

# Module

# 4

# AC to AC Voltage Converters

# Lesson

# 28

## Phase Angle Control in Triac-based Single-phase AC Regulators

## Instructional Objectives

Study of the following:

- The circuit used for the phase angle control in triac-based single-phase ac regulators (ac to ac voltage converters)
- The operation of the various blocks used in the circuit, along with the waveforms
- The harmonic analysis of the output voltage of a single-phase ac regulator with resistive load

## Introduction

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

In this lesson – the third and final one in the first half, firstly, the circuit used for the phase angle control in triac-based single-phase ac regulator, also termed as ac to ac voltage converter, is presented. Then, the operation of the various blocks used in the above circuit, along with the waveforms, is described. Finally, the harmonic analysis of the output voltage of a single-phase ac regulator with resistive load is, briefly discussed.

**Keywords:** Phase angle controller circuit, Triac-based single-phase ac regulator, or ac to ac voltage converter, harmonic analysis of the output voltage waveform.

## Phase Angle Controller Circuit for Triac-based Single-phase AC Regulator

The phase angle controller circuit for a triac-based single-phase ac regulator (ac to ac voltage converter), is shown in Fig. 28.1. The power circuit (also shown in Fig. 26.1c (lesson #26)) consists of a Triac in series with inductive (R-L) load, fed from a single phase supply, with rated voltage of, say 220 V(rms), having rated frequency ( $f = 50$  Hz). Before going into the operation of the phase angle controller circuit, some important points of the bidirectional controlled device (TRIAC), used in the ac circuit, having already been introduced in lesson #4 (module 1), is briefly presented, as it is not frequently used. Similarly, for the same reasons, DIAC (may have been introduced earlier), being used here as an uncontrolled bidirectional device, is also briefly described.

## TRIAC

A Triac is equivalent to two thyristors connected back to back as shown in Fig. 26.1a. Thus, it is a bidirectional switching device, in contrast to the thyristor, which is a unidirectional device, having reverse blocking characteristic, preventing the flow of current from Cathode to Anode. So, when it (triac) is in conduction mode, current flows in both directions (forward and reverse). This switching device is called as TRIAC (TRIode AC switch), with the circuit symbol shown in

Fig. 28.1. The three terminals of the triac are designated as  $MT_1$ ,  $MT_2$  and gate,  $G$ , shown in the same figure. These are similar to the terminals – A (Anode), K (Cathode) and G (Gate), of the thyristor. The terminal,  $MT_1$  is taken as the reference point for the measurement of the voltages and currents at other two terminals,  $G$  (gate) and  $MT_2$ . The gate ( $G$ ) is near to the terminal,  $MT_1$ . The thyristor conducts with the current direction from Anode to Cathode (positive), when a positive pulse is fed at the Gate terminal with respect to Cathode, and at that time, with positive voltage applied between Anode and Cathode terminals, being connected in series with the load. The triac conducts in the positive direction from  $MT_2$  to  $MT_1$ , when a positive pulse is applied at the gate ( $G$ ) terminal with respect to  $MT_1$  and at the same time, the positive voltage is applied between two terminals,  $MT_2$  (+) and  $MT_1$  (-). Similarly, the triac conducts in negative direction from  $MT_1$  to  $MT_2$ , when a negative pulse is applied at the gate ( $G$ ) terminal with respect to  $MT_1$  and at the same time, the positive voltage is applied between two terminals,  $MT_1$  (+) and  $MT_2$  (-). Please note that the voltage between two terminals,  $MT_2$  and  $MT_1$ , is negative, in this case. So, the triac can conduct in both directions (positive and negative) as given here, whereas the thyristor conducts in one (positive) direction only. Only one triac is needed, whereas it is to be replaced by two thyristors, with consequent change in the control circuit. The V-I characteristics of both thyristor and triac, have been discussed in lesson #4 (module 1). A thyristor turns off (non-conducting mode), if the current through it, falls below holding current. Similarly, a triac turns off (non-conducting mode), if the magnitude of the current, irrespective of its direction, falls below holding current. As a triac is connected in an ac circuit, and if the load in the circuit is resistive, the triac turns off at the zero crossing points of the voltage in each half (the supply (input) voltage reaches zero at the end of each half cycle). This will be nearly valid, if the load inductance is small, though the triac in that case turns off, as the current though it goes to zero, after the zero crossing point is reached in each half. The case of higher inductance in the load has been discussed in detail in lesson #26 (module 3).

