2.1 Introduction about Rectifier

- Rectifiers are ac to dc power converters which are used to convert a fixed voltage, fixed frequency ac power supply into variable dc output voltage.
- Type of input: Fixed voltage, fixed frequency ac power
- supply. Type of output: Variable dc outpaut voltage

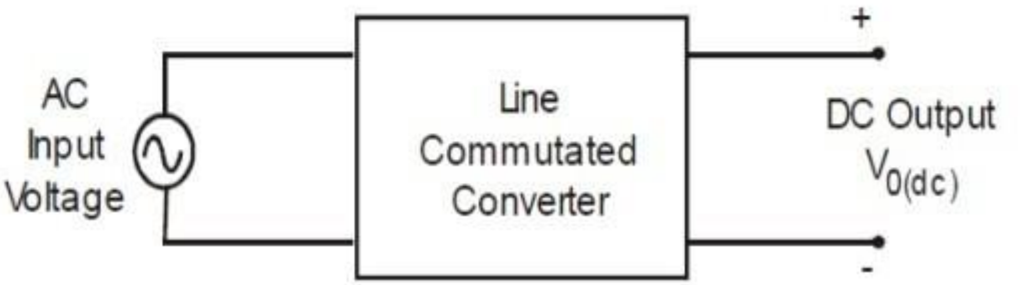


Fig 2.1.1 Block diagram of controlled rectifier

[Source: “Power Electronics” by P.S.Bimbra, Khanna Publishers Page: 176]

- The input supply fed to a controlled rectifier is ac supply at a fixed rms voltage and at a fixed frequency. We can obtain variable dc output voltage by using controlled rectifiers. By employing phase controlled thyristors in the controlled rectifier circuits we can obtain variable dc output voltage and variable dc (average) output current by varying the trigger angle (phase angle) at which the thyristors are triggered. We obtain a uni-directional and pulsating load current waveform, which has aspecific average value.
- The thyristors are forward biased during the positive half cycle of input supply and can be turned ON by applying suitable gate trigger pulses at the thyristor gate leads. The thyristor current and the load

current begin to flow once the thyristors are triggered (turned ON) say at ωt =α. The load current flows when the thyristors conduct from ωt =α to β. The output voltage across the load follows the input supply voltage through the conducting thyristor. At ωt = β, when the load current falls to zero, the thyristors turn off due to AC line (natural) commutation. In some bridge controlled rectifier circuits the conducting thyristor turns off, when the other thyristor is (other group of thyristors are) turned ON. The thyristor remains reverse biased during the negative half cycle of input supply. The type of commutation used in controlled rectifier circuits is referred to AC line commutation or Natural commutation or AC phase commutation.

- When the input ac supply voltage reverses and becomes negative during the negative half cycle, the thyristor becomes reverse biased and hence turns off. There are several types of power converters which use ac line commutation. These are referred to as line commutated converters.

APPLICATIONS OF PHASE CONTROLLED RECTIFIERS

1. DC motor control in steel mills, paper and textile mills.
2. AC fed traction system using dc traction motor.
3. Electro-chemical and electro-metallurgical processes.
4. Magnet power supplies.
5. Portable hand tool drives.

6. Variable speed industrial drives.
7. Battery charges.
8. High voltage DC transmission.
9. Uninterruptible power supply systems (UPS).

The phase controlled converters are simple and less expensive and are widely used in industrial applications for industrial dc drives. These converters are classified as two quadrant converters if the output voltage can be made either positive or negative for a given polarity of output load current. There are also single quadrant ac to dc converters where the output voltage is only positive and cannot be made negative for a given polarity of output current. Of course single quadrant converters can also be designed to provide only negative dc output voltage. The two quadrant converter operation can be achieved by using fully controlled bridge converter circuit and for single quadrant operation we use a half controlled bridge converter.

CLASSIFICATION OF PHASE CONTROLLED RECTIFIERS

The phase controlled rectifiers can be classified based on the type of input power supply as

Single Phase Controlled Rectifiers- which operate from single phase ac input power supply.

Three Phase Controlled Rectifiers -which operate from three phase ac input power supply.

2.2 Two Pulse Converter

FULLY CONTROLLED BRIDGE CONVERTER

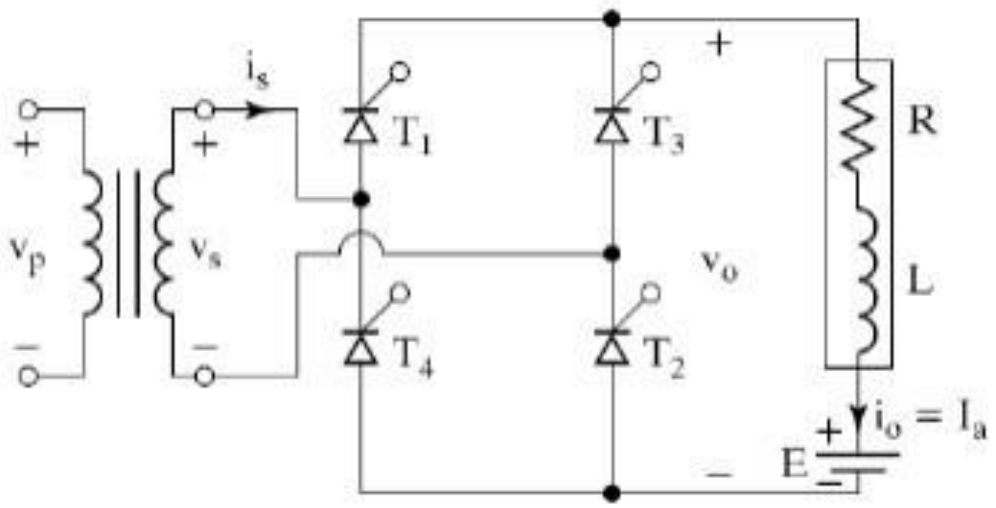


Figure 2.2.1 SINGLE PHASE FULL CONVERTER

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 191]

