Module 4(a)

CONTROLLED RECTIFIERS

Structure

4.0Introduction

Thyristors are semicontrolled devices which can be turned ON by applying a current pulse at its gate terminal at a desired instance. However, they cannot be turned off from the gate terminals. Therefore, the fully controlled converter continues to exhibit load dependent output voltage / current waveforms as in the case of their uncontrolled counterpart. However, since the thyristor can block forward voltage, the output voltage / current magnitude can be controlled by controlling the turn on instants of the thyristors. Working principle of thyristors based single phase fully controlled converters will be explained first in the case of a single thyristor halfwave rectifier circuit supplying an R or R-L load. However, such converters are rarely used in practice.
Full bridge is the most popular configuration used with single phase fully controlled rectifiers. Analysis and performance of this rectifier supplying an R-L-E load (which may represent a dc motor) will be studied in detail in this

4.1 Objectives:

- To explain the design, analysis techniques, performance parameters and characteristics of controlled rectifiers

4.2 Line Commutated AC to DC converters

Type of input: Fixed voltage, fixed frequency ac power supply.

• Type of output: Variable dc output voltage

• Type of commutation: Natural / AC line commutation

Different types of Line Commutated Converters

• AC to DC Converters (Phase controlled rectifiers)

• AC to AC converters (AC voltage controllers)

• AC to AC converters (Cyclo converters) at low output frequency

Differences Between Diode Rectifiers & Phase Controlled Rectifiers

• The diode rectifiers are referred to as uncontrolled rectifiers .

• The diode rectifiers give a fixed dc output voltage .

• Each diode conducts for one half cycle.

• Diode conduction angle = 1800 or radians.

• We cannot control the dc output voltage or the average dc load current in a diode rectifier circuit

4.3 Applications of Phase Controlled Rectifiers

• DC motor control in steel mills, paper and textile mills employing dc motor drives.

• AC fed traction system using dc traction motor.

• Electro-chemical and electro-metallurgical processes.

• Magnet power supplies.

• Portable hand tool drives

Classification of Phase Controlled Rectifiers

• Single Phase Controlled Rectifiers.

• Three Phase Controlled Rectifiers

4.3.1 Different types of Single Phase Controlled Rectifiers.

• Half wave controlled rectifiers.

• Full wave controlled rectifiers.

• Using a center tapped transformer.

• Full wave bridge circuit.

• Semi converter.

• Full converter.

Different Types of Three Phase Controlled Rectifiers

• Half wave controlled rectifiers.

• Full wave controlled rectifiers.

• Semi converter (half controlled bridge converter).

• Full converter (fully controlled bridge converter).

4.4 Principle of Phase Controlled Rectifier Operation Single Phase Half-Wave Thyristor

Converter with a Resistive Load

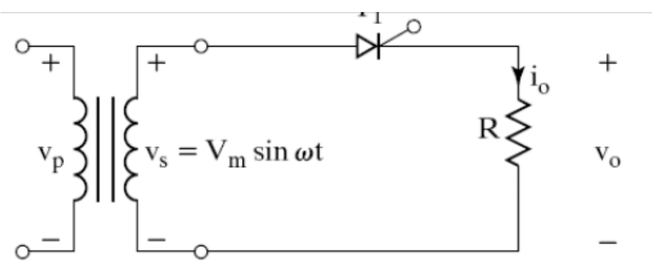
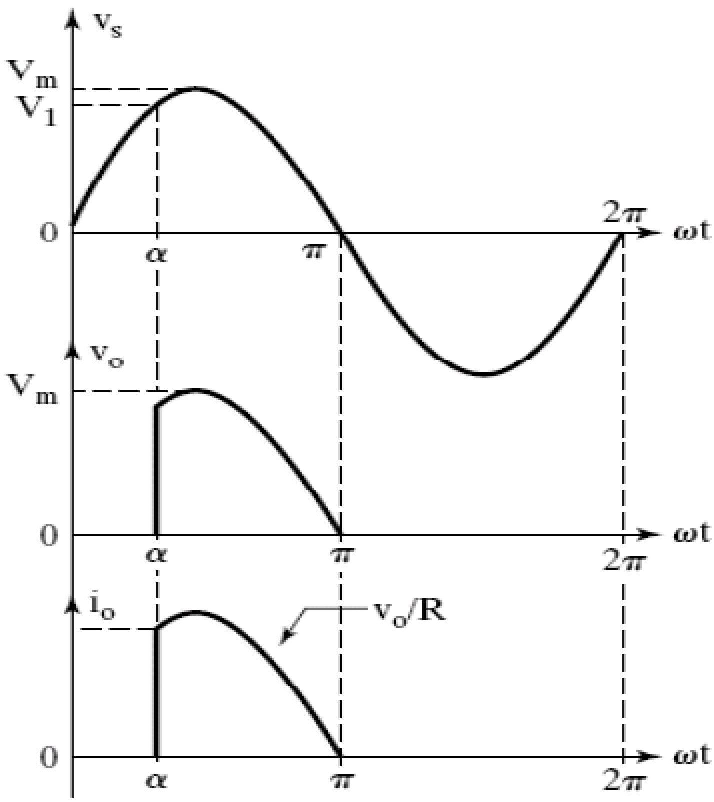


