UNIVERSITY OF ANBAR

COLLEGE OF ENGINEERING

ELECTRICAL ENGINEERING DEPARTMENT

Power Electronic

Fourth Class

Chapter 05

AC to AC Controller

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CHAPTER 5

Ac to Ac Controllers

5.0 Introduction

An alternating current voltage controller or regulator converts a fixed AC voltage source to a variable AC voltage source. The output frequency is always equal to the input frequency. The simplest way to control the AC voltage to a load is by using an AC switch. This switch can be bidirectional switch like a triac or a pair of SCRs connected in antiparallel as shown in Figure 5.1. Switching devices other than thyristors can also be used to implement bidirectional switches. For most purposes, the control result is independent of the switch used. The practical limitations of the presently available triac ratings often make it necessary to use SCRs in very high power applications for which triac might otherwise be used.

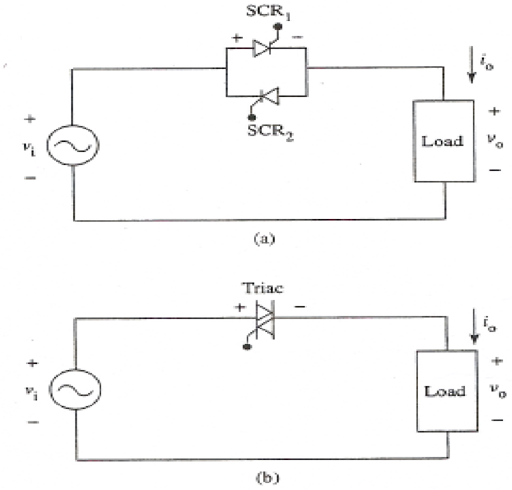


Figure 5.1: Basic AC Power Controller (a) an SCR Circuit, (b) a Triac Circuit

The major applications of AC voltage controllers include lighting control, industrial heating, spot (resistance) welding, on-load transformer tap changing, static var compensation and speed control for induction motors

5.1 Ac Power Control

There are two basic methods for controlling the load power, integral cycle control or on-off control and phase control. The first method is suitable for systems with a large time constant, such as temperature control system. The load power can be controlled by connecting the source to the load for a few complete cycles then disconnecting the source from the load for another number of cycles and repeating the switching cycle. The relative duration of the on and off periods, i.e. the duty cycle d is adjusted so that the average power delivered to the load meets some particular objectives. Figure 5.2 shows the typical pattern. In ideal circumstances, the average power to the load can be controlled from 0% through 100%.

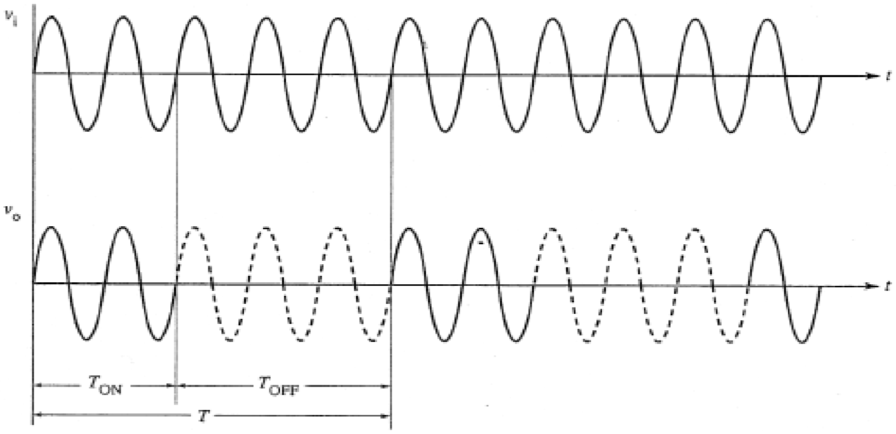


Figure 5.2 : Integral Cycle Control

Integral cycle control is not suitable for loads with a short time constant. Phase control can be used in these situations. In phase control the switch connects the load to the source for part of each cycle of input voltage. The graphs in Figure 5.3 illustrate the waveforms for phase control with a resistive load. The voltage at the load can be varied by alternating the firing angle for each half cycle of a period. If $\alpha = 0$, the output voltage is maximum (V_o=V_i). When $\alpha = \pi$, the output voltage is minimum (V_o=0). Therefore the output voltage can controlled to any value between zero and the source voltage. This process produces a phase controlled alternating output that is suitable for applications such as lighting control and motor-speed control.

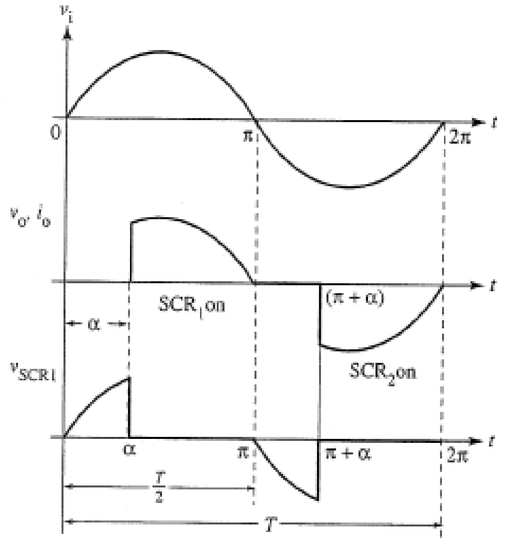


Figure 5.3 : AC Phase Control Waveforms with Resistive Load

5.2 Integral Cycle Control

In the Ac voltage controller in Figure 5.1, the thyristors can be fires at $\alpha = 0^0$ to allow complete cycles of source voltage to be applied to the load. If there is no firing signal in any cycle, then no voltage appears across the load. This it is possible to allow complete cycles of source voltage to be applied to the load followed by complete cycles of extinction. If the load voltage is turned on and off in this matter (Figure 5.2), the average power to the load can be varied. The ratio of on time to total cycle time (the period in which the conduction pattern repeats) controls the average load power. In Figure 5.2 T_{on} is the number of cycles for which the load is energized and T is the number cycles in the full period of operation. During the T_{on} part of the cycle, the switch is on and the load power is maximum. During the remaining T_{off} ($T_{off} = T - T_{on}$) cycles, the switch is off and load power is zero.

For a resistive load R, the average load power is given by

$$P_0(avg) = \frac{V_i^2 T_{on}}{RT} = \frac{V_i^2}{R} d = P_{0(\max)} d \qquad 5.1$$

The RMS value of the output voltage is given by

$$V_0 = \frac{V_m}{\sqrt{2}} \sqrt{\frac{T_{on}}{T}} = V_i \sqrt{d} \qquad 5.2$$

Where

V_m = maximum value of input voltage

V_i = RMS value of input voltage = $V_m / \sqrt{d}$

Because T_{on} can be varied only as an integer, the average value of the load power is not a continuous function but has only discrete levels. The number of steps available for regulating the average power depends on the total number of cycles included in the repeat pattern.

Power conversion is the ratio of the average power output ($P_{o(avg)}$) to the maximum possible power output ($P_{o(max)}$). $P_{o(avg)} / P_{o(max)}$ is equal to the duty cycle

$$d = T_{on}/ (T_{on}+T_{off}) = T_{on}/T$$

where T = time period = Ton+Toff

The source current is always in time phase with the source voltage. However, this does not mean that an integral cycle control circuit operates at unity power factor- for part of the time, the source current is not present at all and therefore is not in phase with the source voltage. The power factor is given by

$$PF = \sqrt{T_{on} / T} = \sqrt{d} \qquad 5.3$$

It is clear from equation 5.3 that a power factor of one will result when Ton = T, which would result in sinusoidal operation.

A closed loop control system can be used to vary the value of Ton to maintain some variable close to a selected set point. Such a system would depend on sufficient energy storage in the controlled system to smooth variations that result from the on-off nature of the control. Integral cycle control has the advantage of fewer switching operations and low radio frequency interference (RFI) due to control during the zero crossing of the AC voltage, that is, in this method, switching occur only at zero voltage for resistive loads. The rate of change of the load current depends on the system frequency, which is small, so there is low electrical noise compared with the other control method

Example 5.1

A single phase 120V AC source controls power to a 5Ω resistive load using integral cycle control. Find

a) the average value of output current

b) the maximum switch current

c) the maximum power produced

d) the duty cycle and the value of T_{on} to produce 1kW power

e) the power factor for part (d)

Solution

a) The average value of the output current over any number of complete conduction cycles is 0

b) $$I_{o(RMS)} = 120/5 = 24\ \mathrm{A}$$

$$I_m = \sqrt{2}(24) = 33.9\ \mathrm{A}$$

c) Maximum power will be produced when the switch is always on $P_{o(\max)} = 120 * 24 = 2880\ \mathrm{W}$

d) For $P_{o(avg)} = 100\ \mathrm{W}$

$$d = \frac{T_{on}}{T} = \frac{P_{o(avg)}}{P_{o(\max)}} = \frac{1000}{2880} = 0.35$$

If we choose T = 15 cycles, then

$T_{on} = 0.35*15 = 5$ cycles

e) $$PF = \sqrt{\frac{T_{on}}{T}} = \sqrt{\frac{5}{15}} = 0.58$$

5.3 AC PHASE CONTROL

5.3.1 In Circuits with a Resistive Load

The basic circuit in Figure 5.1 can be used to control the power to a resistive load. As is done with a controlled rectifier, output voltage is varied by delaying conduction during each half cycle by and angle α. The delay angle α is measured from the source voltage zero.