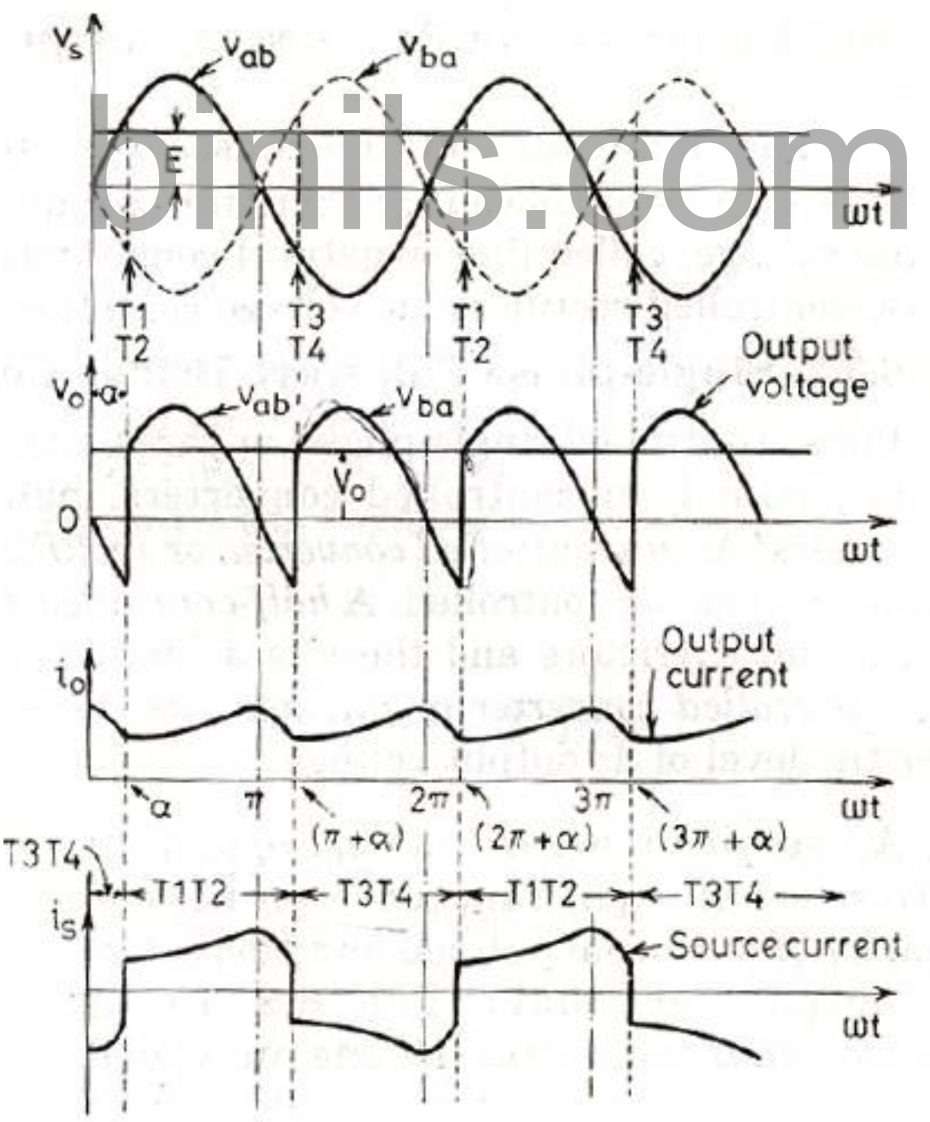
CONSTRUCTION

The circuit diagram of a single phase fully controlled bridge converter is shown in the figure with a highly inductive load and a dc source in the load circuit so that the load current is continuous and ripple free (constant load current operation). The fully controlled bridge converter consists of four thyristors T1, T2,T3 and T4 connected in the form of full wave bridge configuration as shown in the figure. Each thyristor is controlled and turned on by its gating signal and naturally turns off when a reverse voltage appears across it.

During the positive half cycle when the upper line of the transformer secondary winding is at a positive potential with respect to the lower end the thyristors T1and T2are forward biased during the timeinterval ωt = 0 to π. The thyristors T1and T2are triggered simultaneously ωt =α; (0 ≤α≤π) , the load is connected to the input supply through the conducting thyristors T1and T2.. Due to the inductive load T1 and T2will continue to conduct beyond ωt =π, even though the input voltage becomes negative. T1 and T2 conduct together during the time period α to (π+α) , for a time duration of π radians (conduction angle of each thyristor = 180^0).

Figure 2.2.2 FULL CONVERTER WAVEFORM

[Source: “Power Electronics” by P.S.Bimbra, Khanna Publishers Page: 192)



During the negative half cycle of input supply voltage for ωt =π to 2π the thyristors T3and T4are forward biased. T3 and T4are triggered at ωt = (π+α) . As soon as the thyristors 3 T and 4 T are triggered a reverse voltage appears across the thyristors T1and T2and they naturally turn- off and the load current is transferred from T1and T2to the thyristors T3and T4. In the next positive half cycle when T1and T2 are triggered, T3and T4are reverse biased and they turn-off. The figure shows the waveforms of the input supply voltage, the output load voltage, the constant load current with negligible ripple and the input supply current.

During the time period ωt =α to π, the input supply voltage V_S and the input supply current is both positive and the power flows from the supply to the load. The converter operates in the rectification mode during ωt =α to π.

During the time period ωt =π to (π+α) , the input supply voltage Vs is negative and the input supply current is positive and there will be reverse power flow from the load circuit to the input supply. The converter operates in the inversion mode during the time period ωt =π to (π+α) and the load energy is fed back to the input source.

The single phase full converter is extensively used in industrial applications up to about 15kW of output power. Depending on the value of trigger angle α, the average output voltage may be either positive or negative and two quadrant operation is possible.

2.3 Three Pulse Converter

INTRODUCTION TO 3-PHASE CONTROLLED RECTIFIERS

Three phase converters are 3-phase controlled rectifiers which are usedto convert ac input power supply into dc output power across the load.

FEATURES OF 3-PHASE CONTROLLED RECTIFIERS ARE

- Operate from 3 phase ac supply voltage.
-
- They provide higher dc output voltage and higher dc output power.
-
- Higher output voltage ripple frequency.

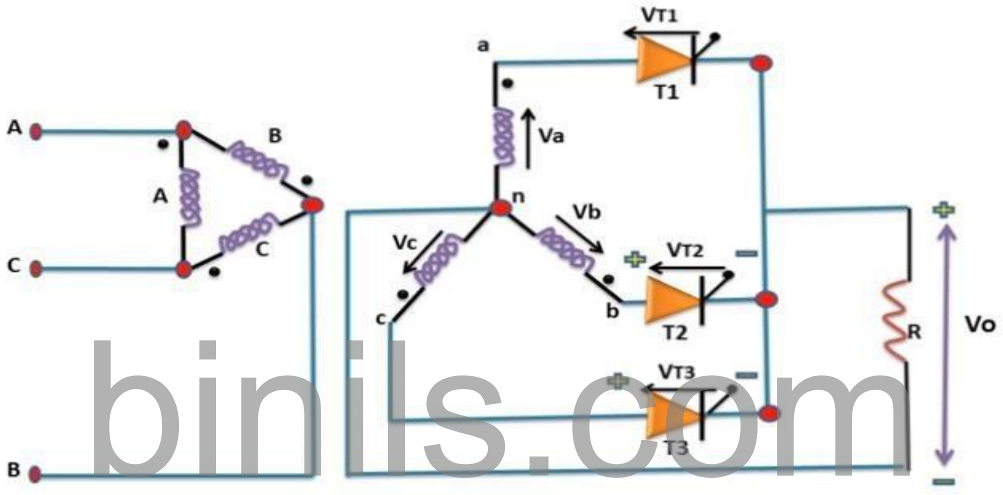
Filtering requirements are simplified for smoothing out load voltage and load current.Three phase controlled rectifiers are extensively used in high power variable speed industrial dc drives.