The triac is a low power device, used in voltage control circuits, used as light dimmers, speed control for fan motors (single-phase), etc. Some of the advantages and disadvantages of the triac vis-a-vis thyristor are given.

## Advantages

1. Triacs are triggered by positive or negative polarity voltages applied at the gate terminal.
2. A triac needs a single heat sink of slightly larger size, whereas anti-parallel thyristor pair needs two heat sinks of slightly smaller sizes, but due to the clearance total space required is more for thyristors.

## Disadvantages

1. Triacs have low  $dv/dt$  rating as compared to thyristors.
2. Triacs are available in lower rating as compared to thyristors.
3. Since a triac can be triggered in either direction, a trigger circuit for triac needs careful consideration.
4. The reliability of triacs is lower than that of thyristors.

## DIAC

A Diac is equivalent to two diodes connected back to back. Also, it is a bidirectional device, in contrast to the diode, which is a unidirectional device, having reverse blocking characteristic, preventing the flow of current from Cathode to Anode. So, when it (diac) is in conduction mode, current flows in both directions (forward and reverse). This switching device is called as DIAC (DIode AC switch), with the circuit symbol shown in Fig. 28.1. The two terminals of the diac are designated as  $T_1$  and  $T_2$ , shown in the same figure. These are similar to the terminals, A (Anode) and K (Cathode), of the diode. The diac conducts, when the break-over voltage is reached in either polarity across its two terminals. When  $T_1$  is positive with respect to  $T_2$ , and if at that time if the voltage,  $V_{12}$  exceeds  $V_{BO1}$  (break-over voltage), the diac conducts in positive direction from  $T_1$  to  $T_2$ . Similarly, when  $T_2$  is positive with respect to  $T_1$ , and if at that time if the voltage,  $V_{21}$  exceeds  $V_{BO2}$  (break-over voltage), the diac conducts in negative direction from  $T_2$  to  $T_1$ . So, a diac can conduct in both directions (positive and negative), whereas a diode conducts only in positive direction from Anode (A) to Cathode (K), if, at that time, the voltage,  $V_{AK}$  exceeds  $V_{BO}$  (break-over voltage). A diode does not conduct in the negative direction, if the voltage,  $V_{AK}$  is negative. A diode turns off (non-conducting mode), if the current through it, falls below holding current. Similarly, a diac turns off (non-conducting mode), if the magnitude of the current, irrespective of its direction, falls below holding current. If the V-I characteristic of diode is known, as given in lesson #2 (module 1), the V-I characteristic of diac, on the lines of the triac can be developed. The students are requested to study the characteristic of diac from a text book, as it is not included here for obvious reason.

Now, the operation of the phase angle controller circuit (Fig. 28.1) is presented, with the waveforms at various points shown in Fig. 28.2. The power circuit, the main component of which is the triac, has been described earlier. The diac is symmetrical, unlike the triac, as described earlier. So, the diac (Fig. 28.1) can be connected in opposite direction, with  $T_1$  in place of  $T_2$ , and vice versa, i.e.,  $T_2, T_1$  in place of  $T_1$ . But the operation here is described with the connection as in the figure. The triac is not symmetrical, though it conducts in both directions like diac. Two reasons are: the presence of third terminal, Gate (G), and the gate signal to be fed between  $G$  &  $MT_1$  (reference) for triggering. The snubber part ( $R_s$  &  $C_s$ ), shown in the figure, is used for the protection of the triac – the power switching device. The remaining part, including the diac used for triggering of the triac, is the controller for the triac.

