

Module

4

AC to AC Voltage Converters

Lesson

27

Three-phase AC
Regulators

Instructional Objectives

Study of the following:

- The circuits used for the three-phase ac regulators (ac to ac voltage converters)
- The operation of the above circuits with three-phase balanced resistive (R) load, along with the waveforms
- The important points of comparison of the performance with different types of circuits

Introduction

In the last lesson – first one in the first half of this module, various circuits of the single-phase ac regulators, also termed as ac to ac voltage converters, are described. In the basic circuit, one Triac, or two thyristors, connected back to back, are used. The operation of the above circuits with different types of loads – resistive (R) and inductive (R-L), along with the waveforms, is then discussed. Lastly, the output voltage waveform is analysed.

In this lesson – the second one in the first half, firstly, the circuits of the three-phase ac regulators, also termed as ac to ac voltage converters, are described. The operation of the above circuits with three-phase balanced resistive (R) load, along with the waveforms, is then discussed. The two basic circuits are three-phase three-wire type with load connected in star and three-phase delta-connected one. Lastly, the important points of comparison of the performance with different types of circuits, including the above two, are presented.

Keywords: Three-phase ac regulator circuits, AC to AC voltage converter, balanced three-phase star- and delta-connected loads

Three-phase AC Regulators

There are many types of circuits used for the three-phase ac regulators (ac to ac voltage converters), unlike single-phase ones. The three-phase loads (balanced) are connected in star or delta. Two thyristors connected back to back, or a triac, is used for each phase in most of the circuits as described. Two circuits are first taken up, both with balanced resistive (R) load

Three-phase, Three-wire AC Regulator with Balanced Resistive Load

The circuit of a three-phase, three-wire ac regulator (termed as ac to ac voltage converter) with balanced resistive (star-connected) load is shown in Fig. 27.1. It may be noted that the resistance connected in all three phases are equal. Two thyristors connected back to back are used per phase, thus needing a total of six thyristors. Please note the numbering scheme, which is same as that used in a three-phase full-wave bridge converter or inverter, described in module 2 or 5. The thyristors are fired in sequence (Fig. 27.2), starting from 1 in ascending order, with the angle between the triggering of thyristors 1 & 2 being 60° (one-sixth of the time period (T) of a complete cycle). The line frequency is 50 Hz, with $T = 1/f = 20$ ms. The thyristors are fired or triggered after a delay of α from the natural commutation point. The natural commutation point is the starting of a cycle with period, ($60^\circ = T/6$) of output voltage waveform, if six thyristors are replaced by diodes. Note that the output voltage is similar to phase-controlled waveform for a converter, with the difference that it is an ac waveform in this case. The current flow is bidirectional, with the current in one direction in the positive half, and then, in other (opposite)

direction in the negative half. So, two thyristors connected back to back are needed in each phase. The turning off of a thyristor occurs, if its current falls to zero. To turn the thyristor on, the anode voltage must be higher than the cathode voltage, and also, a triggering signal must be applied at its gate.