SCR_1 which is forward biased during the positive half cycle, is turned on at an angle α. It conducts from α to π. Supplying power to the load. SCR_2 is turned on half cycle later at π+α. It conducts up to 2π, supplying power to the load. The waveform in Figure 5.3 are identical to those of the full wave rectifier with a resistive load. The difference here is that each second half cycle has a negative current rather than a positive one. There is however no effect on the power, because power is a squared function. The equation for the RMS value of the output voltage is

$$V_{o(RMS)} = V_i \left\{ 1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi} \right\}^{1/2} \qquad 5.4$$

The equation for the RMS value of the output current with a resistive load is similar to equation 5.4

$$I_{o(RMS)} = \frac{V_i}{R} \left\{ 1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi} \right\}^{1/2} \qquad 5.5$$

By varying the delay angle α, the output current of the load can be continuously adjusted between the maximum value of V_i/R at $\alpha = 0$ and zero at $\alpha = 180^0$. The RMS current rating of the triac is given by

$$\mathbf{I_{T(RMS)} = I_{o(RMS)}} \qquad 5.6$$

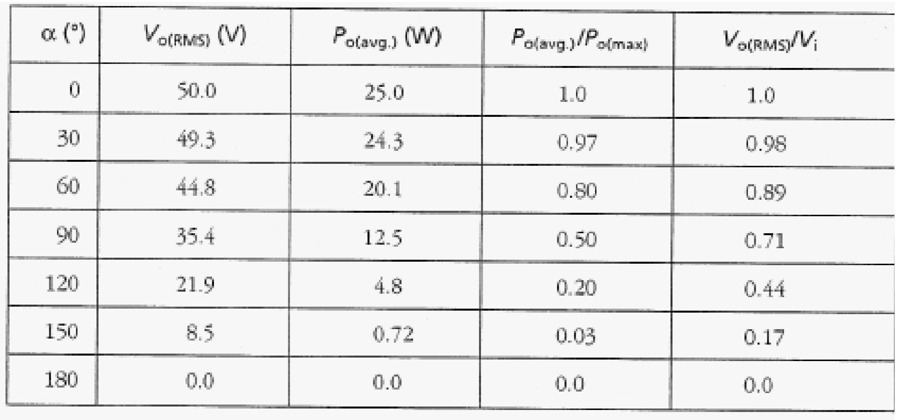
The RMS current rating of the SCRs is given by

$$\mathbf{I_{scr(RMS)} = I_{o(RMS)}/\sqrt{2}} \qquad 5.7$$

Output power is given by

$$\mathbf{P_{o(avg)} = I^2_{o(RMS)} \qquad or \qquad V^2_{o(RMS)}/R} \qquad 5.8$$

Table 5.1:



α (°)	$V_{o(RMS)}$ (V)	$P_{o(avg.)}$ (W)	$P_{o(avg.)}/P_{o(max)}$	$V_{o(RMS)}/V_i$
0	50.0	25.0	1.0	1.0
30	49.3	24.3	0.97	0.98
60	44.8	20.1	0.80	0.89
90	35.4	12.5	0.50	0.71
120	21.9	4.8	0.20	0.44
150	8.5	0.72	0.03	0.17
180	0.0	0.0	0.0	0.0

Examination of equation 5.5 and 5.8 shows that the load power can be varied by changing α over the full range from zero to 180^0. Suitable trigger circuits exist to allow conduction to be adjusted essentially over the entire range.

The control characteristics of a single phase AC power controller can be calculated as a function of the delay angle. If we assume Vi = 50V and load resistance R =100Ω, then at α = 00, using Equation 4 output voltage Vo(RMS) = Vi = 50V and

$$P_{0(\max)} = V_i^2 / R = 50^2 / 100 = 25\ \mathrm{W}$$

While , $P_{o(\max)} = V^2_{o(RMS)}/R$

Evaluating output power and power for succesive values of the delaya angle gives the results shown in Table 5.1. The control characteristics $V_{o(RMS)}/V_i$ and $P_{o(avg)}/P_{o(max)}$ versus α for a resistive load id plotted in Figure 5.4.

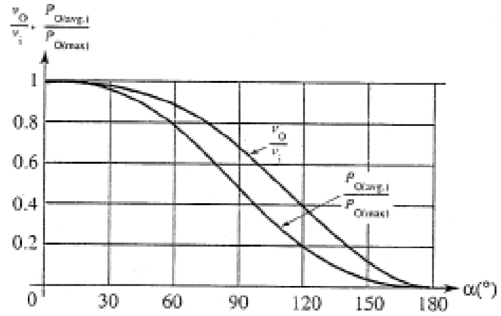


Figure 5.4 : Variation of Output Voltage and Power with Delay Angle for a Resistive Load

Because the current is nonsinusoidal, the power factor presented to the AC source is less than unity, although the load is resistive. Whatever the waveform, by definition the power factor is given by

$$\begin{aligned}\mathbf{PF} &= \frac{\textbf{active power}}{\textbf{apparent power}}\\ &= \frac{P}{V_i I_i}\\ &= \frac{\{V^2_{0(RMS)}/R\}}{V_i\{V_{o(RMS)}/R\}}\\ &= \frac{V_{o(RMS)}}{V_i}\end{aligned}$$

Substituting Equation 4 we obtain

$$PF = V_i\left\{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right\}^{1/2} \qquad 5.9$$

The resulting power factor is unity only when α is zero, it becomes progressively smaller as α increase, becoming approximately zero when α = π. The switch current become zero just when the voltage is zero because the load is resistive. Therefore when the switch begins blocking at the time of the current zero, negligible source voltage is present. The problem of dv/dt being large at turoff does not exist and no snubber is required to reduce the rate of voltage build up across the device terminals.

For the values of $\alpha > 90^0$, the switch block the peak voltage before it turns on. The minimum switch voltage capability therefore is the peak value of the source voltage. This blocking capability is of course necessary in both directions for the either SCR or the triac implementation of the switch.

$$PIV \geq V_{i(m)} \tag{5.10}$$

Example 5.2

A single phase 120 V AC source controls power to a 5Ω resistive load using integral cycle control. If Ton = 2 cycles and T = 4 cycles, find

a) the output power

b) the delay angle required if the phase control method is used to produce the same

power

c) the output power, if the load always connected to the source

Solution

a) From equation 5.1

$$P_{o(avg)} = \frac{V_i^2 T_{on}}{RT} = \frac{120^2 * 2}{5 * 4} = 1440 \text{ W}$$

b) $P_{o(avg)} = I^2_{o(RMS)} R$

From equation 5.5

$$I_{o(RMS)} = \frac{V_i}{R}\left\{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right\}^{1/2}$$

Therefore

$$P_{o(avg)} = \frac{V_i^2}{R}\left\{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right\} = 1440 \text{ W}$$

The required value is $\alpha = 90^0$

c) $P_{o(avg)} = \frac{V_i^2}{R} = \frac{120^2}{5} = 2880 \text{ W}$

Example 5.3

A single phase power controller as shown in Figure 5.1(a) is supplying a resistive load. Plot the waveform of the output voltage if the delay angle is

a) 30^0

b) 120^0

Solution

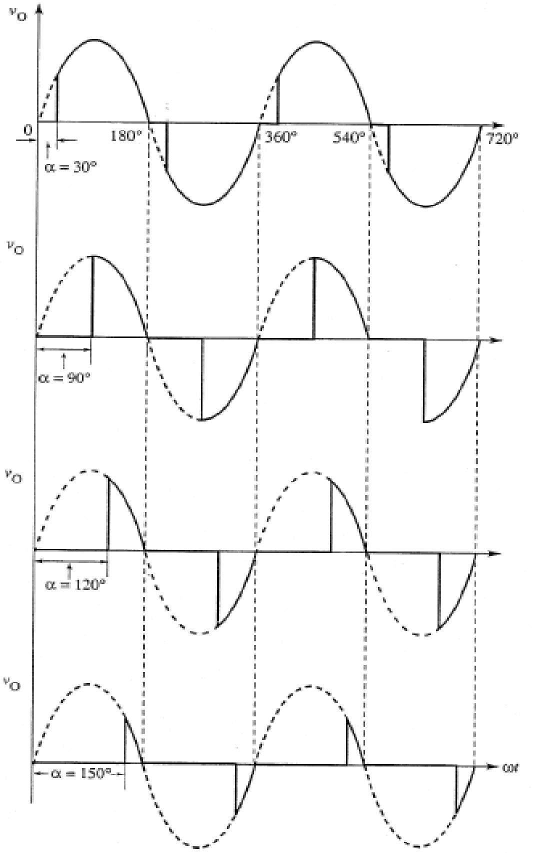


Figure 5.5 : AC Phase Control Waveforms for a Resistive Load, for Delay Angles Varying from 30^0 to 150^0

Example 5.4

A single phase power controller as shown in Figure 5.1(a) is supplying a 100Ω resistive load through a 50V source. Plot the waveforms for output voltage, output current, voltages across SCR_1 and SCR_2 and current through SCR_1 and SCR_2 if the delay angle is 60^0