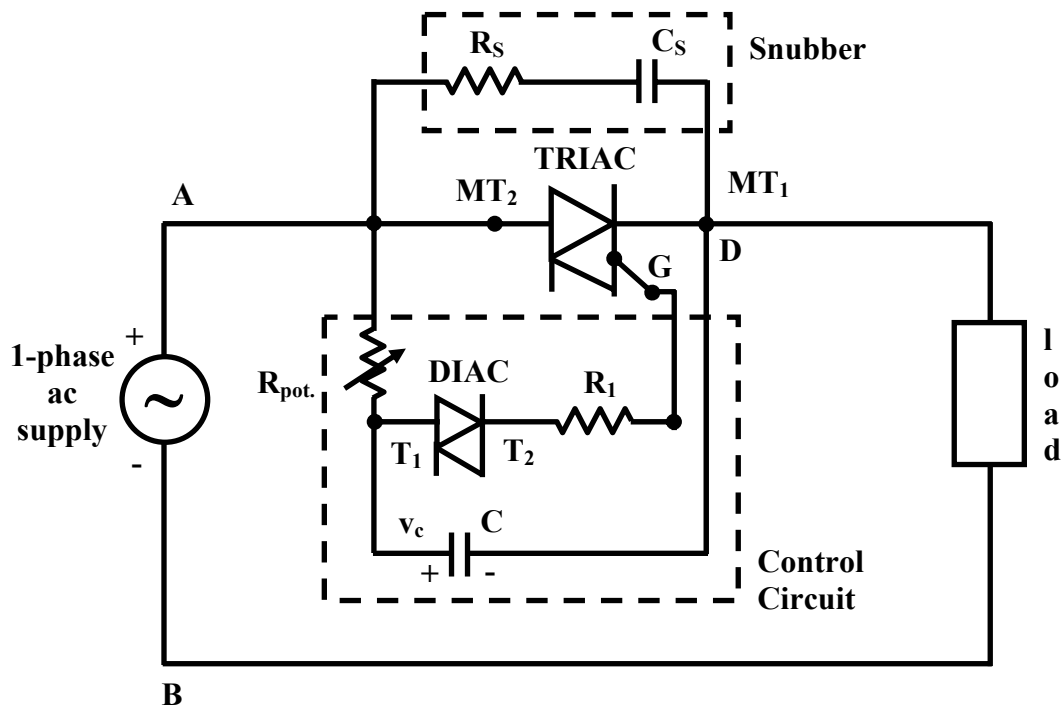
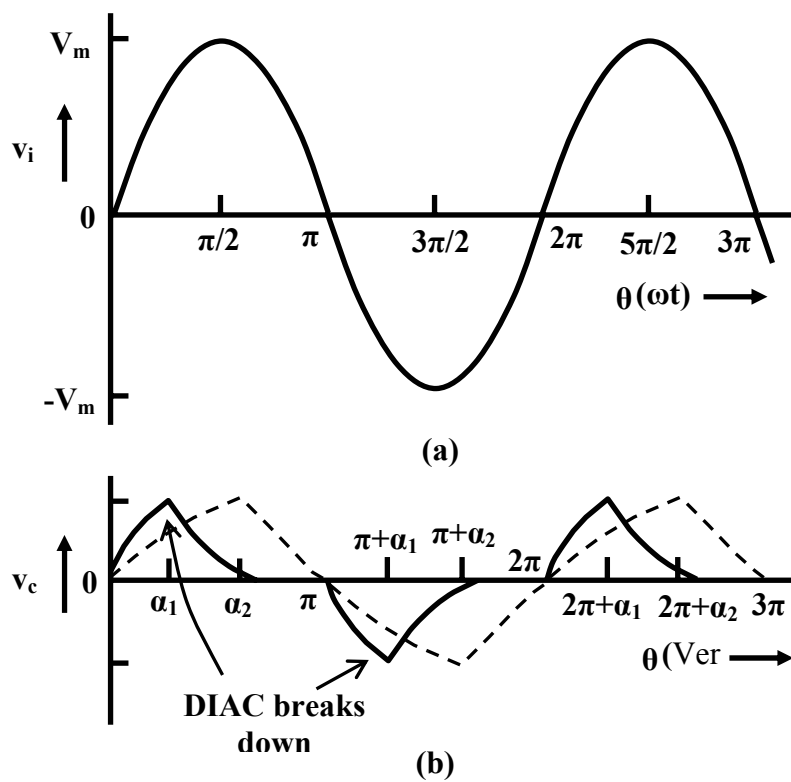
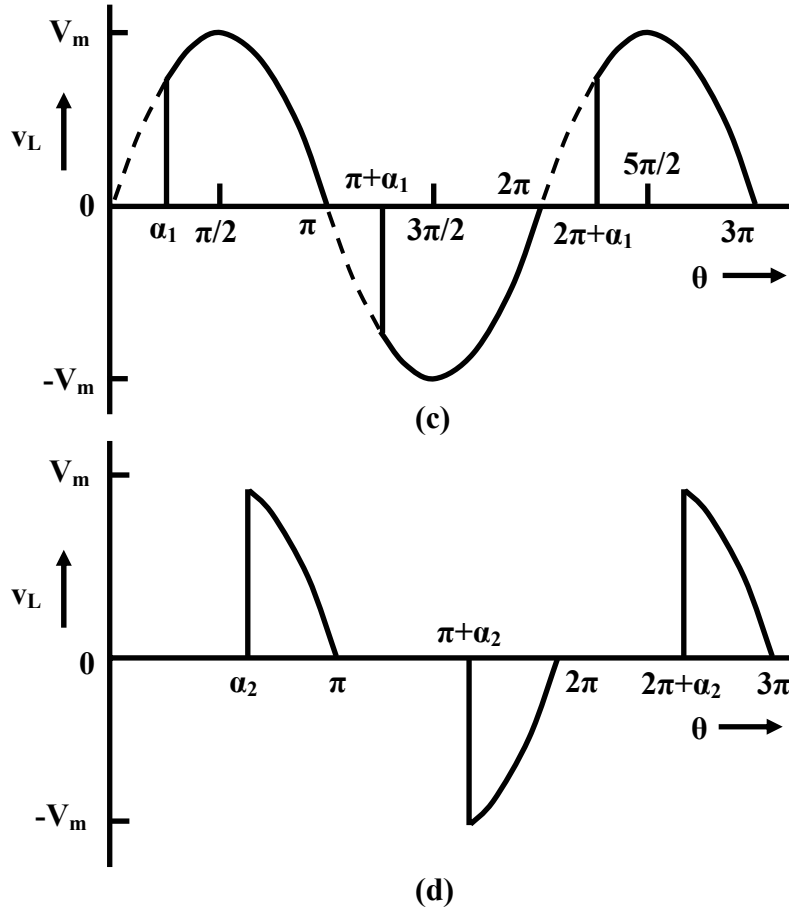