3-PHASE HALF WAVE CONVERTER WITH R LOAD (Three Pulse Converter)

Three single phase half-wave converters are connected together toform a three phase half-wave converter as shown in the figure.

Figure 2.3.1 Three pulse converter circuit diagram

[Source: “Power Electronics” *by* P.S.Bimbra, Khanna Publishers *Page: 214]*



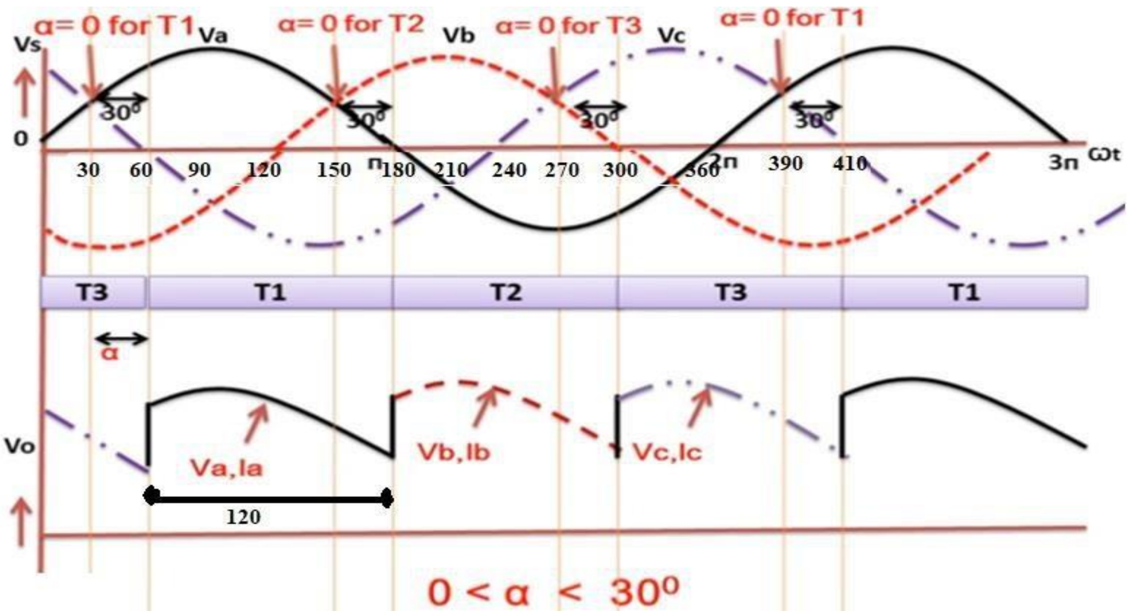


Figure 2.3.2 Three pulse converter Waveforms

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 11]*

The 3-phase half wave converter combines three single phase half wave controlled rectifiers in one single circuit feeding a common load. The thyristor T1 in series with one of the supply phase windings ' a - n ' acts as one half wave controlled rectifier. The second thyristor T2 in series with the supply phase winding,'b - n ' acts as the second half wave controlled rectifier. The third thyristor T3 rectifier in series with the supply phase winding ' c - n ' acts as the third half wave controlled.

The 3-phase input supply is applied through the star connected supply transformer as shown in the figure. The common neutral point of the supply is connected to one end of the load while the other end of the load connected to the common cathode point.When the thyristor T 1 is triggered the load current flows through the supply phase winding 'a - n ' and through thyristor T1 as long as T1 conducts.

When thyristor T 2 is conducts the phase voltage Vbn appears across the load until the thyristor T3 is triggered . When the thyristor T3 is triggered the phase voltage Vcn appears across the load.

For a purely resistive load where the load inductance 'L = 0' and the current appears as discontinuous.

The frequency of output ripple frequency for a 3-phase half wave converter is 3fs , where fs is the input supply frequency.

The 3-phase half wave converter is not normally used in practical converter systems because of the disadvantage that the supply current waveforms contain dc components.

2.4 Six Pulse Converter

THREE PHASE FULL CONVERTER

Three phase full converter is a fully controlled bridge controlled rectifier using six thyristors connected in the form of a full wave bridge configuration. All the six thyristors are controlled switches which are turned on at a appropriate times by applying suitable gate trigger signals.

FEATURES OF 3-PHASE CONTROLLED RECTIFIERS ARE

The three phase fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. Three phase circuits are preferable when large power is involved. The controlled rectifier can provide controllable out put dc voltage in a single unit instead of a three phase autotransformer and a diode bridge rectifier. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. Control over the output dc voltage is obtained by controlling the conduction interval of each thyristor. This method is known as phase control and converters are also called “phase controlled converters”. Since thyristors can block voltage in both directions it is possible to reverse thepolarity of the output dc voltage and hence feed power back to the ac supply from the dc side. Under such condition the converter is said to be operating in the "inverting mode". The thyristors in the converter circuit are commutated with the help of the supply voltage in the rectifying mode of operation and are known as "Line commutated converter". The same circuit while operating in the inverter mode requires load side counter emf. for commutation and are referred to as the "Load commutated inverter".

A three phase fully controlled converter is obtained by replacing all the six diodes of an uncontrolled converter by six thyristors as shown in Fig.