Solution

The waveforms are shown in Figure 5.6

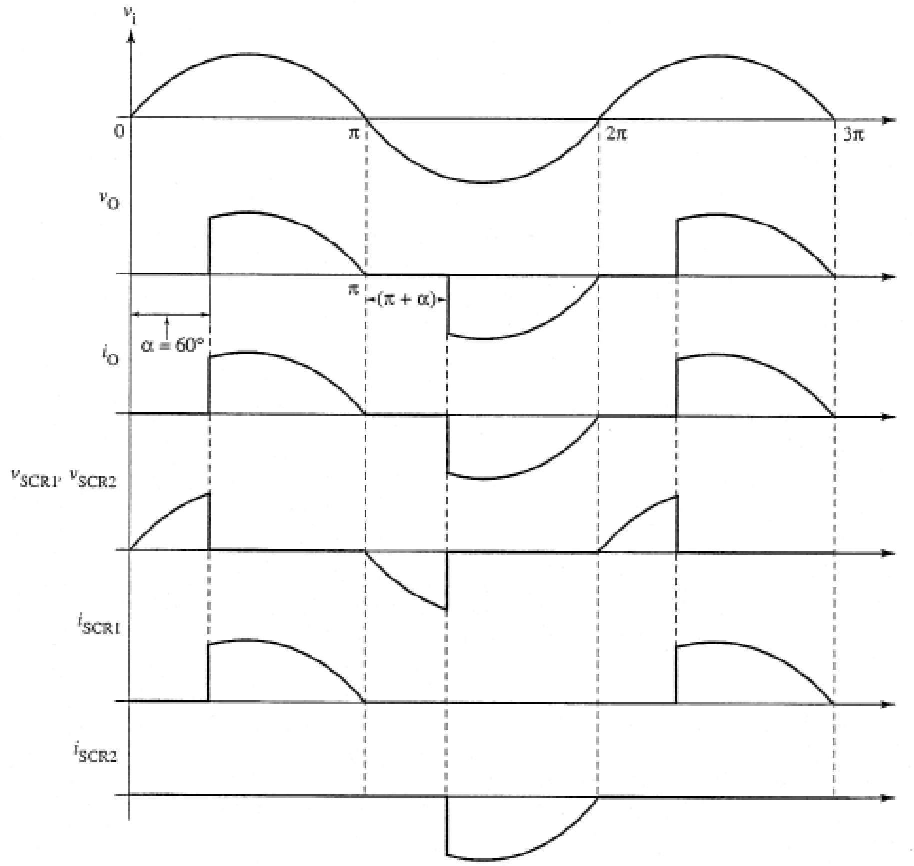


Figure 5.6 : Waveforms for resistive load and a delay angle of 60^0

Example 5

A 120V source control power to a 5 Ω resistive load using a phase control switch. If the load power required is 1 kW, find

a) the maximum load current

b) the RMS value of load current

c) the delay angle α

d) the RMS value of switch current if the switch is triac

e) the average current in each of the two SCRs if the switch is like that in Figure5.1(a)

f) the peak reverse voltage rating of the switch

g) the power factor

Solution

$$V_m = \sqrt{2}(120) = 170\ \text{V}$$

a) $$\text{I}_\text{m} = \frac{V_m}{R} = \frac{170}{5} = 34\ \text{A}$$

$$P_{o(avg)} = 1000\ \text{W}$$

b) for $\mathbf{1000 = I^2_{o(RMS)} * 5}$

$$I_{o(RMS)} = 14.14\ \text{A}$$

c) using equation 5.5 to solve for α so α = 105^0

d) $I_{T(RMS)}$ is the same as the load current , 14.14 A

e) The SCR current is a half wave controlled waveform. The average value of each SCR current can be found by using

$$I_{SCR(avg)} = \frac{I_m}{2\pi}(1+\cos\alpha) = \frac{34}{2\pi}(1+\cos 105^0) = 4\ \text{A}$$

f) The switch block at least the maximum source voltage 170V

g) $$PF = \left\{1 - \frac{105}{\pi} + \frac{\sin 2 * 105}{2\pi}\right\}^{1/2} = 0.58$$

5.3.2 Circuits with an Inductive (RL) Load

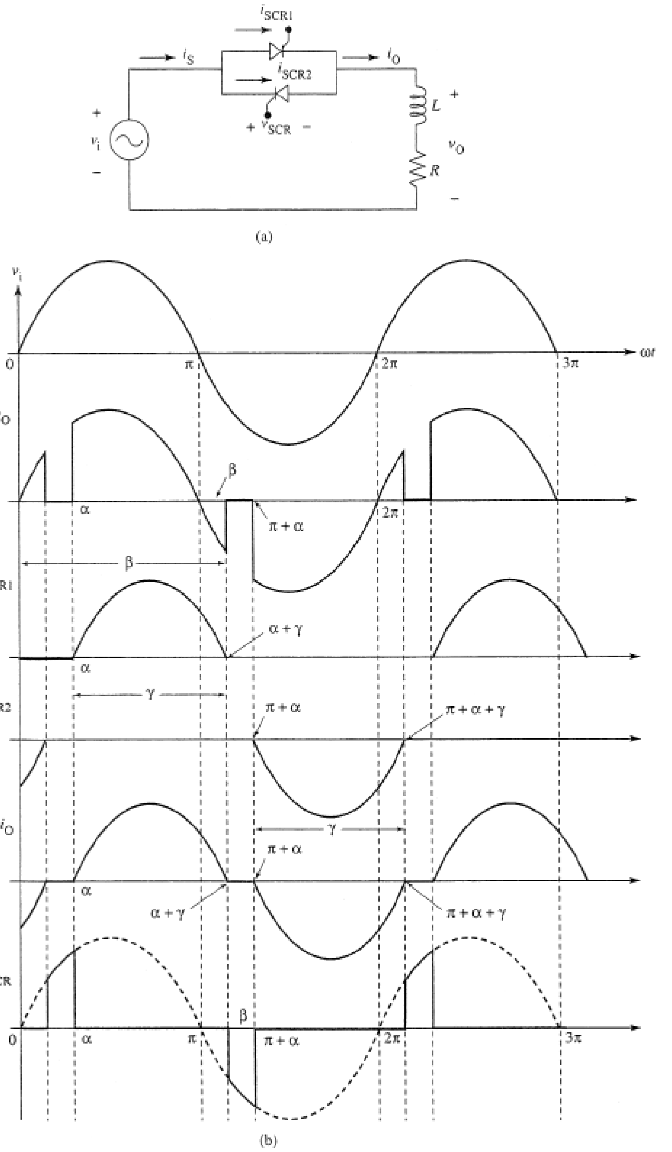


Figure 5.7: (a) AC Phase Control Circuit with an RL Load (b) Voltage and Current Waveform with an RL Load

Consider the AC voltage controller circuit in which the laod now consists of resistor R in series with an inductor L. The circuit is shown in Figure 5.7.(a) and the corresponding waveforms in Figure 5.7(b). SCR_1 is triggered at α and SCR_2 is triggered at $\pi + \alpha$. When SCR_1 turns on the source voltage is connected to the load making the output voltage V_o = Vi. The output current i_o builds up at α. However, it does not become zero at π but continue to flow until β, which is known as extinction angle. The interval during which SCR_1 conducts is called the conduction angle γ ($\gamma = \beta - \alpha$). When SCR_2 turns on, a reverse current flows in the load.

Note in the graph that the onset of output current coincides with the firing angle, that is the load phase angle Φ ($\Phi = \tan^{-1} X_L/R$) the angle by which the output current lags by the voltage is equal to α. Under this condition, full output voltage is obtained. Furthermore, due to the load inductance, current decays to zero, the voltage across the switch has an ideal discontinuity. The output voltage is equal to the source voltage when either SCR conducts. The output voltage waveform has the shape of a sinusoid with a vertical portion removed. The missing portion of the output voltage waveform forms the voltage drop across the SCR switch.

The RMS value of the output current is given by

$$I_{0(RMS)} = \frac{V_i}{R}\left\{4\left(1-\frac{\alpha}{\pi}\right)\left(\cos^2\alpha+\frac{1}{2}\right)+\frac{6}{\pi}\sin\alpha\cos\alpha\right\}^{1/2} \qquad 5.11$$

Where α is in the range from π/2 to π.

Example 6

A single phase power controller as shown in Figure 5.7(a) is supplying an inductive load. Plot the waveforms of the output voltage and current if the delay angle is

a) 30^0, b) 90^0, c) 120^0, d) 150^0

Solution

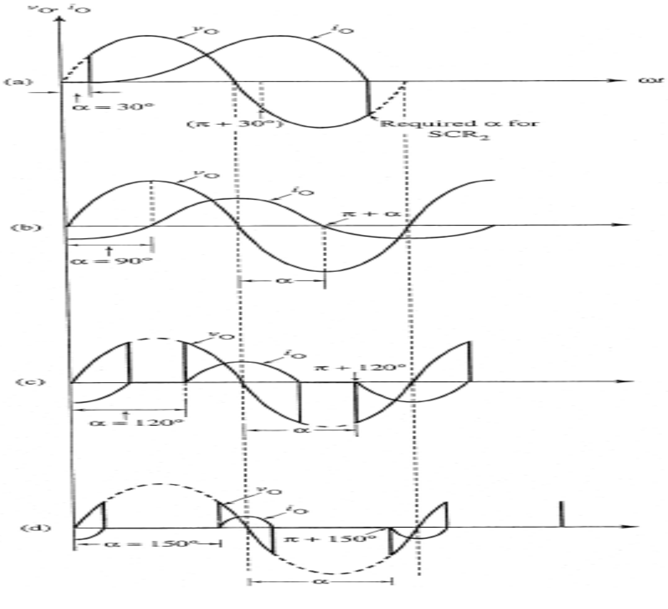


Figure 5.8: Voltage and current waveforms for inductive load with delay angles of (a) 30^0, (b) 90^0, (c) 120^0, (d) 150^0