Fig. shows the circuit diagram of a single phase fully controlled halfwave rectifier supplying a purely resistive load. At $\omega t = 0$ when the input supply voltage becomes positive the thyristor T becomes forward biased. However, unlike a diode, it does not turn ON till a gate pulse is applied at $\omega t = \alpha$. During the period $0 < \omega t \leq \alpha$, the thyristor blocks the supply voltage and the load voltage remains zero as shown in Consequently, no load current flows during this interval. As soon as a gate pulse is applied to the thyristor at $\omega t = \alpha$ it turns ON. The voltage across the thyristor collapses to almost zero and the full supply voltage appears across the load. From this point onwards the load voltage follows the supply voltage. The load being purely resistive the load current i_O is proportional to the load voltage. At $\omega t = \pi$ as the supply voltage passes through the negative going zero crossing the load voltage and hence the load current becomes zero and tries to reverse direction. In the process the thyristor undergoes reverse recovery and starts blocking the negative supply voltage. Therefore, the load voltage and the load current remains clamped at zero till the thyristor is fired again at $\omega t = 2\pi + \alpha$. The same process repeats there after.



Equations:

$v_s = V_m \sin\omega t =$ i/p ac supply voltage

$V_m =$ max. value of i/p ac supply voltage

$V_S = \frac{V_m}{\sqrt{2}} =$ RMS value of i/p ac supply voltage

$v_O = v_L =$ output voltage across the load

When the thyristor is triggered at $\omega t = \alpha$

$v_O = v_L = V_m \sin\omega t;\ \ \omega t = \alpha$ to π

$i_O = i_L = \frac{v_O}{R} =$ Load current; $\omega t = \alpha$ to π

To Derive an Expression for the Average (DC) Output Voltage across the Load

Maximum average (dc) o/p voltage is obtained when 0 and the maximum dc output voltage

$$V_{O(dc)} = V_{dc} = \frac{1}{2\pi}\int_{0}^{2\pi} v_O.d(\omega t) \ ;$$

$$v_O = V_m \sin\omega t \ for \ \omega t = \alpha \ to \ \pi$$

$$V_{O(dc)} = V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t.d(\omega t)$$

$$V_{O(dc)} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t.d(\omega t)$$

$$V_{O(dc)} = \frac{V_m}{2\pi}\int_{\alpha}^{\pi} \sin\omega t.d(\omega t)$$

$$V_{O(dc)} = \frac{V_m}{2\pi}\int_{\alpha}^{\pi} \sin\omega t.d(\omega t)$$

$$V_{O(dc)} = \frac{V_m}{2\pi}\left[-\cos\omega t \Big/_{\alpha}^{\pi}\right]$$

$$V_{O(dc)} = \frac{V_m}{2\pi}(-\cos\pi + \cos\alpha) \ ; \ \cos\pi = -1$$

$$V_{O(dc)} = \frac{V_m}{2\pi}(1 + \cos\alpha) \ ; V_m = \sqrt{2}V_S$$

To Derive an Expression for the RMS Value of Output Voltage of a Single Phase Half Wave Controlled Rectifier with Resistive Load

The RMS output voltage is given by

$$V_{O\ RMS}=\left[\frac{1}{2\pi}\int_{0}^{2\pi}v_O^2.d\ \ \omega t\ \right]$$

Output voltage $v_O=V_m\sin\omega t$; for $\omega t=\alpha$ to π

$$V_{O\ RMS}=\left[\frac{1}{2\pi}\int_{\alpha}^{\pi}V_m^2\sin^2\omega t.d\ \ \omega t\ \right]^{\frac{1}{2}}$$

By substituting $\sin^2\omega t=\dfrac{1-\cos 2\omega t}{2}$, we get

$$V_{O\ RMS}=\left[\frac{1}{2\pi}\int_{\alpha}^{\pi}V_m^2\ \frac{1-\cos 2\omega t}{2}.d\ \ \omega t\ \right]^{\frac{1}{2}}$$

$$V_{O\ RMS}=\frac{V_m}{2}\left[\frac{1}{\pi}\left(\ \pi-\alpha\ \ -\frac{\sin 2\pi-\sin 2\alpha}{2}\ \right)\right]^{\frac{1}{2}};\sin 2\pi=0$$

Performance Parameters of Phase Controlled Rectifiers

Output dc power (avg. or dc o/p power delivered to the load)

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

Where

$V_{O\,dc} = V_{dc} =$ avg./ dc value of o/p voltage.