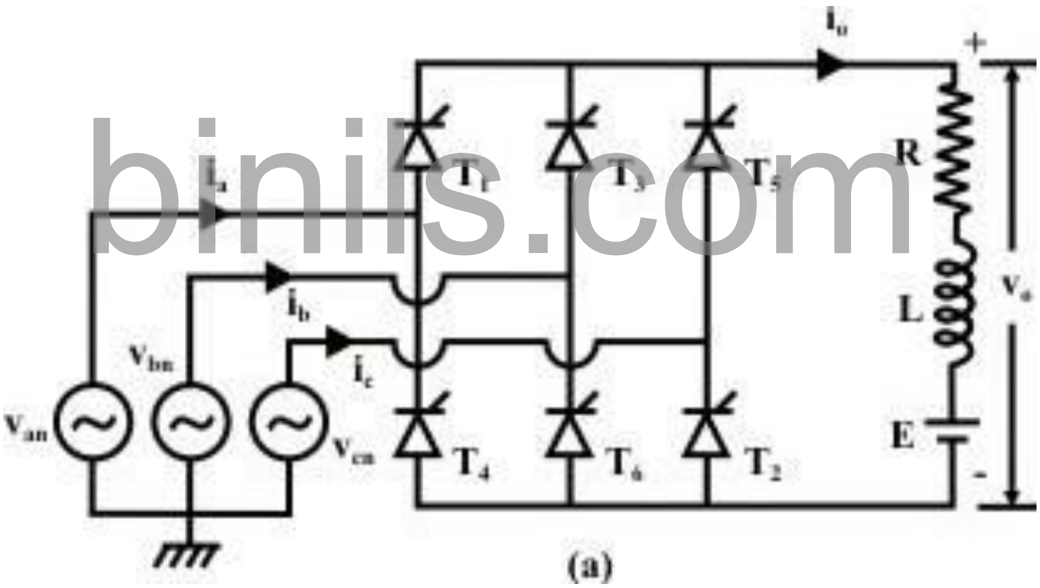


Figure 2.4.1 Six pulse converter

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 210]*

The three thyristors (T1 ,T3 andT5) will not work together at the sametime or two of them also will not work together at the same time.

- The three thyristors (T2 ,T4 andT6) will not work together at the sametime or two of them also will not work together at the same time.

(T1 and T4), (T3 and T6) or (T5 and T2) will not work together at the sametime.

➢ Each thyristor is triggered at an interval of 2pi / 3.

➢ Each thyristors pair ((T6&T1), (T1&T2), (T2&T3), (T3&T4), (T4&T5), (T5&T6)) is triggered at an interval of pi / 3.

➢ The frequency of output ripple voltage is 6fS.

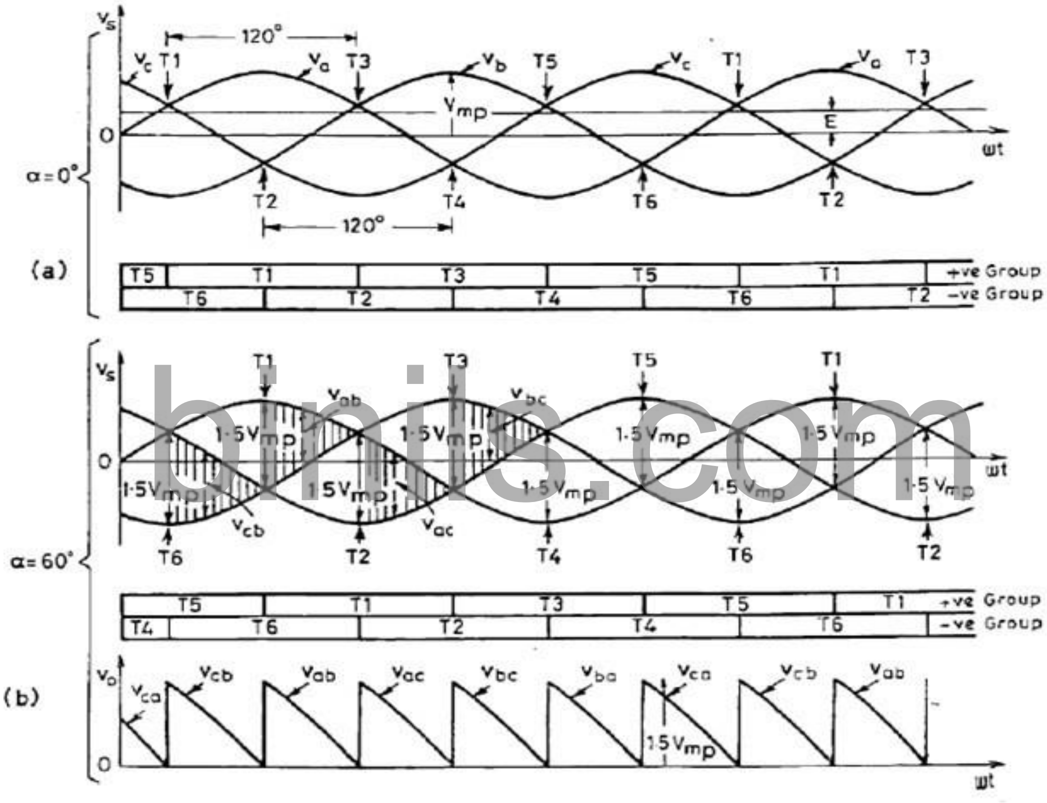


Figure 2.4.2 Six pulse converter Waveforms

[Source: “Power Electronics” *by* P.S.Bimbra, Khanna Publishers *Page: 211]*

➢

➢

➢

- If T1 is triggered at (30 + α), T3 will be triggered at (30 + α+120) and T5 will be triggered at (30 +α+240). T4 will be triggered at (30 + α+180), T6 will be triggered at (30 + α+12
- 0+180) and T2 will be triggered at (30 +α +240+180).

Firing Angle	T1	T2	T3	T4	T5	T6
0°	30°	90°	150°	210°	270°	330°
30°	60°	120°	180°	240°	300°	360°
60°	90°	150°	210°	270°	330°	390°
90°	120°	180°	240°	300°	360°	420°

Three phase full converter – triggering angles of thyristor

At ωt = 30˚+α, thyristor T6 is already conducting when the thyristor T 1is turned on by applying the gating signal to the gate of T 1. During the time period to ωt =30+α to 90˚+α thyristors T 1and T 6 conduct together and the line to line supply voltage Vab appears across the load. At ωt = 90 ˚+α , the thyristor T2 is triggered and T6 is reverse biased immediately and T6 turns off due to natural commutation. During the time period ωt = 90˚+α to 150˚+α , thyristor T1 and T2 conduct together and the line to line supply voltage V ac appears across the load. The thyristors are numbered in the circuit diagram corresponding to the order in which they are triggered.

2.5 PERFORMANCE PARAMETERS

The various parameters to compare the performance of power electronicsconverter are listed below:

1. Output dc power (average or dc output power delivered to the load)

$$P_{O(dc)} = V_{O(dc)} \times I_{O(dc)} \;\; ; \text{ i.e., } P_{dc} = V_{dc} \times I_{dc}$$

Where

$V_{O(dc)} = V_{dc}$ = average or dc value of output (load) voltage.

$I_{O(dc)} = I_{dc}$ = average or dc value of output (load) current.