For an inductive load, the output current lags the voltage. If the load is purely inductive, the phase angle is 90^0. Therefore if the delay angle is less than 90^0, the current will not be symmetrical. With a delay angle of 30^0 the waveform shown in Figure 5.8(a) results, where the conduction in SCR_1 is last for more than 180^0 and SCR_2 is not conducted at all because it does not experience forward voltage when it receives its firing pulse at $\pi + 30^0$. The output current is unidirectional. To avoid this condition the firing angle should be at least 90^0 (figure 5.8(b)). When π is between 90^0 and 180^0 the waveforms are of the from in Figure 5.8(c) and 5.8(d). Thus for inductive loads α is limited to the range 90^0 to 180^0

Example 7

A single phase voltage controller with an RL load is connected to a 110V source. If R = 10Ω, L = 20mH and $\alpha = 80^0$, find

a) the RMS output current

b) the SCR RMS current

c) the power delivered to the load

d) the power factor

Solution

a) $$I_{0(RMS)} = \frac{110}{10}\left\{4\left(1-\frac{80}{180}\right)\left(\cos^2 80+\frac{1}{2}\right)+\frac{6}{180}\sin 80\cos 80\right\}^{1/2} = 5.5\text{ A}$$

b) $$I_{SCR(RMS)} = I_{o(RMS)}/\sqrt{2} = 3.9\text{ A}$$

c) $$P_{o(avg)} = I^2_{o(RMS)}R = 5.5^2(10) = 302.5\text{ W}$$

d) $$PF = \frac{P}{S} = \frac{P_{0(avg)}}{V_i I_{o(RMS)}} = 0.5$$

5.4 Three Phase AC Phase Control

5.4.1 In Circuits with a Resistive Load

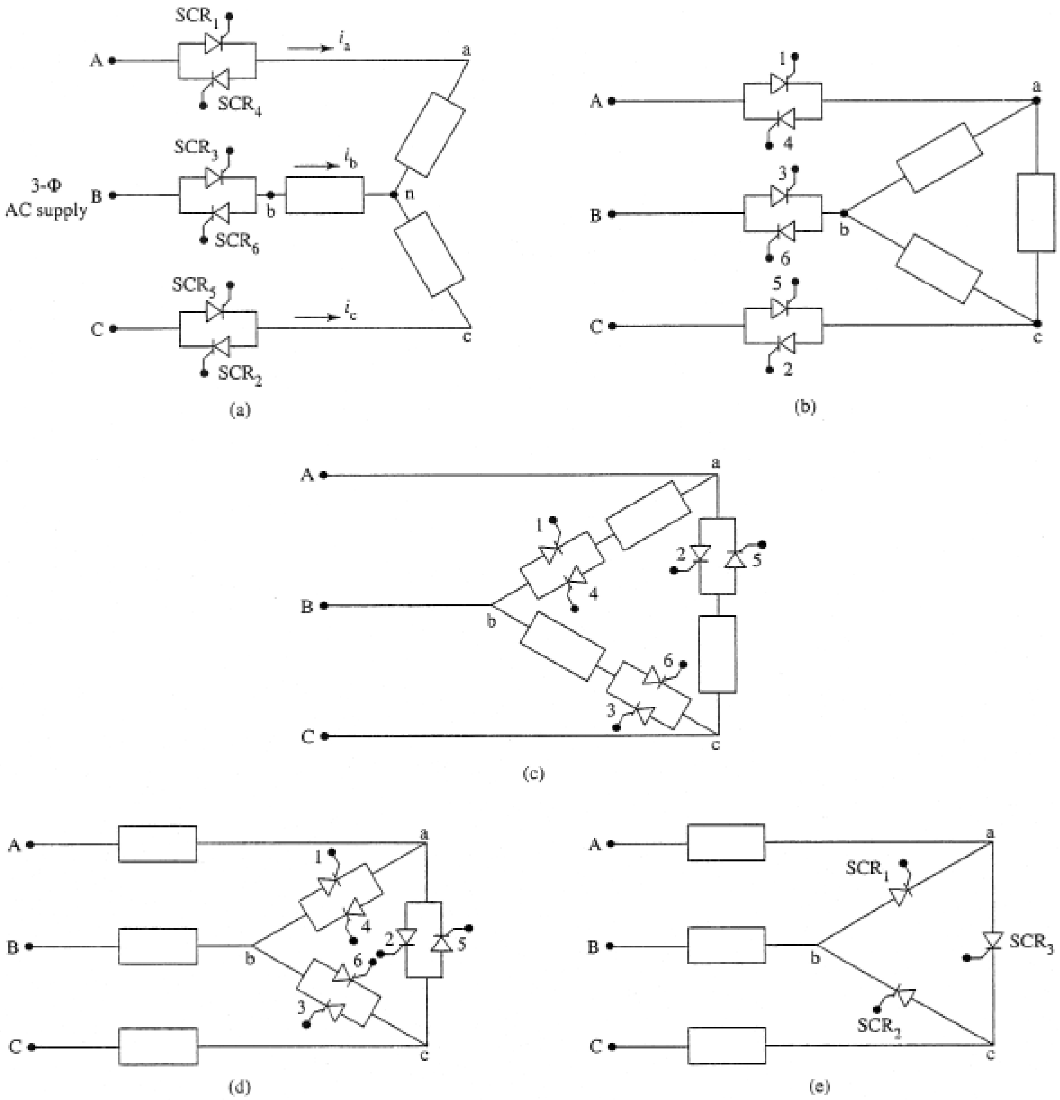


Figure 5.9: AC Phase Control, Three Phase Switch (a) Line Controlled Y-Connected , (b) Line Controlled Δ Connection, (c) Branch Δ Connection, (d) Neutral Point Switching using Six SCRs (e) Neutral Point Switching using Three SCRs

The phase-control methods applied to single phase loads can also be applied to three phase systems. A three phase AC power controller consists of three single phase bidirectional connections using the phase control principle. The circuits shown in Figure 5.9 can be used to vary the power supplied to a three phase Y or

Δ- connected resistive load. As shown, the switch in each line is implemented by using two SCRs in an inverse parallel arrangement.

The primary considerations in the selection of circuits shown in Figure 5.9 are:

i) For a given power, circuits Figure 5.9(a) and (b) give lower voltages ($\sqrt{3}/2$ times the supply phase voltage or half the line voltage) and higher currents in the SCR. Two SCR pairs are always required in series to block voltage or conduct current.

ii) Circuit 5.9(c) gives higher voltages and lower currents in the SCRs. Each SCR can conduct current independently of the other.

iii) Circuit 5.9(d) is functionally similar to Figure 5.9(a). It produces identical output voltage waveforms, but since each SCR is part of only one current path instead of two, the average SCR current is halved. In addition, as in circuit 5.9 (c) each SCR can conduct current independently of other.

iv) For circuit 5.9(e), control of 3Φ output voltage is also possible by using 3 SCRs instead of six. The waveform corresponds to the six SCR current of Fig. 5.9(d), however the SCR current ratings must be doubled.

To illustrate the method of analysis of the three phase AC voltage controllers. We will use circuit shown in Figure 5.9(a) as an example. The SCRs turn on is delayed by the angle α beyond the normal beginning of conduction. For symmetrical operation of the circuit, the gate trigger pulse of the thyristors in the three branches must have the same sequence and phase displacement as the supply voltage. If SCR_1 is trigger at α, SCR_3 must be turned on at $\alpha = 120^0$ and SCR_5 at $\alpha = 240^0$. The inverse parallel SCRs are triggered 180^0 from their partners. Therefore SCR_4 (which is across SCR_1) is triggered at $\alpha = 180^0$, SCR_6 at $\alpha + 300^0$, and finally SCR_2 at $\alpha + 420^0$ (or $\alpha + 60^0$). The SCR conduction order is therefore SCR_1, SCR_2,SCR_3, SCR_4, SCR_5, SCR_6, SCR_1,….., with a phase displacement of 60^0

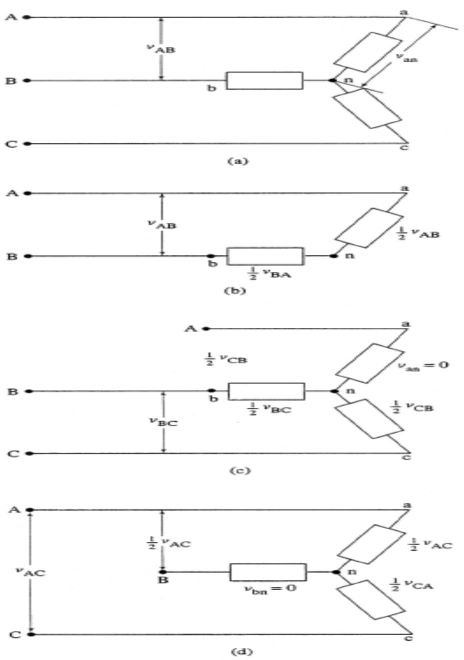


Figure 5.10: Circuit Configurations to obtain The Output Voltage in Figure 5.9a with a Balanced Load

The output voltage waveform can be obtained by first considering the various output voltage constituents resulting from different SCR conduction patterns. There are four such configurations, which are shown in Figure 5.10. Table 5.2 shows the output voltages for each.