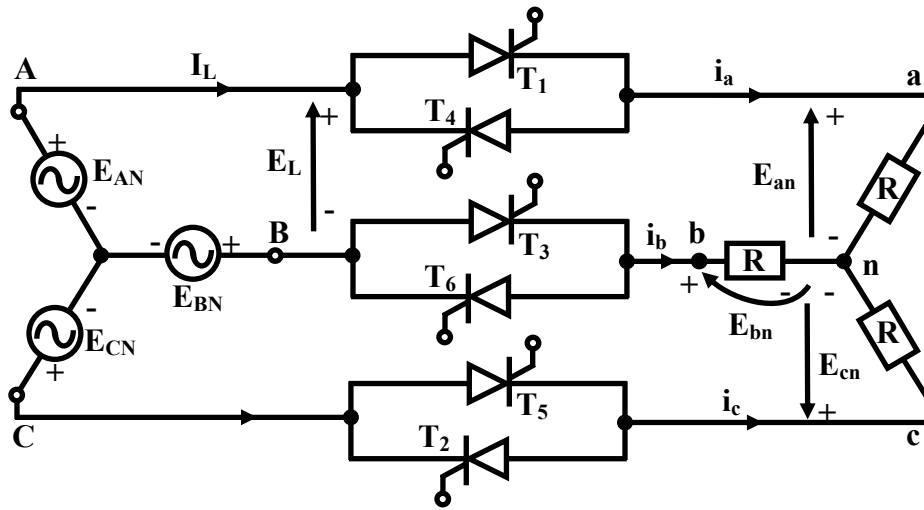


Fig. 27.1 Three-phase, three-wire ac regulator

The procedure for obtaining the expression of the rms value of the output voltage per phase for balanced star-connected resistive load, which depends on range of firing angle, as shown later, is described. If E_s is the rms value of the input voltage per phase, and assuming the voltage, E_{AN} as the reference, the instantaneous input voltages per phase are,

$$e_{AN} = \sqrt{2} E_s \sin \omega t, \quad e_{BN} = \sqrt{2} E_s \sin(\omega t - 120^\circ) \quad \text{and} \quad e_{CN} = \sqrt{2} E_s \sin(\omega t + 120^\circ)$$

Then, the instantaneous input line voltages are,

$$e_{AB} = \sqrt{6} E_s \sin(\omega t + 30^\circ), \quad e_{BC} = \sqrt{6} E_s \sin(\omega t - 90^\circ) \quad \text{and}$$