2. Input Displacement Factor (DSF):

DSF=cos α

3. Output Ac power

$$P_{O(ac)} = V_{O(RMS)} \times I_{O(RMS)}$$

4. Rectification efficiency:

$$\text{Efficiency } \eta = \frac{P_{O(dc)}}{P_{O(ac)}}$$

$$\%\,\text{Efficiency } \eta = \frac{P_{O(dc)}}{P_{O(ac)}} \times 100$$

5. AC component

The output voltage can be composed of two components

- The dc component VO(dc) = DC or average value of output voltage.
- The ac component or the ripple component

  Vac = Vr(rms)= RMS value of all the ac ripple components.

The total RMS value of output voltage is given by

$$V_{O(RMS)} = \sqrt{V_{O(dc)}^2 + V_{r(rms)}^2}$$

Therefore

$$V_{ac} = V_{r(rms)} = \sqrt{V_{O(RMS)}^2 - V_{O(dc)}^2}$$

6. Voltage Ripple Factor

The Ripple Factor (RF) which is a measure of the ac ripple content in the output voltage waveform. The output voltage ripple factor defined for the output voltage waveform is given by

$$r_v = RF = \frac{V_{r(rms)}}{V_{O(dc)}} = \frac{V_{ac}}{V_{dc}}$$

7. Current Ripple Factor

Defined for the output (load) current waveform is given by

$$r_i = \frac{I_{r(rms)}}{I_{O(dc)}} = \frac{I_{ac}}{I_{dc}}$$

Where

$$I_{r(rms)} = I_{ac} = \sqrt{I_{O(RMS)}^2 - I_{O(dc)}^2}$$

the peak to peak ac ripple load current is the difference between the maximum and the minimum values of the output load current

$$\boxed{I_{r(pp)} = I_{O(\max)} - I_{O(\min)}}$$

8. Transformer Utilization Factor (TUF)

A transformer is most often used both to introduce a galvanic isolation between the rectifier input and the AC mains and to adjust the rectifier AC input voltage to a level suitable for the required application. One of the parameters used to define the characteristics of the transformer is the Transformer Utilization Factor (TUF):

$$TUF = \frac{P_{DC}}{Effective\ Transformer\ VA\ Rating}$$

2.6 EFFECT OF SOURCE INDUCTANCE

In actual practice, the converter is connected to ac mains through a transformer.

In a converter,because of source inductance, the current in the outgoing thyristor cannot change from full value to zero instantaneously and the current through the incoming thyristor cannot increase from zero to full value instantaneously. Therefore after the triggering gate pulse is applied to a thyristor, the current of the outgoing thyristor decreases from full value to zero over a time ωt = μ. During this time interval the current through incoming thyristor rises from zero to full value. During this period μ known as commutating period, both the outgoing and incoming thyristors are conducting. μ is also known as overlap angle**.** The overlapping of currents causes a reductionin output voltage. During this commutation period, the output voltage is equal to 0 .

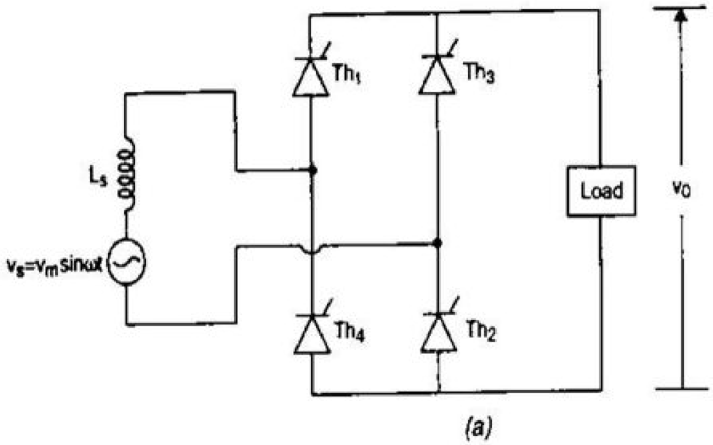
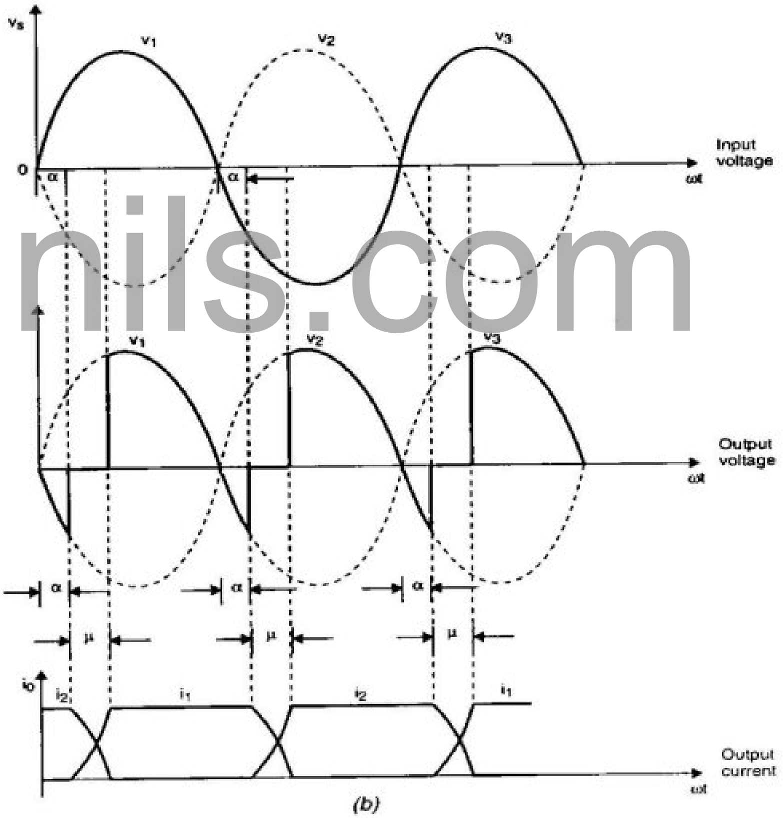


Figure 2.6.1 Single Phase Converter with Source Inductance

[Source: “Power Electronics” by P.S.Bimbra, Khanna Publishers Page: 222]

Figure shows a single phase fully controlled bridge conveter with source inductance L_S. The load is assumed to be highly inductive so that load current can be assumed to be constant and equal to I_0. Let i_1 and i_2 be the currents through Th_1, Th_2 combination and Th_3, Th_4 combination respectively.