$I_{O\,dc} = I_{dc} =$ avg./dc value of o/p current

Output ac power

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

Efficiency of Rectification (Rectification Ratio)

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

The o/p voltage consists of two components

The dc component $V_{O\,dc}$

The ac /ripple component $V_{ac} = V_{r(ms)}$

Output ac power

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

Efficiency of Rectification (Rectification Ratio)

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

The o/p voltage consists of two components

The dc component $V_{O\,dc}$

The ac /ripple component $V_{ac} = V_{r(ms)}$

The Ripple Factor (RF) w.r.t output voltage waveform

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

$$r_v = \frac{\sqrt{V_{O(RMS)}^2 - V_{O(dc)}^2}}{V_{O(dc)}} = \sqrt{\left[\frac{V_{O(RMS)}}{V_{O(dc)}}\right]^2 - 1}$$

$$r_v = \sqrt{FF^2 - 1}$$

Current Ripple Factor $r_i = \frac{I_{r\ rms}}{I_{O\ dc}} = \frac{I_{ac}}{I_{dc}}$

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

$V_{r\ pp}$ = peak to peak ac ripple output voltage

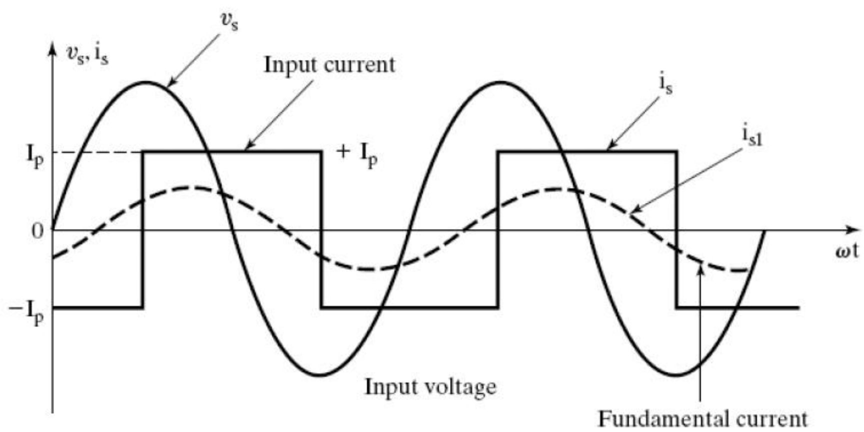
$$V_{r\ pp} = V_{O\ \max} - V_{O\ \min}$$

$I_{r\ pp}$ = peak to peak ac ripple load current

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

Transformer Utilization Factor (TUF)

$$TUF = \frac{P_{O\ dc}}{V_S \times I_S}$$



Harmonic Factor (HF) or Total Harmonic Distortion Factor

$$HF = \left[\frac{I_S^2 - I_{S1}^2}{I_{S1}^2}\right]^{\frac{1}{2}} = \left[\left(\frac{I_S}{I_{S1}}\right)^2 - 1\right]^{\frac{1}{2}}$$

Where

$I_S =$ RMS value of input supply current.

$I_{S1} =$ RMS value of fundamental component of the i/p supply current.

Input Power Factor (PF)

$$PF = \frac{V_S I_{S1}}{V_S I_S}\cos\phi = \frac{I_{S1}}{I_S}\cos\phi$$

The Crest Factor (CF)

$$CF = \frac{I_{S\ peak}}{I_S} = \frac{\text{Peak input supply current}}{\text{RMS input supply current}}$$

For an Ideal Controlled Rectifier

$FF = 1;\ \eta = 100\%\ ;\ V_{ac} = V_{r\ rms} = 0\ ;\ TUF = 1;$

$RF = r_v = 0\ ;\ HF = THD = 0;\ \ PF = DPF = 1$

4.5 Recommended questions:

1. Give the classification of converters, based on: a) Quadrant operation b) Number of current pulse c) supply input. Give examples in each case.

2. With neat circuit diagram and wave forms, explain the working of 1 phase HWR using SCR for R-load. Derive the expressions for V_{dc} and I_{dc}.

4.6 Generic Skills / Outcomes:

- Explain designing, analysis techniques and characteristics of thyristor controlled rectifiers.

4.7 Further Readings

1. http://books.google.co.in/books/about/Power_Electronics.html?id=-WqvjxMXClAC
2. http://www.flipkart.com/power-electronic-2ed/p/itmczynuyqnbvzzj
3. http://www.scribd.com/doc/36550374/Power-Electronics-Notes
4. http://elearning.vtu.ac.in/EC42.html
5. http://www.onlinevideolecture.com/electrical-engineering/nptel-iit-bombay/power-electronics/?course_id=510

MODULE 4(b)

AC VOLTAGE CONTROLLER

Structure

4.0 INTRODUCTION

AC voltage controllers (ac line voltage controllers) are employed to vary the RMS value of the alternating voltage applied to a load circuit by introducing Thyristors between the load and a constant voltage ac source. The RMS value of alternating voltage applied to a load circuit is controlled by controlling the triggering angle of the Thyristors in the ac voltage controller circuits.
In brief, an ac voltage controller is a type of thyristor power converter which is used to convert a fixed voltage, fixed frequency ac input supply to obtain a variable voltage ac output. The RMS value of the ac output voltage and the ac power flow to the load is controlled by varying (adjusting) the trigger angle ‘α’.
There are two different types of thyristor control used in practice to control the ac power flow.