Fig. 28.1: Phase angle controller circuit for a single-phase ac regulator using TRIAC





**Fig. 28.2: Waveforms at various points of the controller circuit**  
**(a) Input (source) voltage,  $v_{AB}$**   
**(b) Voltage across capacitor,  $v_C$**   
**(c) Output (load) voltage,  $v_{DB}$  with  $R_{put} = R_2$  (lower)**  
**(d) Output (load) voltage,  $v_{DB}$  with  $R_{put} = R_3$  (higher)**

As soon the input (supply) voltage is given to the circuit, the capacitor,  $C$  starts getting charged through the potentiometer resistance,  $R_{pot} = R_2$ , the value of which is low and the load resistance. The polarity of the input voltage is important. The start of the input voltage is taken as the positive zero-crossing point (Fig. 28.2a), when the voltage changes from negative to positive. The point,  $A$  is now positive with respect to  $B$  (Fig. 28.1). The polarity of the voltage across the capacitor,  $C$  is that the left hand side is positive, with the right hand side as negative. The capacitor voltage ( $v_C$ ) is shown in Fig. 28.2b. As soon as the capacitor voltage,  $v_C$  reaches the break-over voltage ( $V_{BO}$ ) of the diac (about 30 V), the diac starts to conduct in the positive direction from  $T_1$  to  $T_2$ . At this point, the triac gets a positive pulse at its gate ( $G$  is now positive with respect to  $MT_1$ ) and also  $MT_2$  is at a higher potential than  $MT_1$ . So, the triac is turned on at the angle,  $\theta = \alpha_1 = \omega t_1 = 2\pi f t_1$ . The current through the triac is in the positive direction from  $MT_2$  to  $MT_1$ . Please note that the time constant of the charging circuit is related to the potentiometer resistance ( $R_2$ ), which is low. So, the time needed for the capacitor to reach the break-over voltage ( $V_{BO}$ ) is  $t_1 \propto \alpha_1$ . The triac is turned off at  $\theta = \pi$ , when the input

voltage reaches the negative zero-crossing point. So, the conduction period (angle in rad) is from  $\alpha_1$  to  $\pi$  in the positive half. The output (load) voltage ( $v_L = v_{DB}$ ) waveform (Fig. 28.2c) is nearly same as the input voltage ( $v_i = v_{AB}$ ), neglecting the voltage drop across the triac. The capacitor voltage (Fig. 28.2b) starts decreasing at  $t = t_1$ , and reaches zero after some time, the time being small. The discharge path is through diac, the resistance  $R_1$ , and the gate, G &  $MT_1$  terminals of the triac, the total resistance is quite low. So, the time constant during discharge is quite low, as compared to that during charging. The resistance,  $R_1$  is used to decrease the capacitor current during discharge.