During overlap period μ one of these currents decays to zero and the other builds up from zero to full value. Four thyristors conduct together as shown in Fig



[Source: “Power Electronics” by P.S.Bimbra, Khanna Publishers Page: 223]

2.7 Firing Schemes for Converters

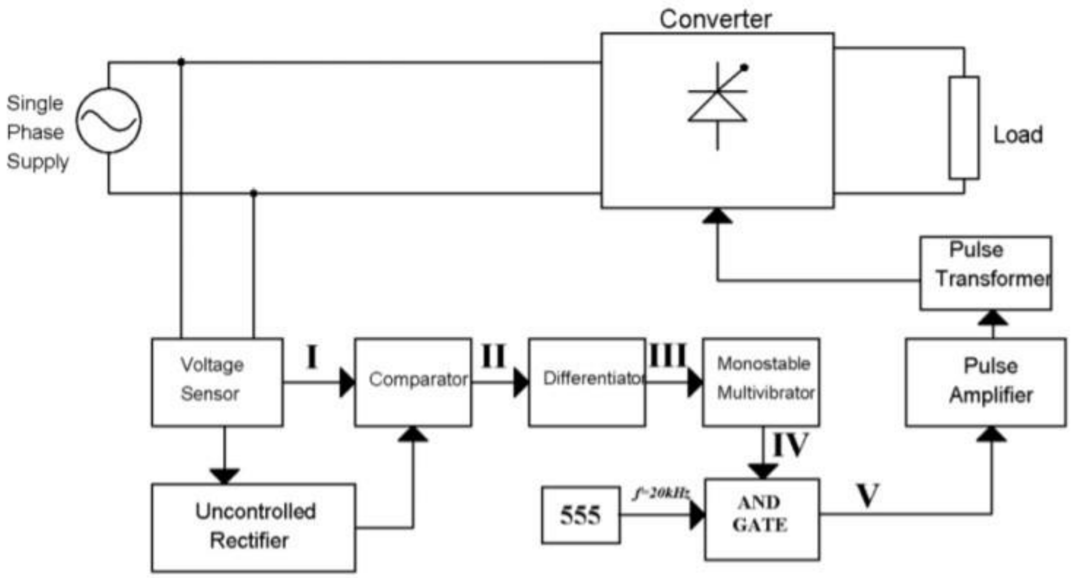
The firing circuit consists of step down transformer, uncontrolled rectifier, comparator, differentiator, mono stable multi vibrator, oscillator, AND gate, pulse amplifier and pulse transformer.

The complete circuit diagram of triggering circuit is shown in Fig. 2.24. A single-phase transformer with center tapped secondary windings has been used. The main purpose of this transformer is to step down 50Hz, 220 V to 6-0-6 V. The secondary voltage of the transformer is compared with a dc reference signal using a 741C op-amp comparator to produce an alternating rectangular waveform of a variable pulse width.

The output of the comparator ideally swings between +5 and -5 V at every crossing transformer output dc reference voltage. Using a variable resistor, the dc reference voltage can be altered and hence the rectangular waveform of variable pulse width is obtained at output terminal.

Figure 2.7.1 Firing circuit for full converter

[Source: “Power Electronics” *by* P.S.Bimbra, Khanna Publishers *Page: 224]*



A simple R-C differentiator is used to differentiate the rectangular voltage waveform. The elements R and C are selected as 10KΩ and 0.01µF, respectively. Monostable multivibrator often called a on shot multivibrator, is a pulse generating circuit in which the duration of this pulse is determined by the RC network connected externally to the 555 timer. A 555 timer produces an output pulse using a positive going edge trigger to produce a delay angle between 0º and 90º for the conversion mode of operation.

The differentiator is blocked by a connected diode. The number of comparators and monostable blocks are 2 blocks to produce firing pulses for conversion and inversion mode together. The values of R9 and C7 for the monostable are chosen so that the pulse width is approximately 0.5ms. Once triggered, the circuit’s output will remain in the high state until the set time elapses. The output will not change its state even if an input trigger is applied again during this time interval. The output will remain in the low state until a trigger is again applied. IC 555 timer is used as oscillator.

The square wave output waveform of of 20kHz by connecting suitable resistor and capacitor. Pulse gating of thyristor is not suitable for RL loads, this difficulty can be overcome by using continuous gating. However, continuous gating may lead to increased thyristor losses and distortion of output pulse. So, a pulse train generated by modulating the gate pulse at high frequency is used to trigger the thyristor. This high frequency wave is known as carrier wave and is generated by using 555 timer.The outputs of monostable multivibrator and oscillator are applied to the AND gate. IC 7408 two input AND gate is used for this purpose. A long duration pulse may saturate the pulse transformer and the firing pulse may be distorted so high frequency modulation is necessary.

The duty cycle is kept less than 50 percent, so that the magnetic flux in the transformer can be reset. The modulation pulse also reduces the gatedissipation.

2.8 Dual converter

- **Dual converter**, the name itself says two converters.
- It is really an electronic converter or circuit which comprises of two converters. One will perform as a rectifier and the other will perform as an inverter.
- Therefore, we can say that double processes will occur at a moment. Here, two full converters are arranged in anti-parallel pattern and linked to the same dc load. These converters can provide four quadrant operations.

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 230]*

The basic block diagram is shown below.

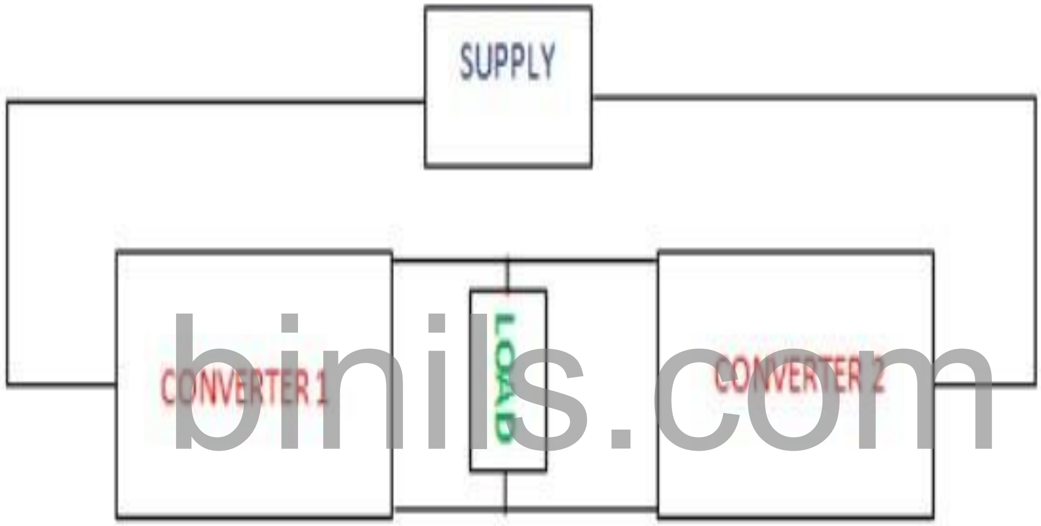


Figure 2.8.1 Block diagram of dual converter

Modes of Operation of Dual Converter

There are two functional modes: Non-circulating current mode and circulating mode.