- On-Off control
- Phase control

These are the two ac output voltage control techniques.
In On-Off control technique Thyristors are used as switches to connect the load circuit to the ac supply (source) for a few cycles of the input ac supply and then to disconnect it for few input cycles. The Thyristors thus act as a high speed contactor (or high speed ac switch).

4.1OBJECTIVES

- To explain the design, analysis techniques, performance parameters and characteristics of AC Voltage controllers

4.2 Phase Control

In phase control the Thyristors are used as switches to connect the load circuit to the input ac supply, for a part of every input cycle. That is the ac supply voltage is chopped using Thyristors during a part of each input cycle.

The thyristor switch is turned on for a part of every half cycle, so that input supply voltage appears across the load and then turned off during the remaining part of input half cycle to disconnect the ac supply from the load.

By controlling the phase angle or the trigger angle ‘’ (delay angle), the output RMS voltage across the load can be controlled. The trigger delay angle ‘’ is defined as the phase angle (the value of t) at which the thyristor turns on and the load current begins to flow.

Thyristor ac voltage controllers use ac line commutation or ac phase commutation. Thyristors in ac voltage controllers are line commutated (phase commutated) since the input supply is ac. When the input ac voltage reverses and becomes negative during the negative half cycle the current flowing through the conducting thyristor decreases and falls to zero. Thus the ON thyristor naturally turns off, when the device current falls to zero.

Phase control Thyristors which are relatively inexpensive, converter grade Thyristors which are slower than fast switching inverter grade Thyristors are normally used.

For applications upto 400Hz, if Triacs are available to meet the voltage and current ratings of a particular application, Triacs are more commonly used.

Due to ac line commutation or natural commutation, there is no need of extra commutation circuitry or components and the circuits for ac voltage controllers are very simple.

Due to the nature of the output waveforms, the analysis, derivations of expressions for performance parameters are not simple, especially for the phase controlled ac voltage controllers with RL load. But however most of the practical loads are of the RL type and hence RL load should be considered in the analysis and design of ac voltage controller circuits.

4.3 Type of Ac Voltage Controllers

The ac voltage controllers are classified into two types based on the type of input ac supply applied to the circuit.

- Single Phase AC Controllers.
- Three Phase AC Controllers.

Single phase ac controllers operate with single phase ac supply voltage of 230V RMS at 50Hz in our country. Three phase ac controllers operate with 3 phase ac supply of 400V RMS at 50Hz supply frequency.

Each type of controller may be sub divided into Uni-directional or half wave ac controller.

Bi-directional or full wave ac controller.

In brief different types of ac voltage controllers are

Single phase half wave ac voltage controller (uni-directional controller).

Single phase full wave ac voltage controller (bi-directional controller).

Three phase half wave ac voltage controller (uni-directional controller).

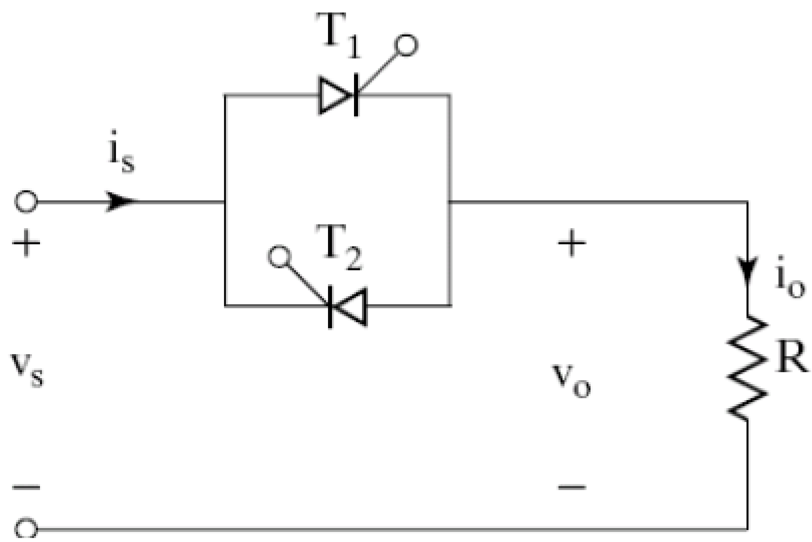
Three phase full wave ac voltage controller (bi-directional controller).

Applications of Ac Voltage Controllers

- Lighting / Illumination control in ac power circuits.
- Induction heating.
- Industrial heating & Domestic heating.
- Transformer tap changing (on load transformer tap changing).
- Speed control of induction motors (single phase and poly phase ac induction motor
- control).
- AC magnet controls.