The pattern is repeated in the negative half of the input voltage, which is briefly described. The capacitor, C starts charging in the opposite direction through the same path as given earlier. The charging starts from the negative zero-crossing of the input voltage (Fig. 28.2a). The polarity of the input voltage is now opposite, with the point, B being positive with respect to A. The polarity of the capacitor voltage (Fig. 28.2b) is also opposite, with the right hand side as positive, and the left hand side as negative. The charging time constant remains same (low), as it was earlier. The capacitor voltage,  $v_C$  (in magnitude) reaches the break-over voltage ( $V_{BO}$ ) of the diac after time  $t_1 \propto \alpha_1$ , measured from the negative zero-crossing of the input voltage ( $\theta = \pi$ ). The diac now starts to conduct in the negative direction from  $T_2$  to  $T_1$ . At this point, the triac gets a negative pulse at its gate (G is now negative with respect to  $MT_1$ ) and also  $MT_1$  is at a higher potential than  $MT_2$ . So, the triac is turned on at the angle, ( $\theta = \pi + \alpha_1$ ). The current through the triac is in the negative direction from  $MT_1$  to  $MT_2$ . The triac is turned off at the next positive zero-crossing point ( $\theta = 2\pi$ ). The conduction period (Fig. 28.2c) is from  $(\pi + \alpha_1)$  to  $(2\pi)$  in the negative half, the total conduction time  $(\pi - \alpha_1)$  being same in both half. The output voltage waveform is identical, but it is opposite in this (negative) half. As in the earlier case, the capacitor voltage (Fig. 29.2b) starts decreasing, and reaches zero after some time, the discharge path remaining same. Thus, the diac helps in the turning on of the triac in both directions, making the control circuit simple with few components only (Fig. 28.1). Though the function of the diac could have been performed by using two diodes connected back to back, the control circuit would have to be modified.

To change the conduction period, or the start of conduction of the triac, the potentiometer resistance is to be increased from  $R_2$  to  $R_3$ , which is higher. The capacitor voltage waveform for this case is shown in Fig. 28.2b as dotted line, as the time constant of the charging circuit also increases. So, the time needed for the capacitor voltage (in magnitude, as both halves are considered) to reach the break-over voltage ( $V_{BO}$ ) of the diac is now ( $t_2 \propto \alpha_2$ ). The conduction period in the positive half (Fig. 28.2d) is from  $\alpha_2 > \alpha_1$  to  $\pi$ , the total time in both half is  $(\pi - \alpha_2)$ . The conduction period decreases. The rms value of the output voltage also decreases. Other conditions, say during discharge of the capacitor voltage remaining same, is not described.

The range of phase angle delay, in the ideal case, is  $0^\circ < \alpha < \pi$ . But normally, the lower limit is higher than  $0^\circ$ , while the upper limit is lower than  $\pi(180^\circ)$ . The input voltage (Fig. 28.2a) is zero at the two limits ( $0^\circ$  &  $180^\circ$ ) in the ideal case. As the input voltage has to exceed at least the voltage drop in the triac, and the capacitor voltage (Fig. 28.2b) also has to reach the break-over voltage of the diac as given earlier, the normal range of phase angle delay is to be used, not the ideal ones. Also, if the load is inductive, the current in the triac has to exceed a threshold value, before the gate pulse can be withdrawn. Otherwise, the triac may not be



triggered, returning to off state again. This point may have been described in the case of phase-controlled single-phase (bridge) converters (ac-dc), with inductive load in series with battery or back emf, in lessons #10-11 (module 2).

## Harmonic Analysis of the Output Voltage Waveform

Before the harmonic analysis of the output voltage waveform is taken up, the following points may be noted. The output (load) voltage in ac regulators (both single-phase and three-phase) decreases, as the delay angle is increased. This can be observed from the voltage waveforms given in the previous lessons (#26-27) in the first half of this module (#4), for both types of ac regulators. These are mainly used to decrease the speed of the induction motor with fan type load ( $T_L \propto N^2$ ), not for constant load torque operation. The application is in the low power range. The major disadvantage of these regulators is that the power factor and also displacement factor decrease, with the increase in delay angle.