Table 5.2

Circuit configuration	Conducting lines	Nonconducting lines	Output voltage	
			Phase (v_{an})	*Line* (v_{ab})
a	All	None	$v_{an} = v_{AB}/\sqrt{3}$	v_{AB}
b	A, B	C	$(1/2)v_{AB}$	v_{AB}
c	B, C	A	0	$(1/2)v_{CB}$
d	C, A	B	$(1/2)v_{AC}$	$(1/2)v_{AC}$
	None	All	0	v_{AB}

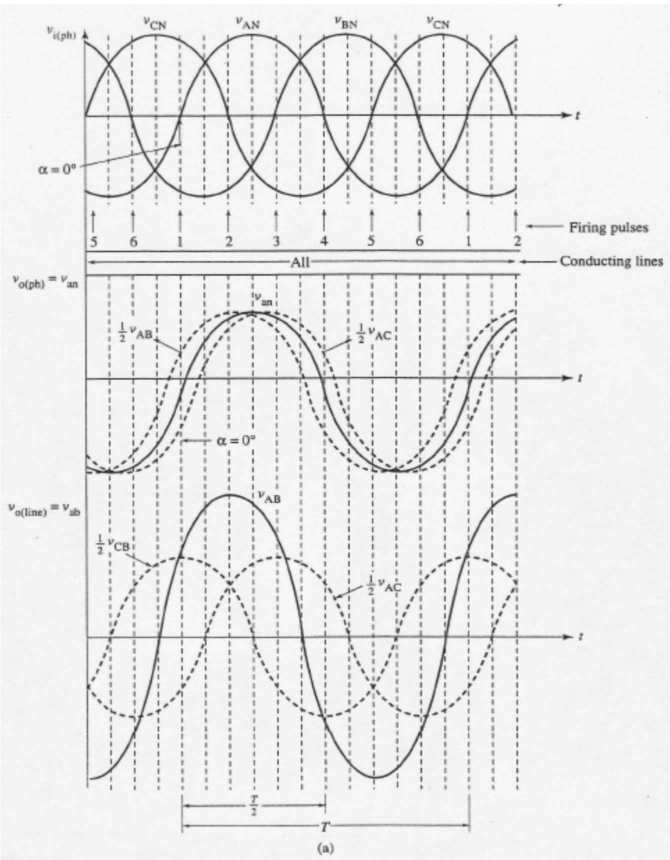


Figure 5.11 : Output Voltage Waveforms for The Circuit in Figure 5.9a with Delay Angle of (a) 0^0

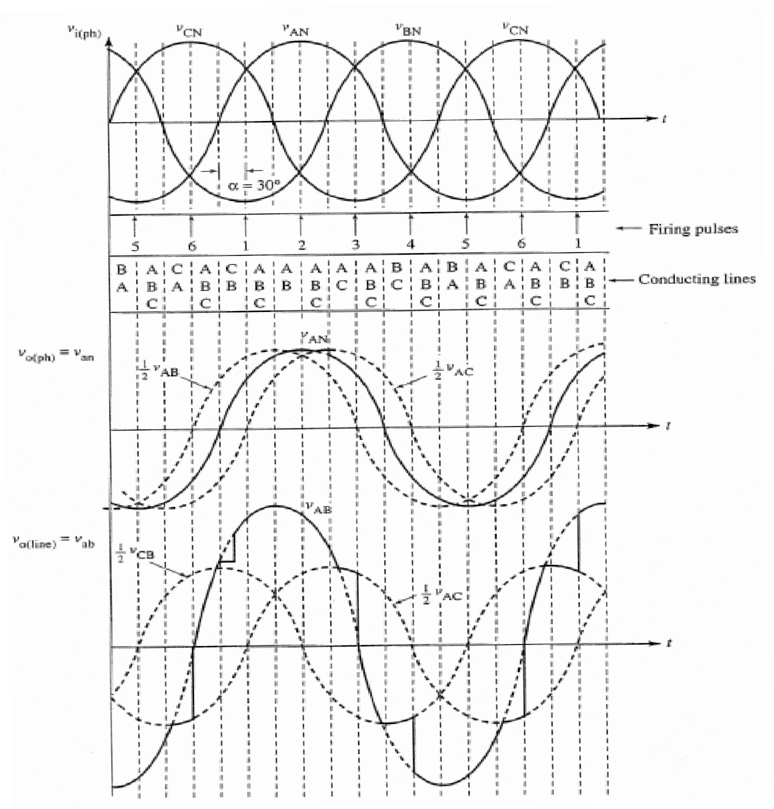


Figure 5.11.(b) 30^0

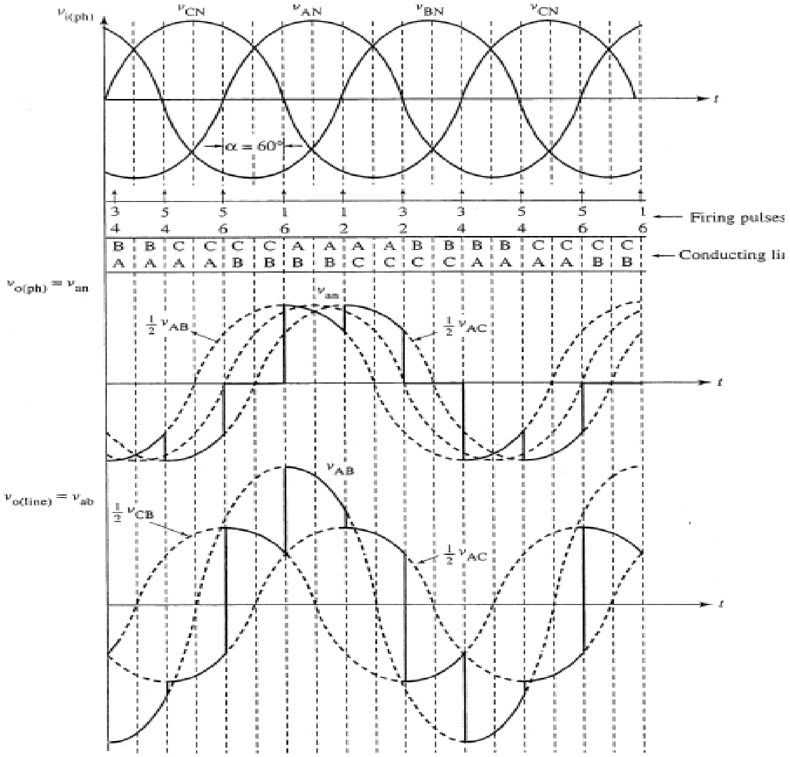


Figure 5.11.(c) 60^0

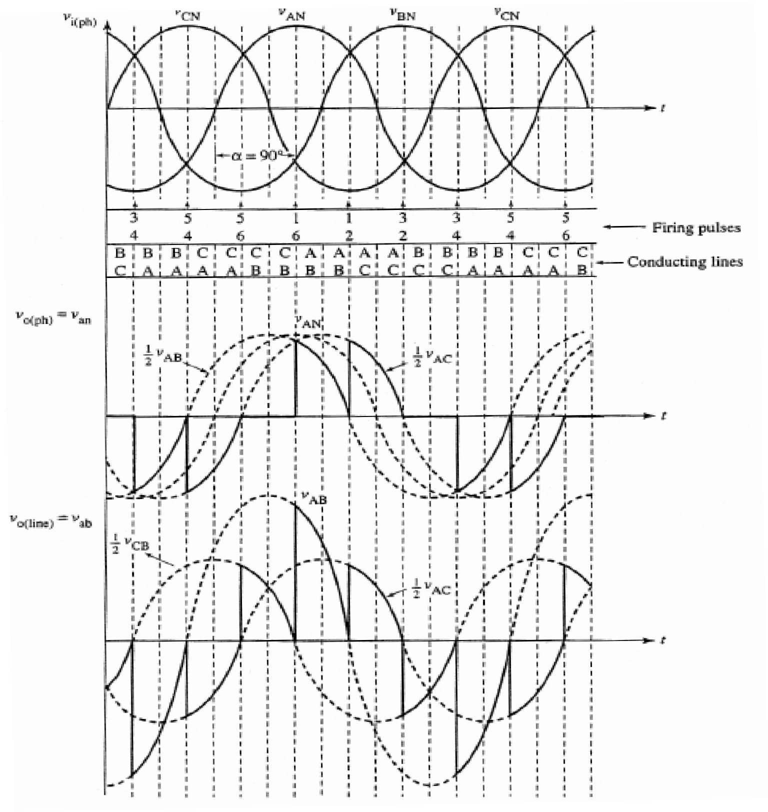


Figure: 5.11.(d) 90^0

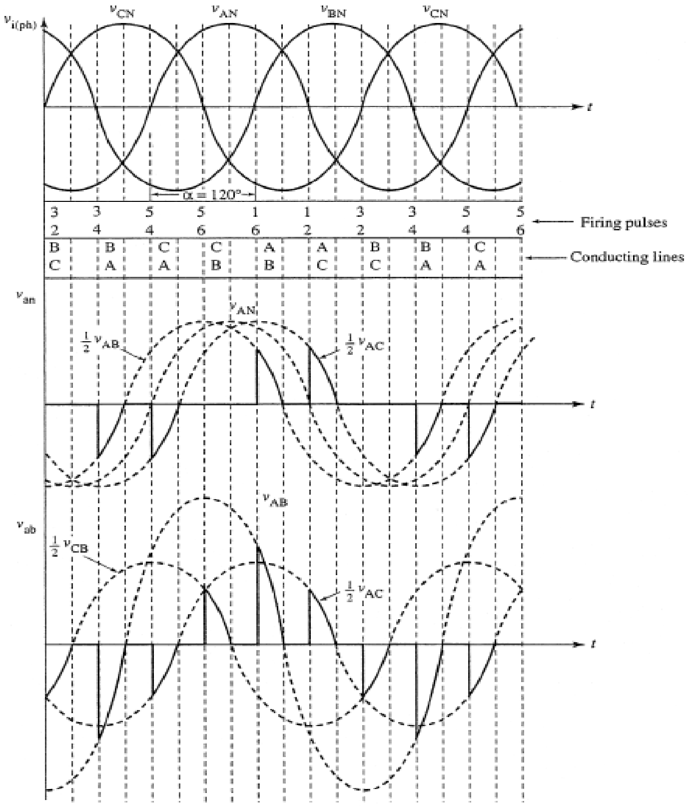


Figure5.11:(e) 120^0

Figure 5.11 shows the phase and line voltage waveforms for the circuit in Figure 5.9(a) for different delay angles. Figure 5.11(a) shows the maximum output condition which occurs when $\alpha = 0^0$. Note that the delay angle α for each SCR is measured from the reference point where current start to flow through a purely resistive load. When the delay angle is small, as in Figure 5.11(b), where $\alpha = 30^0$ conduction in each phase stops 180^0 after the reference point. All three lines start conducting again as each SCR is turned on. When α become 60^0 (Figure 5.11(c)), the turning on of one SCR causes another SCR that was previously conducting to turn off, so that only two lines are always conducting. For $\alpha > 90^0$, the conduction period is reduced to the point where it becomes necessary to fire pairs of SCRs simultaneously to establish conducting paths. This means that each SCR must received two firing pulses separated by 60^0 in each cycle as shown in Figure 5.11(d) and (e). If α reaches 150^0, the current in each line falls to zero, giving zero output. Thus the operating range for the delay angle is form 0^0 to 150^0.