$$e_{CA} = \sqrt{6} E_s \sin(\omega t + 150^\circ)$$

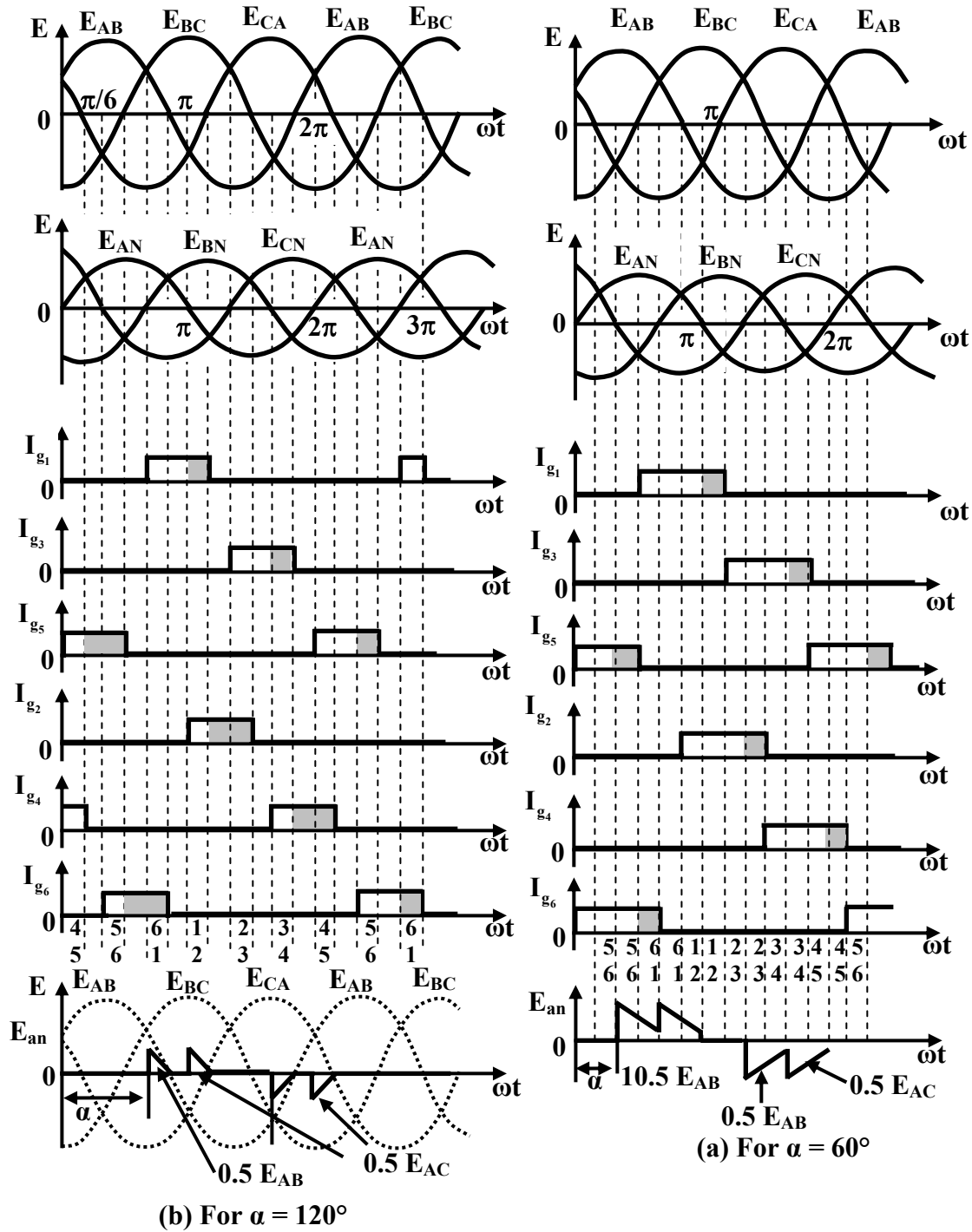


Fig. 27.2 Waveforms for three-phase three-wire ac regulator

The waveforms of the input voltages, the conduction angles of thyristors and the output voltage of one phase, for firing delay angles (α) of (a) 60° and (b) 120° are shown in Fig. 27.2. For $0^\circ \leq \alpha \leq 60^\circ (\pi/6)$, immediately before triggering of thyristor 1, two thyristors (5 & 6) conduct. Once thyristor 1 is triggered, three thyristors (1, 5 & 6) conduct. As stated earlier, a thyristor turns off, when the current through it goes to zero. The conditions alternate between two and three conducting thyristors.

At any time only two thyristors conduct for $60^\circ \leq \alpha \leq 90^\circ$. Although two thyristors conduct at any time for $90^\circ \leq \alpha \leq 150^\circ$, there are periods, when no thyristors are on. For $\alpha \geq 150^\circ$, there is no period for which two thyristors are on, and the output voltage becomes zero at $\alpha = 150^\circ (5\pi/6)$. The range of delay angle is $0^\circ \leq \alpha \leq 150^\circ$.

The expressions of the rms value of the output voltage per phase for balanced star-connected resistive load are as follows. Please note that $\theta = \omega t$.

For $0^\circ \leq \alpha \leq 60^\circ$:

$$E_0 = \left[\frac{1}{2\pi} \int_0^{2\pi} (e_{AN})^2 d\theta \right]^{\frac{1}{2}}$$

$$= \sqrt{6} E_s \left\{ \frac{2}{2\pi} \left[\int_\alpha^{\pi/3} \frac{\sin^2 \theta}{3} d\theta + \int_{\pi/2}^{\pi/2+\alpha} \frac{\sin^2 \theta}{4} d\theta + \int_{\pi/3+\alpha}^{2\pi/3} \frac{\sin^2 \theta}{3} d\theta + \int_{\pi/2}^{\pi/2+\alpha} \frac{\sin^2 \theta}{4} d\theta + \int_{2\pi/3+\alpha}^{\pi} \frac{\sin^2 \theta}{3} d\theta \right] \right\}^{\frac{1}{2}}$$

$$= \sqrt{6} E_s \left[\frac{1}{\pi} \left(\frac{\pi}{6} - \frac{\alpha}{4} + \frac{\sin 2\alpha}{8} \right) \right]^{\frac{1}{2}}$$