Non Circulating Current Mode

- One converter will perform at a time. So there is no circulating current between the converters.
- During the converter 1 operation, firing angle (α_1) will be $0<\alpha_1< 90^o$; V_{dc} and I_{dc} are positive.
- During the converter 2 operation, firing angle (α_2) will be $0<\alpha_2< 90^o$; V_{dc} and I_{dc} are negative.

Circulating Current Mode

- Two converters will be in the ON condition at the same time. So circulating current is present.
- The firing angles are adjusted such that firing angle of converter 1 (α_1) + firing angle of converter 2 (α_2) = 180^o.
- Converter 1 performs as a controlled rectifier when firing angle be $0<\alpha_1< 90^o$ and Converter 2 performs as an inverter when the firing angle be $90^o<\alpha_2< 180^o$. In this condition, V_{dc} and I_{dc} are positive.
- Converter 1 performs as an inverter when firing angle be $90^o<\alpha_1< 180^o$ and Converter 2 performs as a controlled rectifier when the firing angle be $0<\alpha_2< 90^o$ In this condition, V_{dc} and I_{dc} are negative.

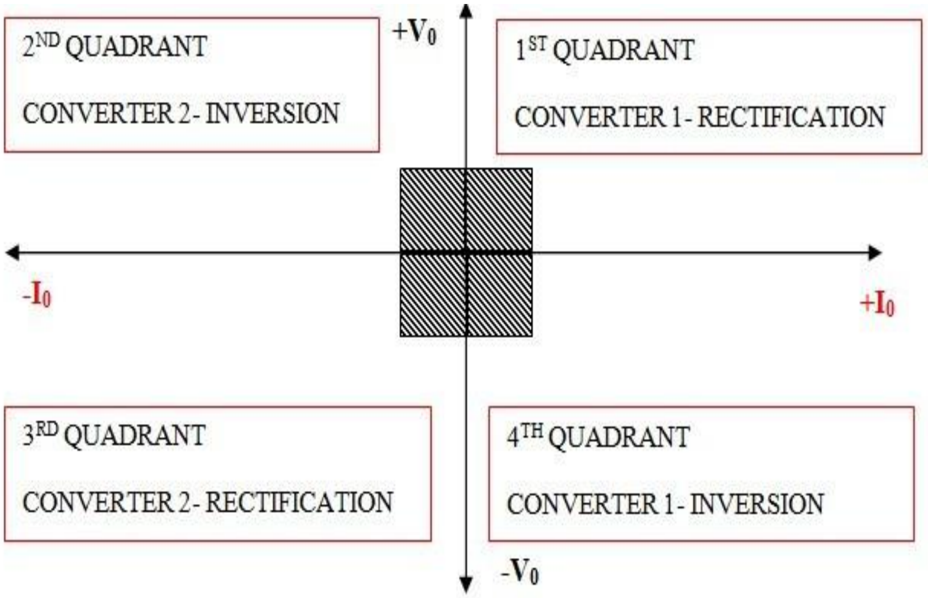


Figure 2 .8.2 Four quadrant operation

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 230]*

The term 'ideal' refers to the ripple free output voltage. For the purpose of unidirectional flow of DC current, two diodes (D1 and D2) are incorporated between the converters. However, the direction of current can be in any way. The average output voltage of the converter 1 is V01 and converter 2 is V02. To make the output voltage of the two converters in same polarity and magnitude, the firing angles of the thyristors have to be controlled.

Average output voltage of Single-phase converter

= 2Vm cosα/π

Average output voltage of Three-phase converter

= 3Vml cos

Output voltage, Vo =

VO1+VO2

Types of Dual Converters

They are of two types: Single-phase dual converter and three-phase dual converter.

Single Phase Dual Converter

The source of this type of converter will be single-phase supply. Consider, the converter is in non-circulating mode of operation. The input is given to the converter 1 which converts the AC to DC by the method of rectification. It is then given to the load after filtering. Then, this DC is provided to the converter 2 as input. This converter performs as inverter and converts this DC to AC. Thus, we get AC as output.