The preceding analysis can be summarized into the following three possible modes of operation for the circuit in figure 11a.

Mode I $\left(0 \le \alpha \le 60^0\right)$

One device in each line conducts in other words, three devices conduct simultaneously and normal three phase theory applies. Full output occurs when α = 0. When $\alpha = 60^0$ and all three devices are in conduction, the load currents are the same as for an uncontrolled three phase resistive load. The RMS value of the output current is given by

$$I_{o(RMS)} = \frac{V_i}{R}\left\{\frac{1}{3} - \frac{\alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right\}^{1/2}$$

5.12

Mode II $\left(60^0 \le \alpha \le 90^0\right)$

One device conducts in each of two AC lines, that is the total of only two SCRs are conducting and two lines act as a single phase supply to the load. During the intervals when one of the line currents is zero, the remaining two phases are effectively in series and form a single phase load connected to two of three lines of the voltage source. The phase voltage is equal to half the line voltage. The conduction pattern during any 60^0 is repeated during the following 60^0 interval with the permutation in phases and the sign of the current. For example the current variation for phase A during a given 60^0 interval is repeated during the next 60^0 for phase C, except for a change in the algerabic sign of the current. The RMS value of the output current is given by

$$I_{o(RMS)} = \frac{V_i}{R}\left\{\frac{1}{6} - \frac{3\sin 2\alpha}{8\pi} + \frac{\sqrt{3}\cos 2\alpha}{8\pi}\right\}^{1/2}$$

5.13

Mode III $\left(90^0 \le \alpha \le 150^0\right)$

No more than two SCRs conduct at any one time. At times none of the devices conduct. For $\alpha \ge 90^0$, when all three devices are off, a zero output periods develops. The output voltage become zero for $\alpha = 150^0$. The equation for the RMS value of the output current is

$$I_{o(RMS)} = \frac{V_i}{R}\left\{\frac{5}{12} - \frac{\alpha}{2\pi} - \frac{\sqrt{3}\cos 2\alpha}{8\pi} + \frac{\sin 2\alpha}{8\pi}\right\}^{1/2}$$

5.14

Note that for all three modes (Equations 5.12-5.14)

$$V_{o(RMS)} = \sqrt{3} I_{o(RMS)} R$$

5.15

The waveform in Figure 5.11 suggest that the maximum switch current may be less than in the case without phase control. For $\alpha < 30^0$, maximum current is not affected, wheareas for $\alpha > 30^0$, maximum current is reduced. If we operate the controller with a zero value of α, the current rating of the switching device should be selected based on full conduction conditions.

The circuit shown in Figure 5.12 can be used to find the voltage rating of the switching devices. During the interval when phase A is not conducting, the voltage across the switch can be determined by writing KVL in the upper loop

$$V_{AB} - V_{SW} + V_{bn} = 0$$

$$V_{SW} = V_{AB} + V_{bn}$$

NOW

$$V_{bn} = \frac{V_{BC}}{2}$$

Therefore

$$V_{SW} = V_{AB} + (V_{bc} / 2) = 1.5V_{phase}$$

5.16

A suitable rating for the switching device would therefore be at least equal to $V_{L(max)}$

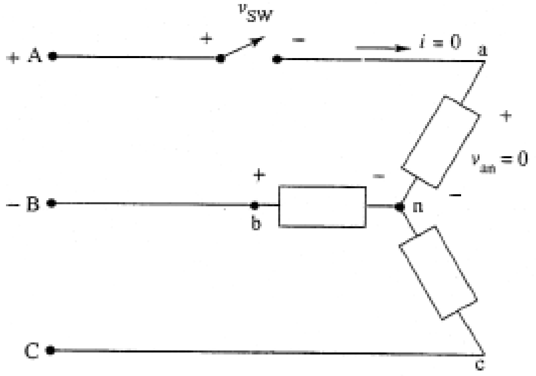


Figure 5.12: Voltage Rating of The Switching Device

Example 8

The three phase power controller shown in Figure 5.13 is supplying a balanced Δ connected resistive load. If the delay angle is 45^0, plot the waveforms for the output voltage across any one phase and the voltage across any pair of SCRs

Solution

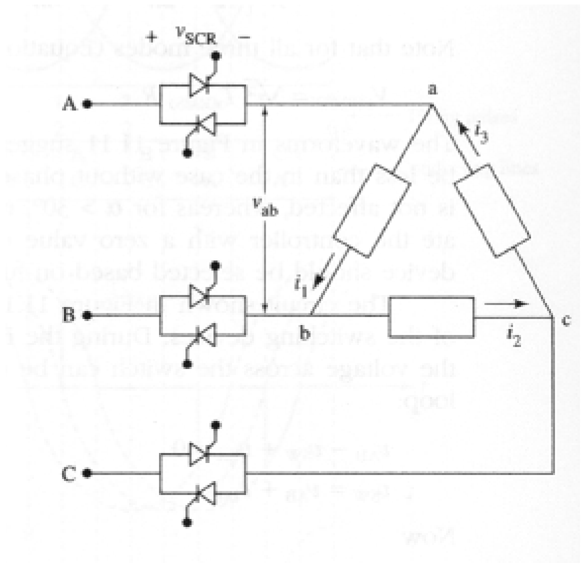


Figure 5.13

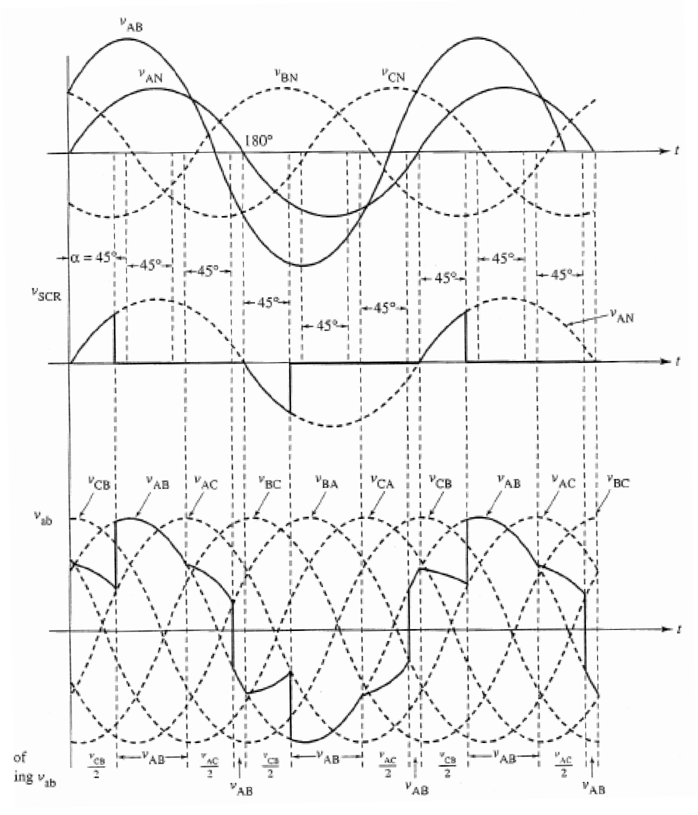


Figure 5.14: Voltage Waveforms for a Δ- Connected Resistive Load

5.4.2 In Circuits with an Inductive (RL) Load

With an RL load, the waveforms in Figure 5.11 are slightly different because the current is no longer continuous at the points where it switches. The voltages and currents cannot be determined easily since each depends not only on the present value but also on the previous conditions.