For $60^\circ \leq \alpha \leq 90^\circ$:

$$E_0 = \sqrt{6} E_s \left\{ \frac{2}{2\pi} \left[\int_{\pi/2-\pi/3+\alpha}^{5\pi/6-\pi/3+\alpha} \frac{\sin^2 \theta}{4} d\theta + \int_{\pi/2-\pi/3+\alpha}^{5\pi/6-\pi/3+\alpha} \frac{\sin^2 \theta}{4} d\theta \right] \right\}^{\frac{1}{2}}$$

$$= \sqrt{6} E_s \left[\frac{1}{\pi} \left(\frac{\pi}{12} - \frac{3 \sin 2\alpha}{16} + \frac{\sqrt{3} \cos 2\alpha}{16} \right) \right]^{\frac{1}{2}} = \sqrt{6} E_s \left[\frac{1}{\pi} \left(\frac{\pi}{12} + \frac{\sqrt{3} \sin(2\alpha + 30^\circ)}{8} \right) \right]^{\frac{1}{2}}$$

For $90^\circ \leq \alpha \leq 150^\circ$:

$$E_0 = \sqrt{6} E_s \left\{ \frac{2}{2\pi} \left[\int_{\pi/2-\pi/3+\alpha}^{\pi} \frac{\sin^2 \theta}{4} d\theta + \int_{\pi/2-\pi/3+\alpha}^{\pi} \frac{\sin^2 \theta}{4} d\theta \right] \right\}^{\frac{1}{2}}$$

$$= \sqrt{6} E_s \left[\frac{1}{\pi} \left(\frac{5\pi}{24} - \frac{\alpha}{4} + \frac{\sin 2\alpha}{16} + \frac{\sqrt{3} \cos 2\alpha}{16} \right) \right]^{\frac{1}{2}} = \sqrt{6} E_s \left[\frac{1}{\pi} \left(\frac{5\pi}{24} - \frac{\alpha}{4} + \frac{\sin(2\alpha + 60^\circ)}{8} \right) \right]^{\frac{1}{2}}$$

Three-phase Delta-connected AC Regulator with Balanced Resistive Load

The circuit of a three-phase, delta-connected ac regulator (termed as ac to ac voltage converter) with balanced resistive load is shown in Fig. 27.3. It may be noted that the resistance connected in all three phases are equal. Two thyristors connected back to back are used per phase, thus needing a total of six thyristors. As stated earlier, the numbering scheme may be noted. It may be observed that one phase of the balanced circuit is similar to that used for single-phase ac regulator described in the previous lesson (26) of the module. Since the phase current in a balanced three-phase system is only $(1/\sqrt{3})$ of the line current, the current rating of the thyristors would be lower than that if the thyristors are placed in the line.