4.4 Principle of On-Off Control Technique (Integral Cycle Control)

The basic principle of on-off control technique is explained with reference to a single phase full wave ac voltage controller circuit shown below. The thyristor switches 1 *T* and 2 *T* are turned on by applying appropriate gate trigger pulses to connect the input ac supply to the load for 'n' number of input cycles during the time interval *ON t* . The thyristor switches 1 *T* and 2 *T* are turned off by blocking the gate trigger pulses for 'm' number of input cycles during the time interval *OFF t* . The ac controller ON time *ON t* usually consists of an integral number of input cycles.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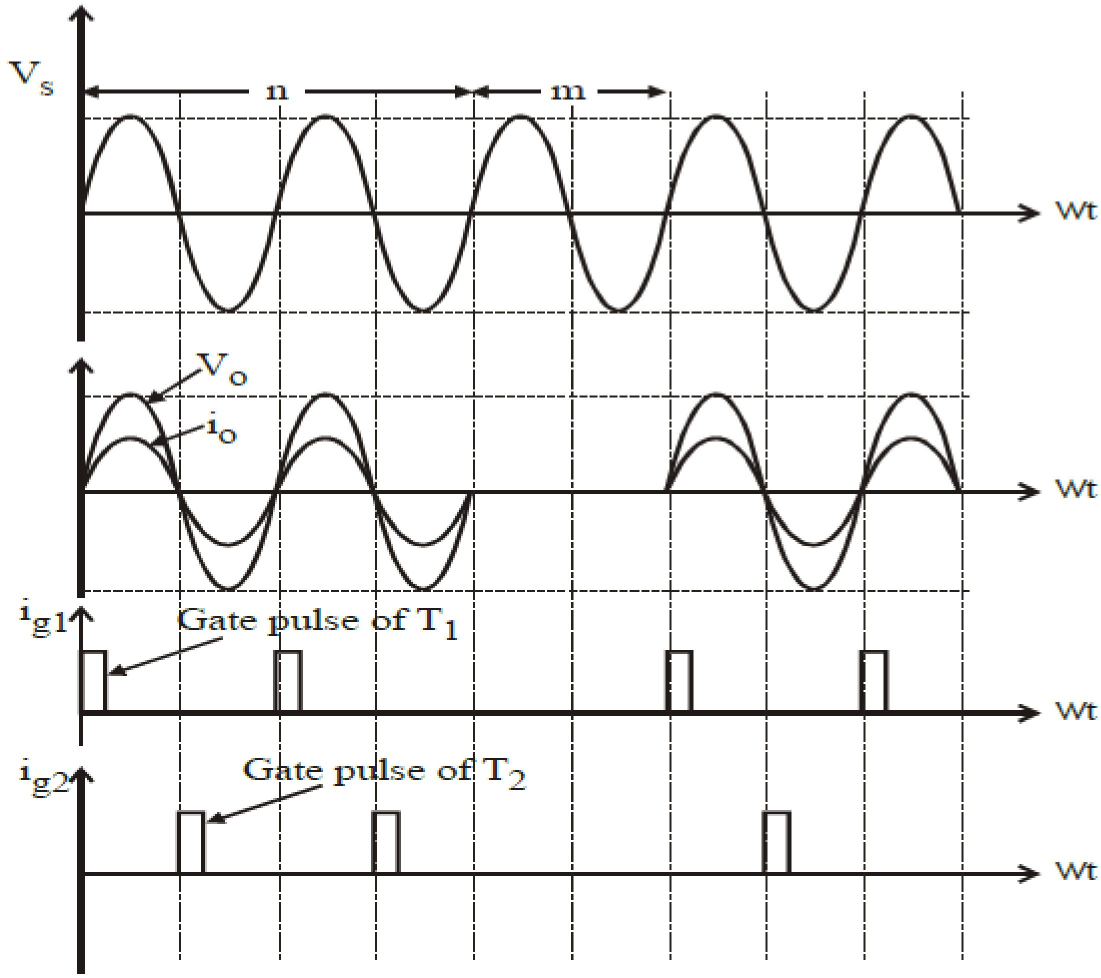


Example

Referring to the waveforms of ON-OFF control technique in the above diagram, Two input cycles. Thyristors are turned ON during for two input cycles. n ON t One input cycle. Thyristors are turned OFF during for one input cycle m OFF t Thyristors are turned ON precisely at the zero voltage crossings of the input supply.

The thyristor 1 *T* is turned on at the beginning of each positive half cycle by applying the gate trigger pulses to 1 *T* as shown, during the ON time *ON t* . The load current flows in the positive direction, which is the downward direction as shown in the circuit diagram when 1 *T* conducts. The thyristor 2 *T* is turned on at the beginning of each negative half cycle, by applying gating signal to the gate of 2 *T* , during *ON t* . The load current flows in the reverse direction, which is the upward direction when 2 *T* conducts. Thus we obtain a bi-directional load current flow (alternating load current flow) in a ac voltage controller circuit, by triggering the thyristors alternately. This type of control is used in applications which have high mechanical inertia and high thermal time constant (Industrial heating and speed control of ac motors). Due to zero voltage and zero current switching of Thyristors, the harmonics generated by switching actions are reduced.

(i) To derive an expression for the rms value of output voltage, for on-off control method.