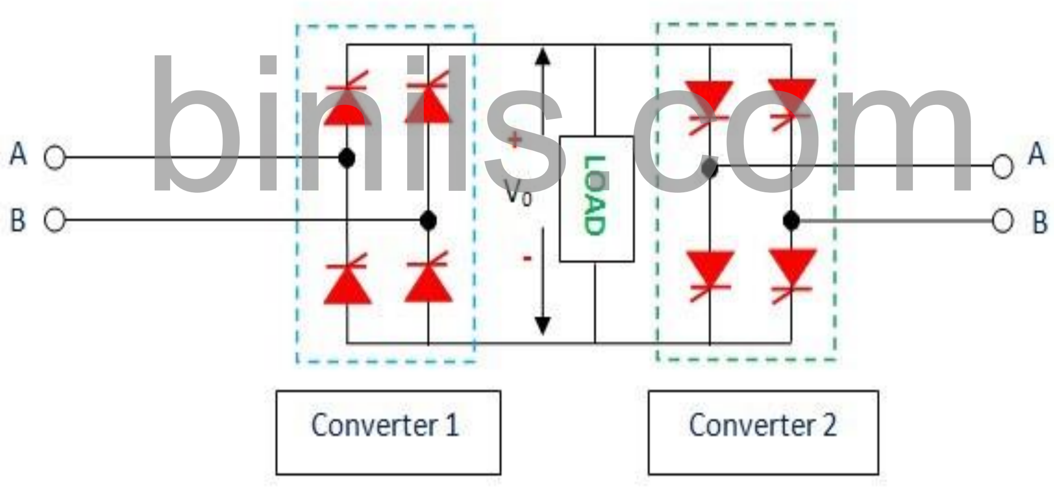


Figure 2.8.3 Single phase Dual converter

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 231]*

Three Phase Dual Converter

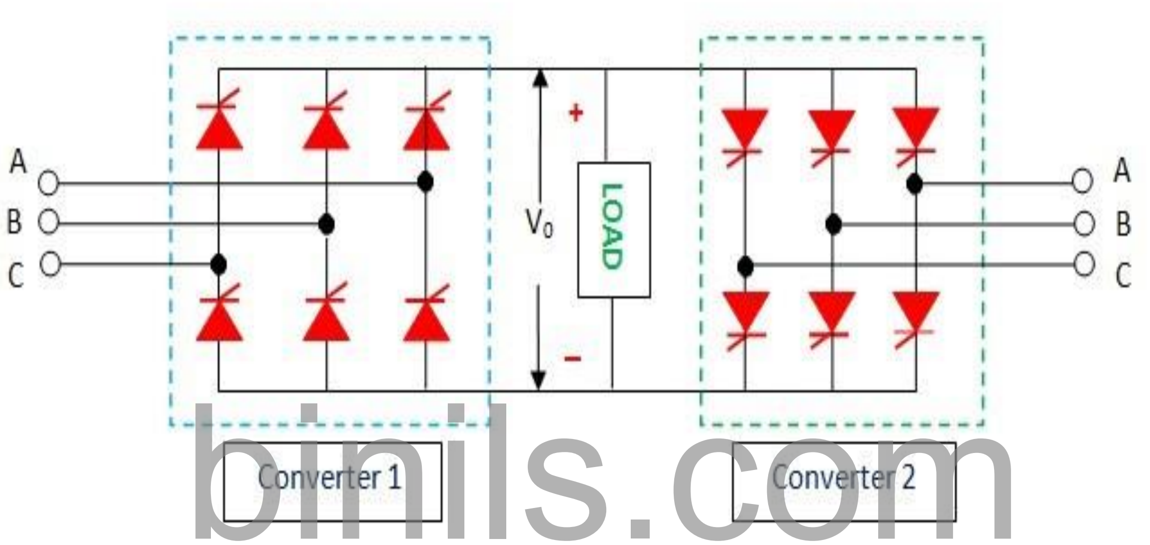


Figure 2.8.4 Three phase Dual converter

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 231]*

Application of Dual Converter

- Direction and speed control of DC motors.
- Applicable wherever the reversible DC is required.
- Industrial variable speed DC drives.

Here, three-phase rectifier and three-phase inverter are used. The processes are similar to single-phase dual converter. The three-phase rectifier will do the conversion of the three-phase AC supply to the DC. This DC is filtered and given to the input of the second do the DC to AC conversion and the output that we get is the three- phase AC. Applications where the output is up to 2 megawatts. The circuit is shown below.

2.9 Applications of converter

LIGHT DIMMERS

Semiconductor dimmers switch on at an adjustable time (phase angle) after the start of each alternating current half-cycle, thereby altering the voltage waveform applied to lamps and so changing its RMS effective value. Because they switch instead of absorbing part of the voltage supplied, there is very little wasted power. Dimming can be almost instantaneous and is easily controlled by remote electronics. This development also made it possible to make dimmers small enough to be used in place of normal domestic light switches.

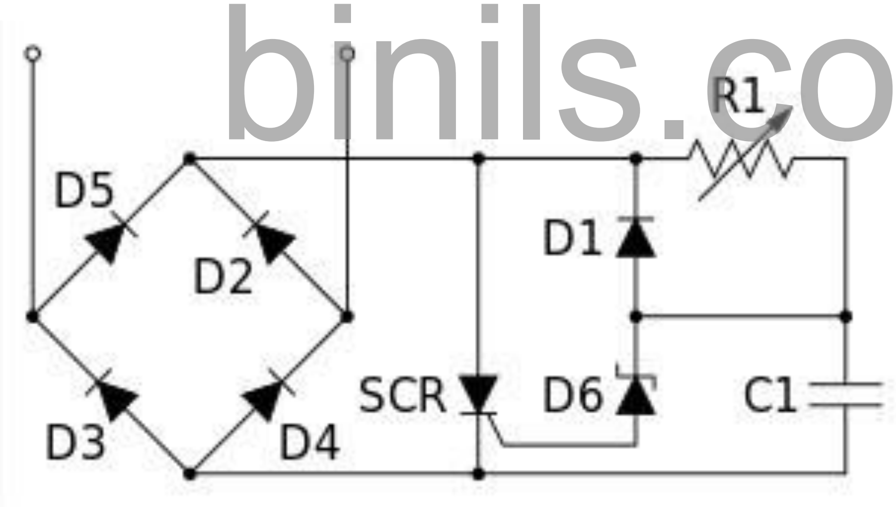


Figure 2.9.1 An electrical schematic for a SCR-based light dimmer

[Source: “Power Electronics” by P.S.Bimbra, Khanna Publishers Page: 219]

In the electrical schematic shown, a typical silicon-controlled rectifier (SCR) based light dimmer dims the light through phase-angle control. This unit is wired in series with the load. Diodes (D2, D3, D4 and D5) form a bridge, which generates pulsed DC. R1 and C1 form a circuit with a time constant. As the voltage increases from zero (at the start of every halfwave) C1 will charge up. When C1 is able to make Zener diode D6 conduct and inject current into the SCR, the SCR will fire. When the SCR conducts, D1 will discharge C1 via the SCR. The SCR will shut off when the current falls to zero and the supply voltage drops at the end of the half cycle, ready for the circuit to start work on the next half cycle. This circuit is called a Leading-Edge Dimmer or Forward Phase Dimming.

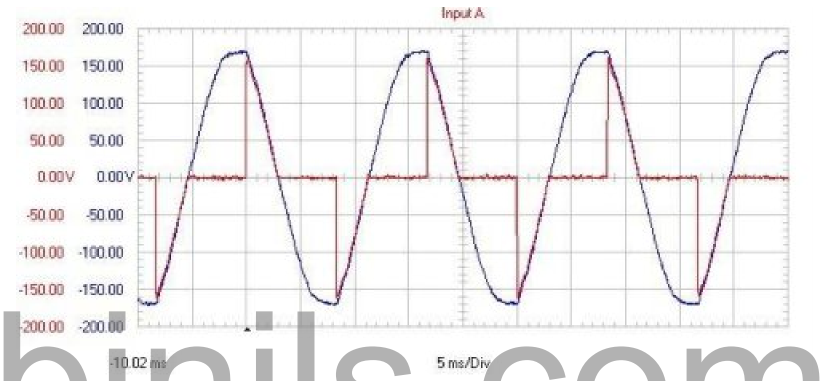


Figure 2.9.2 Phase control waveform of SCR-based light dimmer

[Source: “Power Electronics” by P.S.Bimbra, Khanna Publishers Page: 220]

Waveform of the output voltage of a thyristor dimmer set for 60 volts RMS output, with 120 V input. The red trace shows the output device switching on about 5.5 ms after the input (blue) voltage crosses zero. Switching the thyristor on earlier in each half cycle gives a higher output voltage and brighter lights.