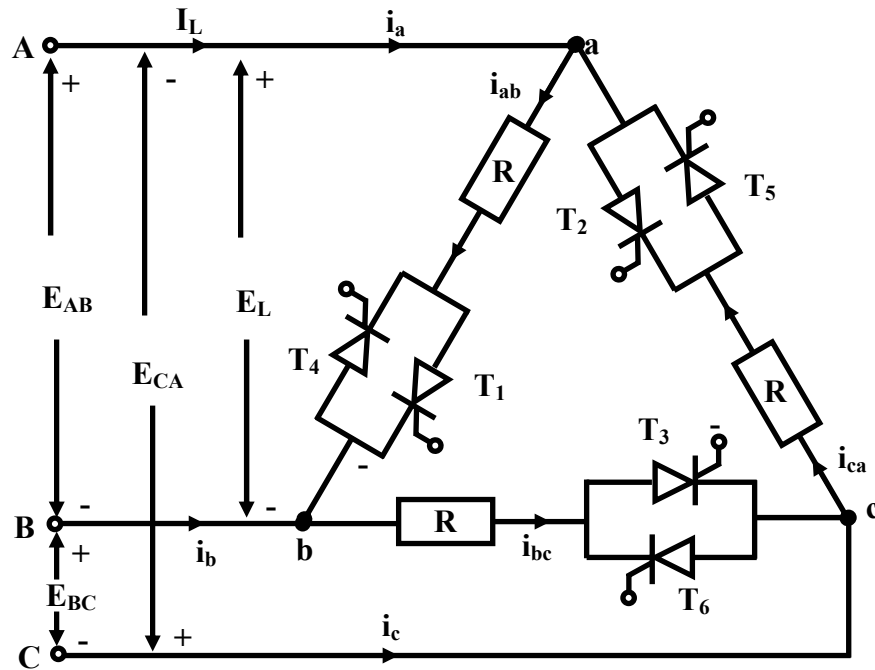


Fig. 27.3 Delta connected three-phase ac regulator

Assuming the line voltage E_{AB} as the reference, the instantaneous input line voltages are,

$$e_{AB} = \sqrt{2} E_s \sin \omega t, \quad e_{BC} = \sqrt{2} E_s \sin(\omega t - 120^\circ) \quad \text{and} \quad e_{CA} = \sqrt{2} E_s \sin(\omega t + 120^\circ)$$

It may be noted that E_s is the rms value of the line voltage in this case. The waveforms of the input line voltages, phase and line currents, and the thyristor gating signals, for $\alpha = 120^\circ$ are shown in Fig. 27.4.