The waveform of the load currents shown in Figure 5.15 are drawn for an inductive load with a delay angle of 100^0. As shown the current waveform in one phase is identical to the current waveform of another phase, except for a 60^0 phase shift and reversal of sign.The voltage rating of the switches should be at least equal to the maximum line voltage of the source. Since the load is inductive, each switch is subjected to a rapid change in voltage as its current becomes zero. A snubber circuit across the switch is usually used to prevent unscheduled firing. The current rating of the switching devices is determined by the current at $\alpha = 0^0$

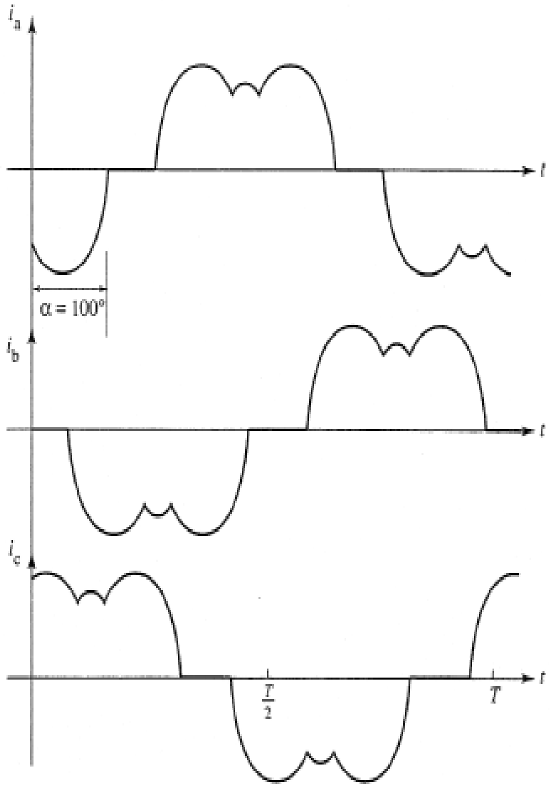


Figure 5.15: Waveforms for an Inductive Load with a Delay Angle of 100^0

Example 9

The three phase power controller shown in Figure 5.9(c) supplies a balanced inductive load. Plot the waveform of the output voltage, the voltage across the SCR and the phase and line currents for the following delay angles

a) 90^0

b) 120^0

c) 150^0

d) 165^0

Solutions

Refer to Figure 5.16 (a),(b),(c),(d)

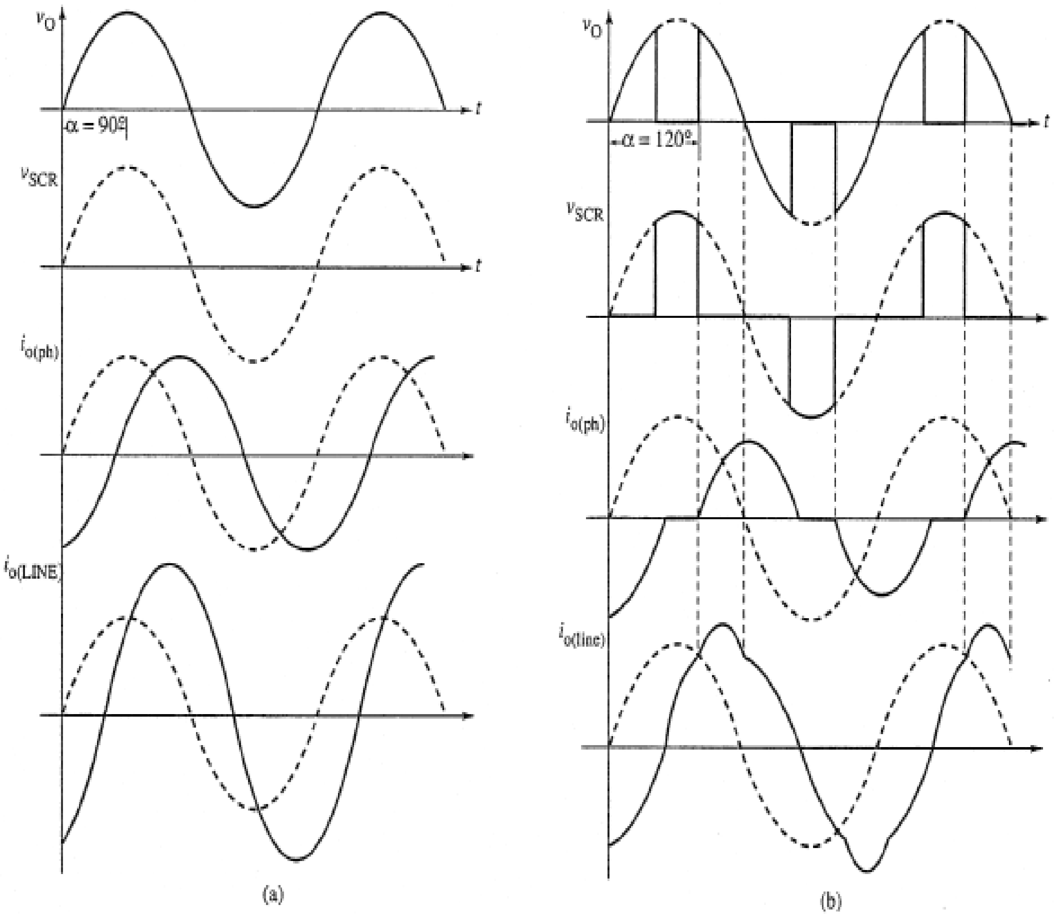


Figure 5.16: Waveforms for a Balanced RL load (a) $\alpha = 90^0$, (b) $\alpha = 120^0$

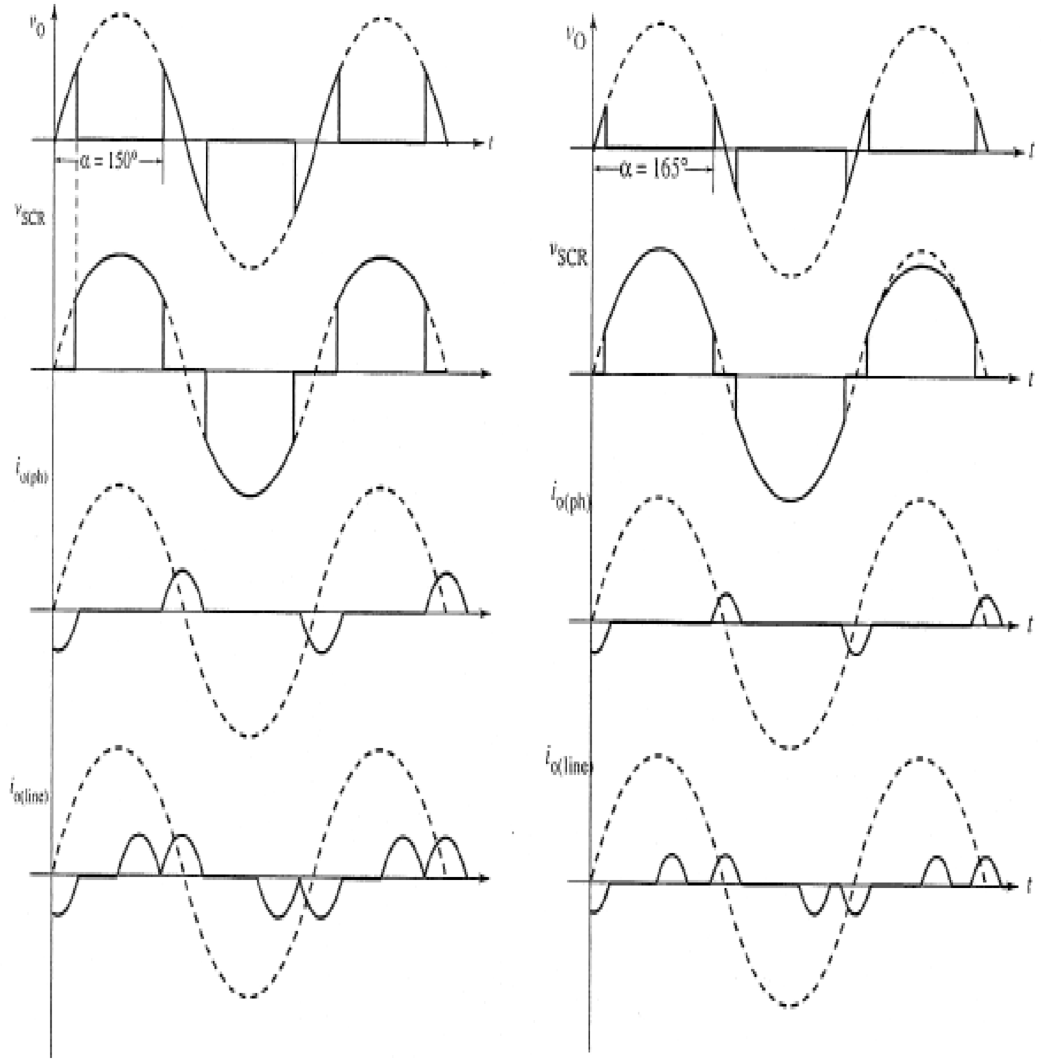


Figure 5.16 : Waveforms for a Balanced RL Load : left $\alpha = 150^0$, right $\alpha = 165^0$

5.5 Half Controlled AC Voltage Controllers

The half-controlled three phase controller is simpler as it requires only three SCRs. The return path is through the diodes. Figure 5.17 shows the circuit with balanced Y and Δ-connected resistive loads. The phase and line voltage waveforms for three different delay angles are shown in Figure 5.18. There are three different modes of operation.