The harmonics are also present in the output (load) voltage waveforms, being phase-controlled ones, of ac regulators. The harmonic analysis of the output voltage waveform (Fig. 28.3) of a single-phase ac regulator with resistive (R) load (please see the waveforms given in figures 28.2c-d, which are nearly same as Fig. 28.3) is briefly presented. The symbols, including some described earlier, are given.

$v_0$  = Instantaneous value of the output (load) voltage

$V_m = \sqrt{2} V$  = Peak value of the input voltage

$V = V_m / \sqrt{2}$  = RMS value of the input voltage

$f = 1/T$  = Frequency (Hz) of the supply (input)

$\omega = 2\pi f$  = Angular frequency (rad/s)

$\theta = \omega t$  = Angle (rad)

$T = 1/f$  = Time period (s)

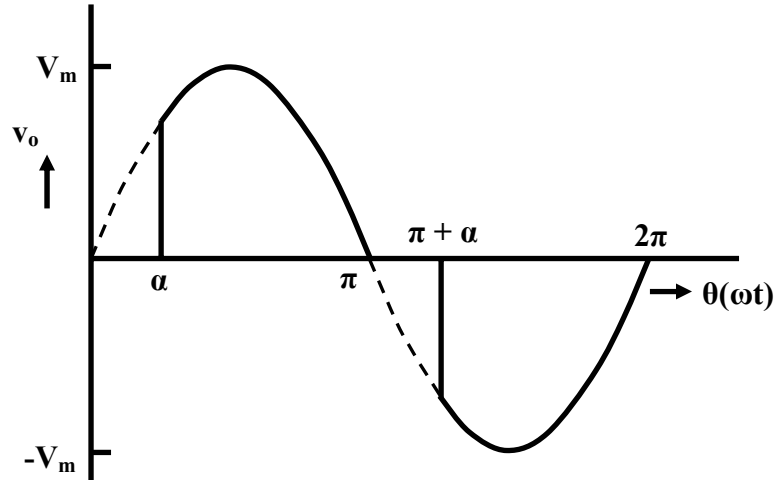
$a_n$  &  $b_n$  are the maximum values of the sine and cosine components of the harmonics of order n, present in the output voltage waveform respectively.

$c_n$  &  $\theta_n$  are the maximum value (amplitude), and phase angle, of  $n^{\text{th}}$  harmonic component respectively.

The relationships are  $c_n = \sqrt{a_n^2 + b_n^2}$ , and  $\theta_n = \tan^{-1}(b_n / a_n)$ ,

and the other relationships are  $a_n = c_n \cos \theta_n$  and  $b_n = c_n \sin \theta_n$ .

The rms value of  $n^{\text{th}}$  harmonic component =  $c_n / \sqrt{2}$



**Fig. 28.3: Input and output voltage waveforms of a single-phase ac regulator with resistive load.**

The output (load) voltage waveform (Fig. 28.3) consists of two parts, the first one is positive in the positive half cycle, while the second part is negative in the next (negative) half cycle. The waveform has half-wave asymmetry, with only odd ( $n = 2m + 1$ ) harmonics being present. The even ( $n = 2m$ ) harmonics are not present in this case, as the second part is cancelled by the first part. Also to be noted that the average value is zero. This can also be computed by the formulas for the harmonic analysis of the output (load) voltage waveform of the buck converter (dc-dc) circuit, given in lesson #18 in module 3. It can be observed for the single-phase ac regulator circuit shown in lesson #26 in this module (#4) that the switching device (triac or two thyristors connected back to back) is turned on at the delay angle,  $\theta = \alpha$ , and then turns off at  $\theta = \pi$ , when the input voltage and also the output current goes to zero, in the first (positive) half, as the load is resistive (R). This is repeated in the second (negative) half.