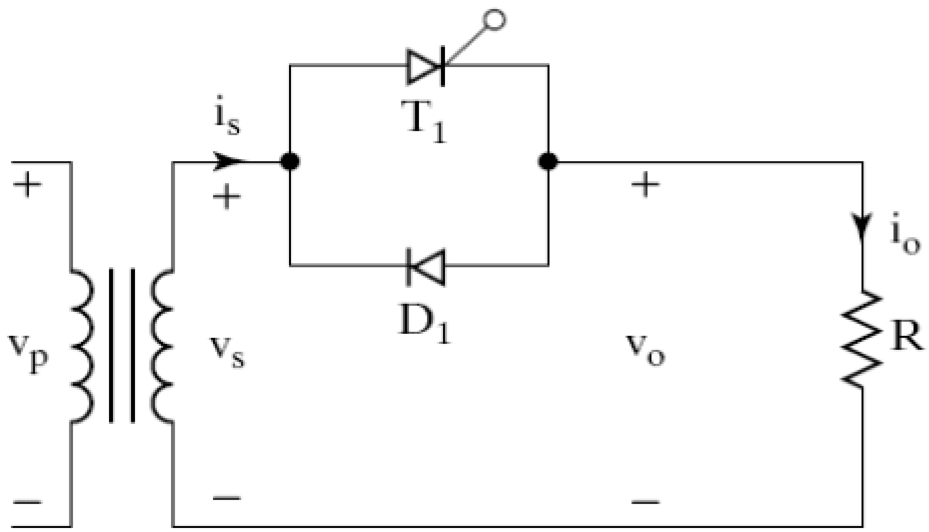
$$\text{Output RMS voltage} \quad V_{O\,RMS} = \sqrt{\frac{1}{\omega T_O}\int_{\omega t=0}^{\omega t_{ON}} V_m^{\,2} Sin^2\omega t.d\ \ \omega t}$$

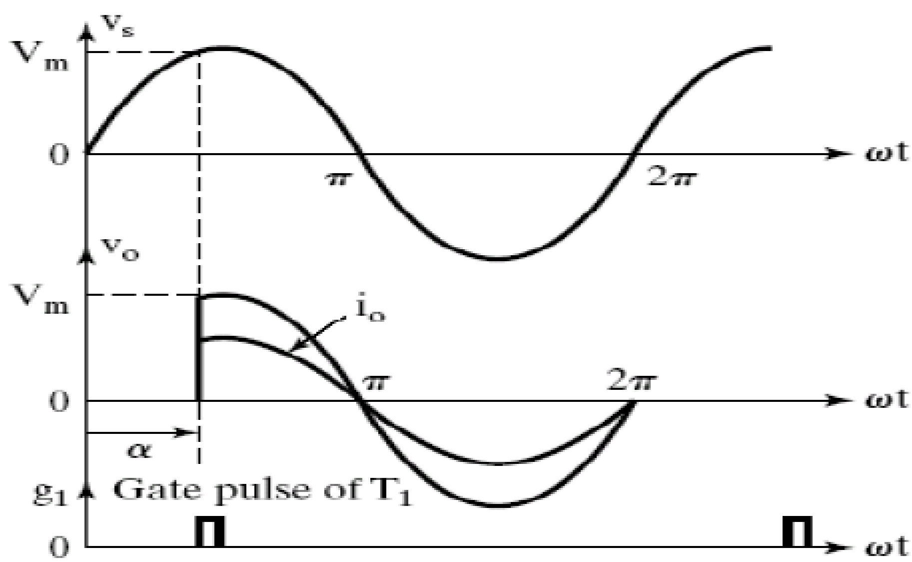
$$V_{O\,RMS} = \sqrt{\frac{V_m^{\,2}}{\omega T_O}\int_{0}^{\omega t_{ON}} Sin^2\omega t.d\ \ \omega t}$$

$$V_{O\,RMS} = \sqrt{\frac{V_m^{\,2}}{2\omega T_O}\left[\ \omega t_{ON} - 0\ \ - \frac{\sin 2\omega t_{ON} - \sin 0}{2}\right]}$$

4.5 Principle of AC Phase Control

The basic principle of ac phase control technique is explained with reference to a single phase half wave ac voltage controller (unidirectional controller) circuit shown in the below figure. The half wave ac controller uses one thyristor and one diode connected in parallel across each other in opposite direction that is anode of thyristor 1 T is connected to the cathode of diode 1 D and the cathode of 1 T is connected to the anode of 1 D . The output voltage across the load esistor 'R' and hence the ac power flow to the load is controlled by varying the trigger angle. The trigger angle or the delay angle ' ' refers to the value of t or the instant at which the thyristor 1 T is triggered to turn it ON, by applying a suitable gate trigger pulse between the gate and cathode lead. The thyristor 1 T is forward biased during the positive half cycle of input ac supply. It can be triggered and made to conduct by applying a suitable gate trigger pulse only during the positive half cycle of input supply. When 1 T is triggered it conducts and the load current flows through the thyristor 1 T , the load and through the transformer secondary winding.