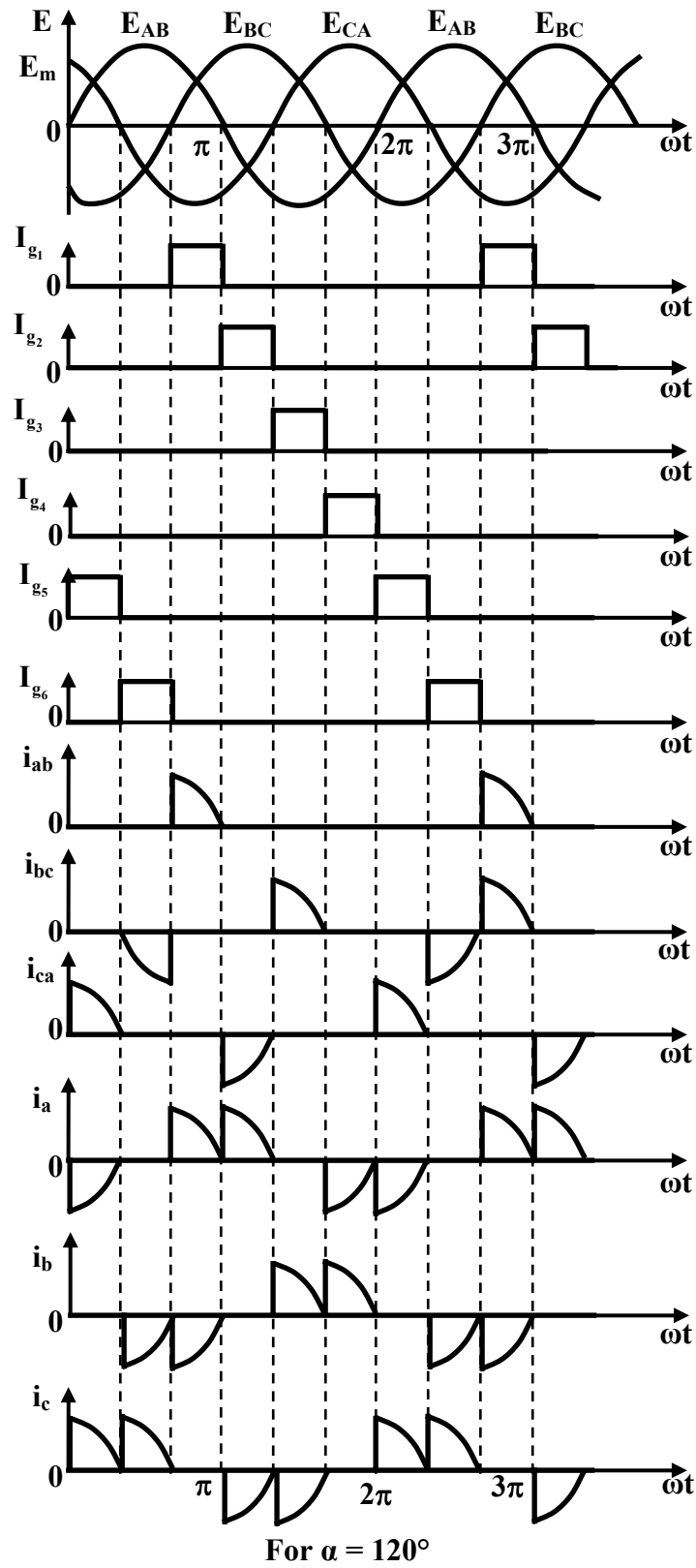


Fig. 27.4 Waveforms for three-phase delta-connected ac regulator

The rms value of the output phase voltage is obtained as

$$E_0 = \left[\frac{1}{2\pi} \int_{\alpha}^{2\pi} (e_{AB})^2 d\theta \right]^{\frac{1}{2}} = \left[\frac{2}{2\pi} \int_{\alpha}^{\pi} 2(E_s)^2 \sin^2 \theta d\theta \right]^{\frac{1}{2}} = E_s \left[\frac{1}{\pi} \left(\pi - \alpha + \frac{1}{2} \sin 2\alpha \right) \right]^{\frac{1}{2}}$$

When $\alpha = 0^\circ$, the maximum value of the output voltage is obtained, and the control range of delay angle is $0^\circ \leq \alpha \leq 180^\circ (\pi)$.

The line currents, which can be determined from the phase current, are,

$$i_a = i_{ab} - i_{ca}, \quad i_b = i_{bc} - i_{ab} \quad \text{and} \quad i_c = i_{ca} - i_{bc}.$$

From Fig. 27.4, it can be observed that the line currents depend on the delay angle, and may be discontinuous. The rms value of line and phase currents in this case can be determined by numerical solution or Fourier analysis.

If I_n is the rms value of the n^{th} harmonic component of a phase current, the rms value of the phase current is obtained from

$$I_{ab} = \left[I_1^2 + I_3^2 + I_5^2 + I_7^2 + I_9^2 + I_{11}^2 + \dots + I_n^2 \right]^{\frac{1}{2}}$$

For delta connection, the triplen harmonic components (i.e., those of order, $n = 3m$, where m is an odd integer) of the phase currents flow around the delta, and would not appear in the line. This is due to the fact that these harmonic currents are like the zero sequence component, being in phase in all three phases of the load. So, the rms value of the line current is,

$$I_a = \sqrt{3} \left[I_1^2 + I_5^2 + I_7^2 + I_{11}^2 + \dots + I_n^2 \right]^{\frac{1}{2}}$$

As a result, the rms value of the line current would not follow the normal relationship of a three-phase system such that $I_a < \sqrt{3} I_{ab}$.

Comparison of the Different Circuits used for Three-phase AC Regulators

Besides the two circuits shown in figures 27.1 & 27.3, other circuits used for three-phase ac regulators (ac to ac voltage converters), are shown in Fig. 27.5a-c. As given in point #6, the balanced load for the circuits (Fig. 27.1 & 27.3) is taken as inductive (R-L) one, not resistive as shown. The important points of comparison between the circuits are stated.