The output (load) voltage waveform for one cycle is,

$$v_0 = 0 \text{ for } \alpha < \theta < 0; \quad v_0 = V_m \sin \theta = \sqrt{2} V \sin \theta \text{ for } \pi < \theta < \alpha;$$

$$v_0 = 0 \text{ for } (\pi + \alpha) < \theta < \pi; \quad v_0 = V_m \sin \theta = \sqrt{2} V \sin \theta \text{ for } (2\pi) < \theta < (\pi + \alpha)$$

In terms of the Fourier components, the expression is,

$$v_0 = \sum_{n=1,3,5,7,\dots}^{\infty} (a_n \sin n\theta + b_n \cos n\theta) = \sum_{n=1,3,5,7,\dots}^{\infty} c_n \sin(n\theta + \theta_n)$$

where,

$$a_n = \frac{2}{\pi} \int_0^{\pi} v_0 \sin(n\theta) d\theta; \quad b_n = \frac{2}{\pi} \int_0^{\pi} v_0 \cos(n\theta) d\theta$$

Please note that two formulas given here, differ from two formulas given in lesson #18 (module 3). The expressions for the components of the fundamental and third harmonic, of the output voltage are derived. The students are requested to derive, say the expressions for the other, say fifth harmonic components.

$$a_1 = \frac{2}{\pi} \int_0^{\pi} v_0(\theta) \sin \theta d\theta = \frac{2}{\pi} \int_{\alpha}^{\pi} \sqrt{2} V (\sin \theta)^2 d\theta = \left( \frac{\sqrt{2} V}{\pi} \right) \int_{\alpha}^{\pi} (1 - \cos 2\theta) d\theta$$

$$= \left( \frac{\sqrt{2} V}{\pi} \right) (\theta - \frac{1}{2} \sin 2\theta) \Big|_{\alpha}^{\pi} = \left( \frac{\sqrt{2} V}{\pi} \right) ((\pi - \alpha) + \frac{1}{2} \sin 2\alpha) = \left( \frac{\sqrt{2} V}{\pi} \right) ((\pi - \alpha) + 0.5 \sin 2\alpha)$$

$$= \left( \frac{\sqrt{2} V}{\pi} \right) ((\pi - \alpha) + \sin \alpha \cos \alpha)$$

$$b_1 = \frac{2}{\pi} \int_0^{\pi} v_0(\theta) \cos \theta d\theta = \frac{2}{\pi} \int_{\alpha}^{\pi} \sqrt{2} V \sin \theta \cos \theta d\theta = \left( \frac{\sqrt{2} V}{\pi} \right) \int_{\alpha}^{\pi} \sin 2\theta d\theta$$

$$= \left( \frac{V}{\sqrt{2} \pi} \right) (\cos 2\theta) \Big|_{\alpha}^{\pi} = - \left( \frac{V}{\sqrt{2} \pi} \right) (1 - \cos 2\alpha) = - \left( \frac{\sqrt{2} V}{\pi} \right) (\sin \alpha)^2$$

$$a_3 = \frac{2}{\pi} \int_0^{\pi} v_0(\theta) \sin 3\theta d\theta = \frac{2}{\pi} \int_{\alpha}^{\pi} \sqrt{2} V \sin \theta \sin 3\theta d\theta = \left( \frac{\sqrt{2} V}{\pi} \right) \int_{\alpha}^{\pi} (\cos 2\theta - \cos 4\theta) d\theta$$

$$= \left( \frac{\sqrt{2} V}{\pi} \right) (\frac{1}{2} \sin 2\theta - \frac{1}{4} \sin 4\theta) \Big|_{\alpha}^{\pi} = \left( \frac{\sqrt{2} V}{4\pi} \right) (\sin 4\alpha - 2 \sin 2\alpha)$$

$$b_3 = \frac{2}{\pi} \int_0^{\pi} v_0(\theta) \cos 3\theta d\theta = \frac{2}{\pi} \int_{\alpha}^{\pi} \sqrt{2} V \sin \theta \cos 3\theta d\theta = \left( \frac{\sqrt{2} V}{\pi} \right) \int_{\alpha}^{\pi} (\sin 4\theta - \sin 2\theta) d\theta$$

$$= \left( \frac{\sqrt{2} V}{\pi} \right) (\frac{1}{4} \cos 4\theta - \frac{1}{2} \cos 2\theta) \Big|_{\alpha}^{\pi} = \left( \frac{\sqrt{2} V}{4\pi} \right) (\cos 4\alpha - 2 \cos 2\alpha + 1)$$

Using two sets of two expressions given earlier, the rms value ( $c_n / \sqrt{2}$ ) and phase angle ( $\theta_n$ ), of the harmonic components of the output (load) voltage, are obtained. As there is no inductance in the load circuit, the rms values of the harmonic components of the output current are proportional to those (the rms values of the harmonic components) of the output voltage. It may be stated that the rms values of the harmonic components of both output voltage and current decrease, though not in inverse proportion to ( $n$ ) as given in lesson #18 (module 3), as the order of harmonic ( $n$ ) increases.