Disadvantages of single phase half wave ac voltage controller

The output load voltage has a DC component because the two halves of the output voltage waveform are not symmetrical with respect to '0' level. The input supply current waveform also has a DC component (average value) which can result in the problem of core saturation of the input supply transformer. The half wave ac voltage controller using a single thyristor and a single diode provides control on the thyristor only in one half cycle of the input supply. Hence ac power flow to the load can be controlled only in one half cycle. Half wave ac voltage controller gives limited range of RMS output voltage control. Because the RMS value of ac output voltage can be varied from a maximum of 100% of S V at a trigger angle 0 to a low of 70.7% of S V at Radians . These drawbacks of single phase half wave ac voltage controller can be over come by using a single phase full wave ac voltage controller.

Applications of rms Voltage Controller

- Speed control of induction motor (polyphase ac induction motor).
- Heater control circuits (industrial heating).
- Welding power control.
- Induction heating.
- On load transformer tap changing.
- Lighting control in ac circuits.
- Ac magnet controls

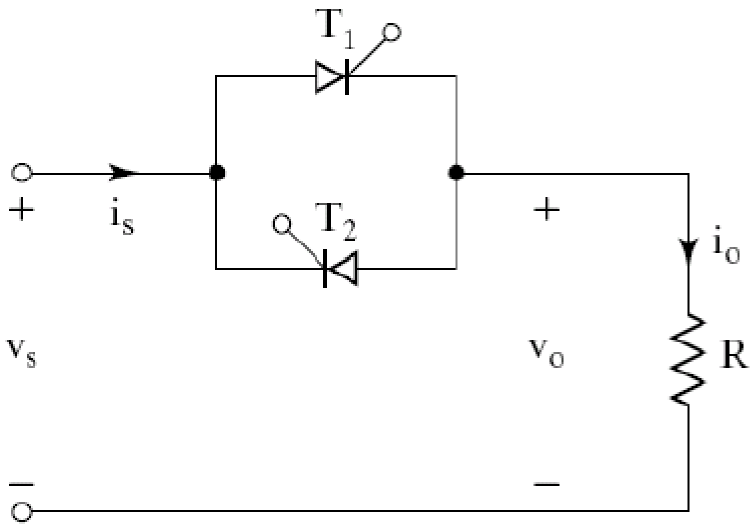
4.6 Single Phase Full Wave Ac Voltage Controller (Ac Regulator) or Rms Voltage Controller with Resistive Load

Single phase full wave ac voltage controller circuit using two SCRs or a single triac is generally used in most of the ac control applications. The ac power flow to the load can be controlled in both the half cycles by varying the trigger angle' '**.**The RMS value of load voltage can be varied by varying the trigger angle ' '**.** The input supply current is alternating i the case of a full wave ac voltage controller and due to the symmetrical nature of the input supply current waveform there is no dc component of input supply current i.e., the average value of the input supply current is zero.

A single phase full wave ac voltage controller with a resistive load is shown in the figure below. It is possible to control the ac power flow to the load in both the half cycles by adjusting the trigger angle' '. Hence the full wave ac voltage controller is also referred to as to a bi-directional controller.

The thyristor 1 T is forward biased during the positive half cycle of the input supply voltage. The thyristor 1 T is triggered at a delay angle of ' ' 0 radians . Considering the ON thyristor 1 T as an ideal closed switch the input supply voltage appears across the load resistor L R and the output voltage O S v v during t to radians. The load current flows through the ON thyristor 1 T and through the load resistor L R in the downward direction during the conduction time of 1 T from t to radians.

At t , when the input voltage falls to zero the thyristor current (which is flowing through the load resistor L R) falls to zero and hence 1 T naturally turns off . No current flows in the circuit during t to . The thyristor 2 T is forward biased during the negative cycle of input supply and

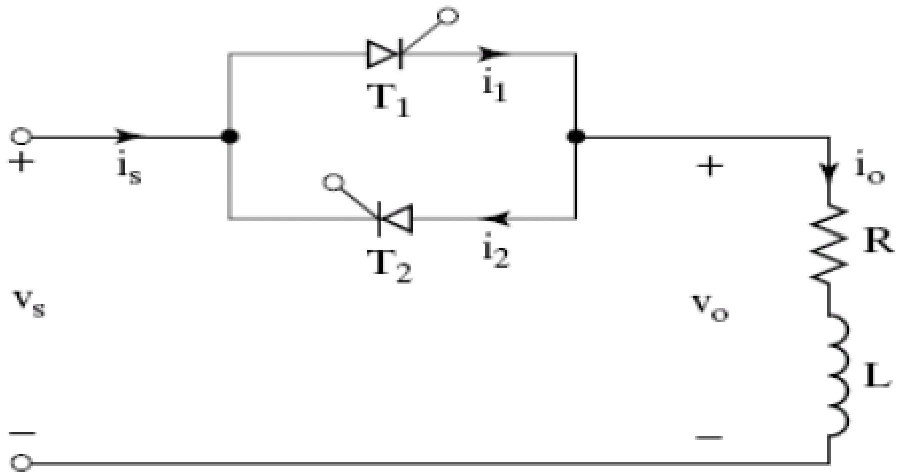


when thyristor 2 *T* is triggered at a delay angle , the output voltage follows the negative halfcycle of input from *t* to 2 . When 2 *T* is ON, the load current flows in the reverse direction (upward direction) through 2 *T* during *t* to 2 radians. The time interval (spacing) between the gate trigger pulses of 1 *T* and 2 *T* is kept at radians or 1800. At *t* 2 the input supply voltage falls to zero and hence the load current also falls to zero and thyristor 2 *T* turn off naturally.