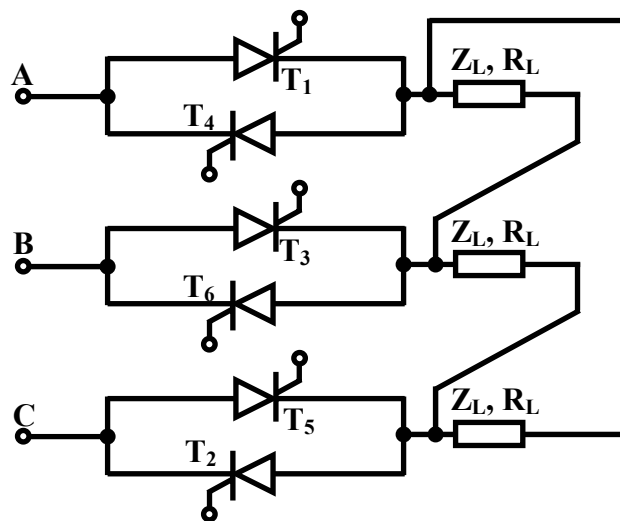


Fig. 27.5(a) 3-wire delta load

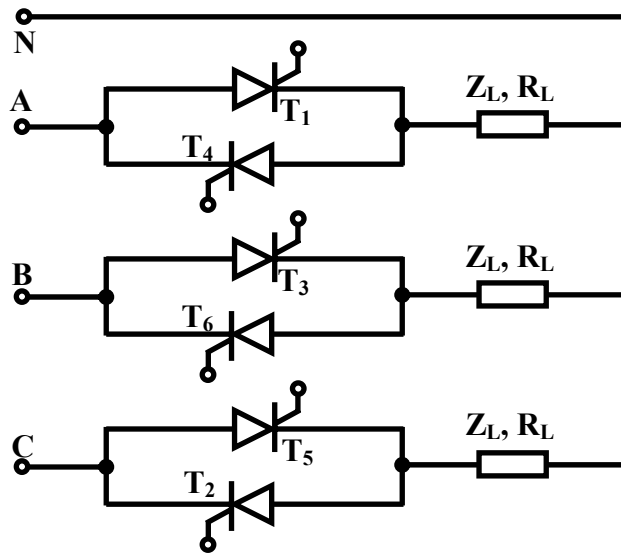


Fig. 27.5(b) 4-wire star load

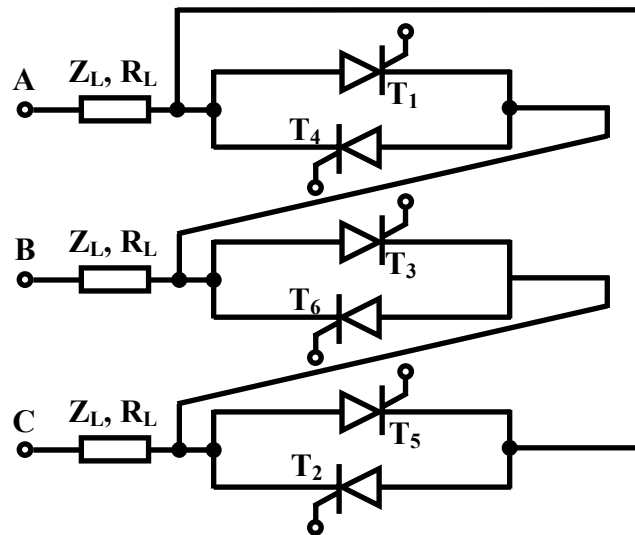


Fig. 27.5(c) Control in delta

1. In two circuits (Fig. 27.3 & 27.5b), the individual phase controllers control their own loads independently of the other. As stated earlier, they can, therefore be studied as three single-phase controllers.
2. In other circuits, the individual phase controllers affect the other phase loads also, and they have to be studied as complete three-phase circuits, as stated earlier in one case (Fig. 27.1).
3. The peak voltages occur across thyristors at or near the fully off state. In case of two circuits (Fig. 27.3 & 27.5c), the maximum thyristor voltage is the peak of the line voltage, whereas in the circuit (Fig. 27.5b), it is the peak of the phase voltage; in two circuits (Fig. 27.1 & 27.5a), the maximum thyristor voltage will be somewhere between the peak of the phase and line voltages depending on the leakage currents of the thyristors, the method of firing and the presence of voltage-sharing resistors across the thyristors.
4. All the five circuits can be used under phase control.