The expression for the rms value of the output voltage, as a function of phase angle delay  $\alpha$ , is given in lesson #26 of this module (4), and not repeated here. The relation between the rms value,  $V_{0r}$ , and the rms values of all odd harmonic components is,

$$V_{0r} = \sqrt{\sum_{n=1,3,5,7,\dots} (c_n / \sqrt{2})^2}$$

It may be noted that this expression is different from that given in the section on the harmonic analysis of the output voltage waveform of a buck converter (dc-dc) in lesson #18 (module 3). This is, because the average value,  $V_0$  is zero, and the rms values of all even harmonic components are also zero, with only odd harmonic components being present, as this waveform has half-wave asymmetry (given earlier). The rms values of all odd harmonic components, including that of fundamental one, can, first, be computed as per the formula given earlier. It may be noted that, the rms values of only a few odd harmonic components need be computed, because the rms values decrease, as the order of harmonic increases, as given earlier. Then, using the expression for the rms value, it (rms value) can be computed. Finally, it can be checked from the expression for the rms value (given in lesson #26).

The rms value of the fundamental ( $n=1$ ) component of the output voltage,  $(c_1/\sqrt{2})$  is maximum (highest) for  $\alpha \approx 0^\circ$  with  $\alpha > 0^\circ$ , in normal case, though it reaches maximum at  $\alpha = 0^\circ$  (ideal case). Also the rms value of the output voltage,  $V_{0r}$  is maximum (nearly same as the rms value of input voltage) for  $\alpha \approx 0^\circ$ , and is slightly higher than the rms value of its fundamental component. If the expression under the square root for the rms value is divided into two parts – the rms value of fundamental component and the rms values of other odd harmonic components, starting from third one, the new form is,

$$V_{0r} = \sqrt{(c_1/\sqrt{2})^2 + \sum_{n=3,5,7,\dots} (c_n/\sqrt{2})^2}$$

This expression can also be written as,

$$\sqrt{\sum_{n=3,5,7,\dots} (c_n/\sqrt{2})^2} = \sqrt{(V_{0r})^2 - (c_1/\sqrt{2})^2}$$

From this expression, and also from the expressions given earlier, it can be observed that the rms values of all odd harmonic components, except fundamental one, starting from third, are very low.

The rms value of the fundamental component of the output voltage,  $(c_1/\sqrt{2})$  is minimum (lowest) for  $\alpha \approx \pi(180^\circ)$  with  $\alpha < \pi$ , in normal case, though it is minimum (zero) at  $\alpha = \pi$  (ideal case). Also the rms value of the output voltage,  $V_{0r}$  is minimum (not zero, but nearly zero) for  $\alpha \approx \pi$ , and is slightly higher than the rms value of its fundamental component. From the expression, using the rms value, and the rms value of fundamental component only, and other expressions given earlier, it can be observed that the rms values of all odd harmonic components, which also includes fundamental one in this case, are very low.

This type of harmonic analysis can be performed for the output voltage of controlled (half/full) single/three-phase converters (ac-dc) with resistive load, as discussed in lessons #10-11 & 13-14 in module 2. In the case of three-phase ones, the resistive load is balanced one. Taking the case of a single-phase controlled bridge converter with resistive load, the output voltage waveform obtained is of the same type, except that it is a dc one, with the second half of the periodic waveform being also positive, unlike the case shown in Fig. 28.1. The voltage waveform in that case, has half-wave symmetry (having dc and only even ( $n = 2m$ ) harmonic components, but no odd harmonic components), unlike the case here, of the voltage waveform having half-wave asymmetry (with only odd ( $n = 2m + 1$ ) harmonic components, but no even harmonic and also dc components, as given earlier).

In this lesson – the third and final one in the first half of this module, the circuit used for the phase angle control in triac-based single-phase ac regulator or ac to ac voltage converter is, first, presented. Then, the operation of the various blocks used in the above circuit, along with the waveforms, is described. Finally, the harmonic analysis of the output voltage of a single-phase ac regulator with resistive load is, briefly discussed. Starting with the next (fourth) lesson – first one in the second half, the various types of cyclo-converters, used as ac to ac voltage converters, are presented. The power circuit using mostly thyristors, the output voltage waveforms for both single-phase and three-phase ones, and the various blocks of control circuit required (in brief), are mostly described in detail.