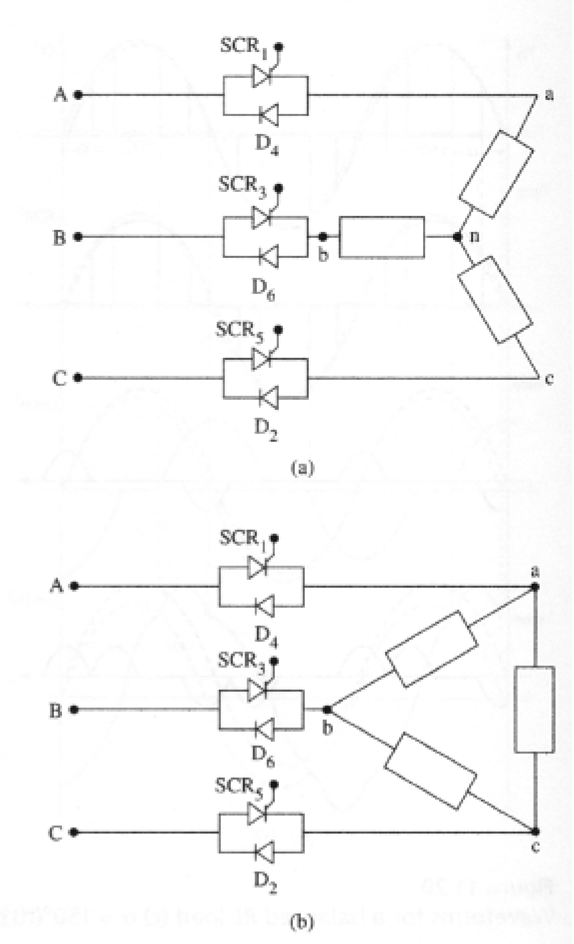


Figure 5.17: Three Phase AC voltage Controller Circuit, (a) Y- connected load, (b) Δ connected load

Mode I $\left(0 \le \alpha \le 60^0\right)$

Before turn-on, one SCR and one diode conduct in the other two phases. After turn-on, two SCRs and one diode conduct and the three phase AC source appears across the output. The equation for the RMS value of the output current is

$$I_{o(RMS)} = \frac{V_i}{R}\left\{\frac{1}{3} - \frac{\alpha}{4\pi} + \frac{\sin 2\alpha}{8\pi}\right\}^{1/2}$$

5.17

Mode II $\left(60^0 \le \alpha \le 120^0\right)$

Only one SCR at a time conducts, and the return current is shared at different intervals by one or two diodes. The equation for the RMS value of the output current is

$$I_{o(RMS)} = \frac{V_i}{R}\left\{\frac{11}{24} - \frac{\alpha}{2\pi}\right\}^{1/2}$$
5.18

Mode III $\left(120^0 \le \alpha \le 210^0\right)$

Only one SCR and one diode conduct and at 210^0 the power delivered to the load is zero. The equation for the RMS value of the output current is

$$I_{o(RMS)} = \frac{V_i}{R}\left\{\frac{7}{24} - \frac{\alpha}{4\pi} - \frac{\sqrt{3}\cos 2\alpha}{16\pi} + \frac{\sin 2\alpha}{16\pi}\right\}^{1/2}$$
5.19

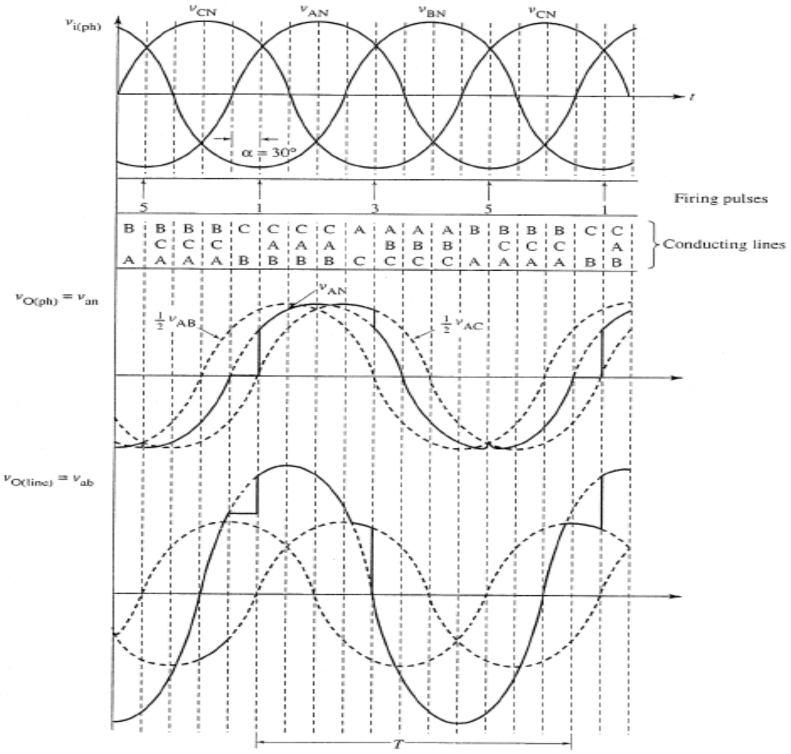


Figure 5.18 (a): Three Phase Half Wave AC Voltage Controller Phase Voltage and Line Voltage for Delay Angles of 30^0

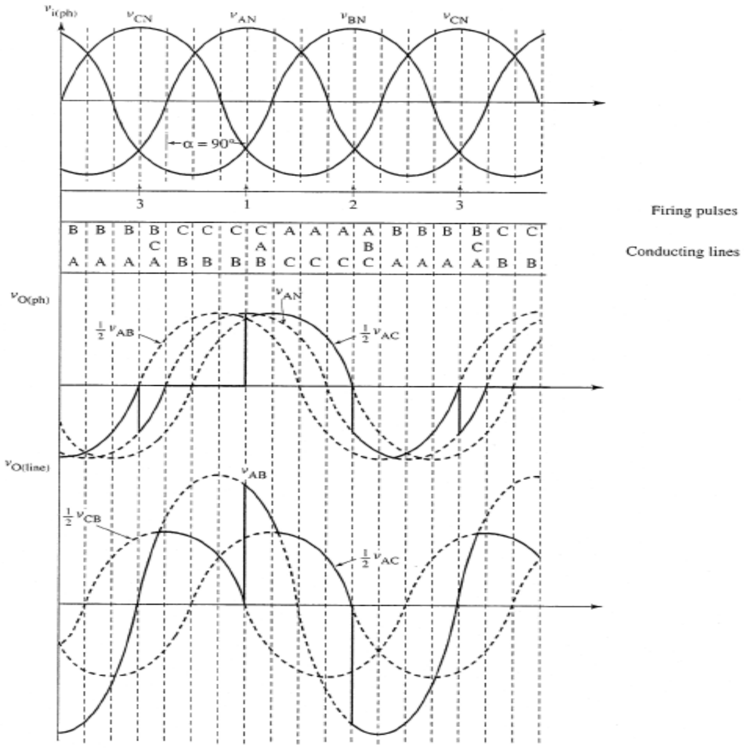


Figure 5.18 (b) : 90^0

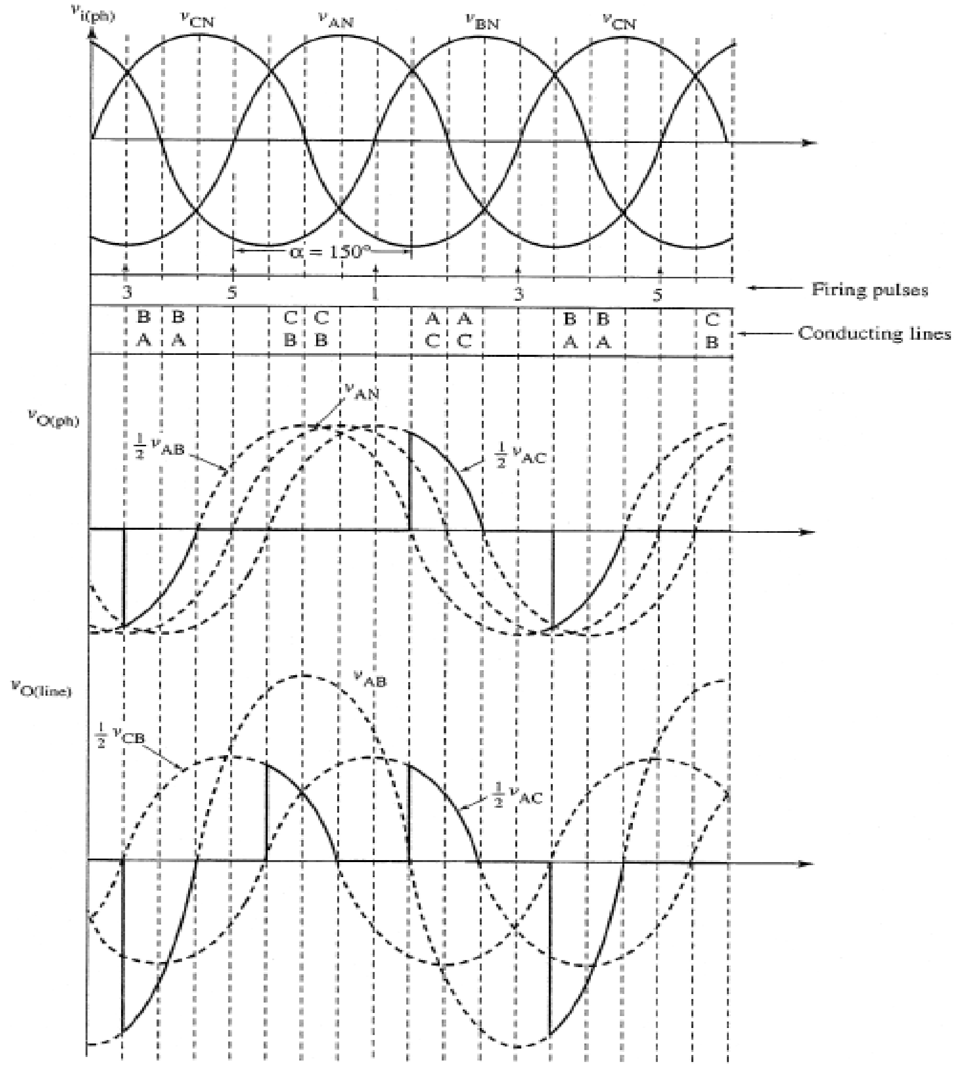


Figure 5.18 (c) : 150^0