5. The range of phase angle required to achieve full output range from zero to maximum varies between the circuits, and are given in Table 27.1.
6. The maximum current in the thyristors is decided from the fully on condition, and the size of the thyristors to be used should be chosen from this condition. The peak, mean and rms values of the thyristor currents (Table 27.1) are related to the rms value of the input (ac) current, which should be found by applying the full supply voltage to the load circuit. The load impedance per phase is equal in magnitude (Z) and angle (ϕ), which is taken as positive, as it is mostly inductive (R-L).
7. The difference between the two circuits (Fig. 27.1 & 27.5b) is that in the second one, the neutral point is available, making it a 4-wire one.
8. The difference between the two circuits (Fig. 27.1 & 27.5a) is that in the second one, the three-phase balanced loads are connected in delta, which can be converted into its equivalent star, making it identical to the first circuit (Fig. 27.1). Also, the current in the thyristors in the second case (Fig. 27.5a) are the line currents, which are higher than the phase currents, which are flowing in the thyristors in the first one.
9. The difference between the two circuits (Fig. 27.1 & 27.5c) is that, in the second one, the thyristors connected back to back, are in delta, with the load connected in the three lines. Also, the current in the thyristors in the second case (Fig. 27.c) are the phase currents, which are lower than the line currents, which are flowing in the thyristors in the first one.

Table 27.1 summarises the current and voltage rating parameters associated with all these circuits used as three-phase ac controllers. E_{ac} and I_{ac} are the rms values of the line voltage and line current respectively.

It may be mentioned that other types of circuits for three-phase ac regulator can be used, but either the circuits are not bidirectional, i.e. unidirectional, or if they are bidirectional, in one half, only diode connected back to back per phase, instead of thyristor, is used. In the second case, only in one half with the thyristor per phase, controlled output voltage as shown earlier is obtained, but in the other one, uncontrolled output voltage, same as input one, is obtained. In the first case, where only one thyristor per phase is used, in one half, controlled output voltage is obtained, but in the second half, output voltage is zero, as only one device, but not two devices, is used. The readers are requested to refer to text books.

In this lesson – the second one in the first half, firstly the study of two basic circuits – one with star connection and the other with delta connection, for three-phase ac regulator (ac to ac voltage converter) are taken up. The operation with three-phase balanced resistive load, along with waveforms, is then described. Lastly, the important points of comparison of the performance with different types of circuits, including the above two, are presented. In the next, i.e. third and final lesson in the first half, the control circuit for ac regulators will be described in detail.

**Table 27.1 Rating of the Parameters used in
Three-phase AC Regulators**

Circuits (Fig. No.)	Delay angle, α for full control (degrees)	Maximum input line current (I_{ac} - rms)	Maximum load power dissipation	Thyristor		Thyristor current	
				$\frac{V_{Rwm}}{V_{ac}}$	$\frac{Peak}{I_{ac}}$	$\frac{Mean}{I_{ac}}$	$\frac{RMS}{I_{ac}}$
27.1	150	$\frac{E_{ac}}{\sqrt{3} Z}$	$3I_{ac}^2 R$	1.225	1.414	0.45	0.707
27.3	180	$\frac{\sqrt{3} E_{ac}}{Z}$	$I_{ac}^2 R$	1.414	0.816	0.26	0.408
27.5a	150	$\frac{\sqrt{3} E_{ac}}{Z}$	$I_{ac}^2 R$	1.225	1.414	0.45	0.707
27.5b	180	$\frac{E_{ac}}{\sqrt{3} Z}$	$3I_{ac}^2 R$	0.816	1.414	0.45	0.707
27.5c	150	$\frac{E_{ac}}{\sqrt{3} Z}$	$3I_{ac}^2 R$	1.414	0.816	0.26	0.408

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