.	Semi converters	1.	Additional reactive power loading
b.	Source inductance of the converter	2.	Two quadrant operation with improved displacement factor on the AC side
c.	Sequence control of converters	3.	Unity displacement factor
d.	Current limit control of converters	4.	One quadrant operation with better displacement factor

Codes:

	a	b	c	d
(A)	2	1	4	3
(B)	2	3	4	1
(C)	4	1	2	3
(D)	4	3	2	1

14. The chopper in the figure has a load resistance $R = 0.25\ \Omega$ input voltage $V_s = 550$ V. The average load current $I_a = 200$ A and chopping frequency $f = 250$ Hz. The inductance L which would limit the maximum load ripple to 10% of I_a is



(A) 12.5 mH (B) 20.5 mH
(C) 27.5 mH (D) 38.5 mH

Common Data for Questions 15 and 16:
The single phase half controlled AC to DC bridge converter of Figure 5 supplies a 10 Ω resistor in series with a 100 V back emf load. The firing angle of the thyristors is set to 60°

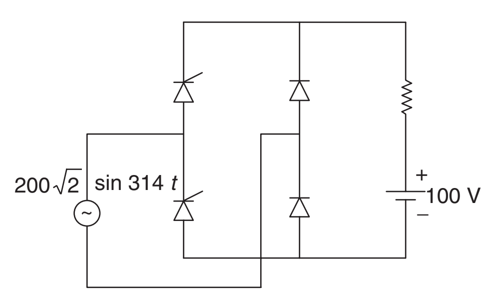


Figure 5

15. Average current through the resistor is
(A) 10.5 A (B) 5.4 A
(C) 7.2 A (D) 10 A

16. What will be the new average current through the resistor if a very large inductor is connected in series with the load.
(A) 10.5 A (B) 13.5 A
(C) 15 A (D) 8 A

17. In a 3 phase half converter, if the average output voltage obtained is 230 V. If it is required to obtain a maximum possible output voltage of 200% of average output voltages, then the per phase input voltage applied shall be
(A) 393.31 V (B) 268.31 V
(C) 681.23 V (D) 556.23 V

18. For a single phase fully controlled bridge converter fed from a 230 V, 50 Hz supply and connected to an *RL* load, the power factors at firing angles of 60° and 45° respectively are
(A) 0.64, 0.45 (B) 0.45, 0.64
(C) 0.78, 0.45 (D) 0.64, 0.78

19. A 230 V, 50 Hz supply feeds a full bridge converter connected to an *RL* load across the output, (The inductance is large enough to provide a constant and ripple free current). If $\alpha = 45°$, for an average out current of 5A to flow through the load, the value of R_L must be
(A) 29.3 Ω (B) 19.3 Ω
(C) 9.3 Ω (D) 22.76 Ω

Common Data for Questions 20 and 21:
The three-phase full-wave controller shown in figure 6 supplies a *Y*-connected resistive load of $R = 10\ \Omega$ and the line-to-line input voltage is 208 V, 60 Hz. The delay angle is $\alpha = \dfrac{\pi}{3}$

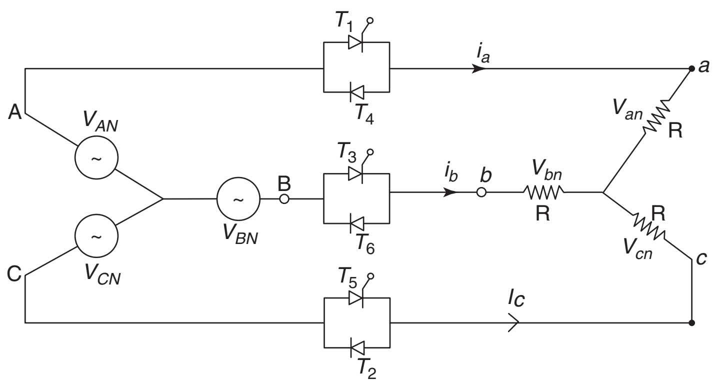


Figure 6

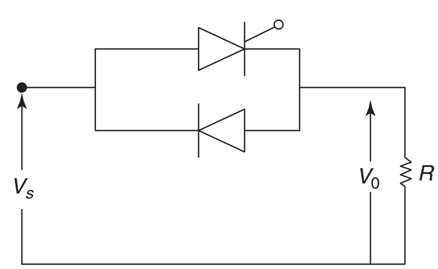
20. The rms output voltage per phase is
(A) 99.9 V
(B) 100.9 V
(C) 149.9 V
(D) 190 V

21. The input power factor is
(A) 0.64 lag
(B) 0.78 lag
(C) 0.84 lag
(D) 0.92 lag

22. A single phase half controlled bridge converter with input of 380 sinωt, 50 Hz; supplies power to an *RL* load. The thyristors are operated in the range of 45° to 60° for the converter to supply a constant average output current of 10 A, the value of R should be
(A) 10 Ω
(B) 30 Ω
(C) 40 Ω
(D) 20 Ω

23. A Chopper circuit is operating on TRC principle at a frequency of 2 kHz on a 220 V DC supply. If the load voltage is 170 V, the conduction and blocking period of the thyristor in each cycle are, respectively
(A) 3.86 μs and 1.14 μs
(B) 38.6 μs and 11.4 μs
(C) 3.86 ms and 1.14 ms
(D) 0.386 ms and 0.114 ms

Common Data for Questions 24 and 25:
A 1-ϕ unidirectional AC voltage controller shown in the following figure has a resistive load of $R = 10\ \Omega$ and the input voltage is $V_s = 120$ V, 60 Hz. The delay angle of thyristor is $\alpha = \dfrac{\pi}{2}$.



24. The rms value of output voltage V_0 is
(A) 103.92 V
(B) 130.92 V
(C) 169.7 V
(D) 196.7 V

25. The input power factor is
(A) 0.75 lag
(B) 0.8 lag
(C) 0.866 lag
(D) None of these

Answer Keys

1. A	**2.** B	**3.** A	**4.** A	**5.** D	**6.** D	**7.** C	**8.** C	**9.** B	**10.** A
11. A	**12.** A	**13.** C	**14.** C	**15.** C	**16.** B	**17.** A	**18.** B	**19.** A	**20.** B
21. C	**22.** D	**23.** D	**24.** A	**25.** C					