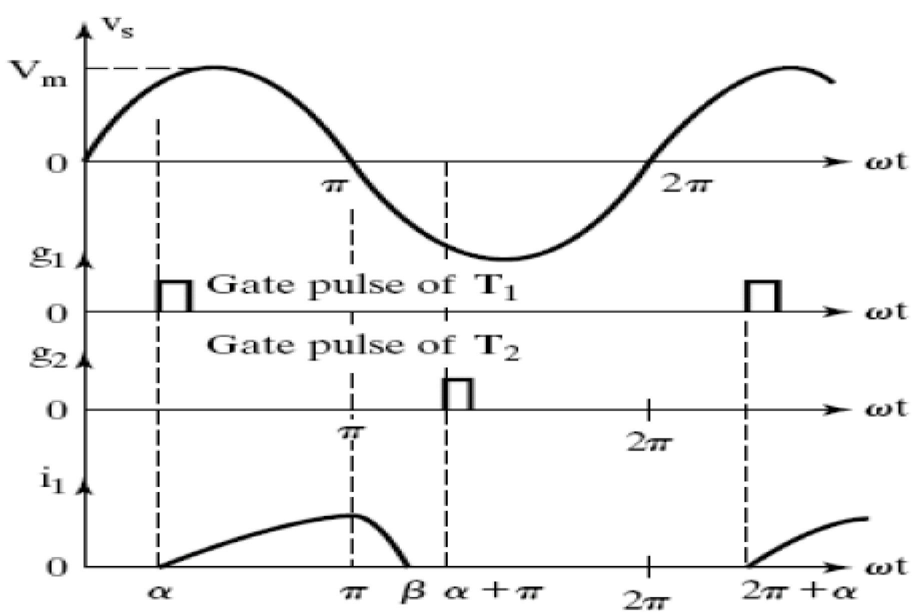
4.7 Single Phase Full Wave Ac Voltage Controller (Bidirectional Controller) With RL Load

In this section we will discuss the operation and performance of a single phase full wave ac voltage controller with RL load. In practice most of the loads are of RL type. For example if we consider a single phase full wave ac voltage controller controlling the speed of a single phase ac induction motor, the load which is the induction motor winding is an RL type of load, where R represents the motor winding resistance and L represents the motor winding inductance. A single phase full wave ac voltage controller circuit (bidirectional controller) with an RL load using two thyristors 1 *T* and 2 *T* (1 *T* and 2 *T* are two SCRs) connected in parallel is shown in the figure below. In place of two thyristors a single Triac can be used to implement a full wave ac controller, if a suitable Traic is available for the desired RMS load current and the RMS output voltage ratings.

The thyristor 1 *T* is forward biased during the positive half cycle of input supply. Let us assume that 1 *T* is triggered at *t* , by applying a suitable gate trigger pulse to 1 *T* during the positive half cycle of input supply. The output voltage across the load follows the input supply voltage when 1 *T* is ON. The load current *O i* flows through the thyristor 1 *T* and through the load in the downward direction. This load current pulse flowing through 1 *T* can be considered as the positive current pulse. Due to the inductance in the load, the load current *O I* flowing through 1 *T* would not fall to zero at *t* , when the input supply voltage starts to become negative.



The thyristor 1 *T* will continue to conduct the load current until all the inductive energy stored in the load inductor L is completely utilized and the load current through 1 *T* falls to zero at *t* , where is referred to as the Extinction angle, (the value of *t*) at which the load current falls to zero. The extinction angle is measured from the point of the beginning of the positive half cycle of input supply to the point where the load current falls to zero. The thyristor 1 *T* conducts from *t* to . The conduction angle of 1 *T* is , which depends on the delay angle and the load impedance angle . The waveforms of the input supply voltage, the gate trigger pulses of 1 *T* and 2 *T* , the thyristor current, the load current and the load voltage waveforms appear as shown in the figure below



Note

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

For very large load inductance 'L' the SCR may fail to commutate, after it is triggered and the load voltage will be a full sine wave (similar to the applied input supply voltage and the output control will be lost) as long as the gating signals are applied to the thyristors 1 T and 2 T . The load current waveform will appear as a full continuous sine wave and the load current waveform lags behind the output sine wave by the load power factor angle.

4.8 Recommended questions

1. Discuss the operation of a single phase controller supplying a resistive load, and controlled by the on-off method of control. Also highlight the advantages and disadvantages of such a control. Draw the relevant waveforms.

2. What phase angle control is as applied to single phase controllers? Highlight the advantages and disadvantages of such a method of control. Draw all the wave forms.

3. What are the effects of load inductance on the performance of voltage controllers?

4. Explain the meaning of extinction angle as applied to single phase controllers supplying inductive load with the help of waveforms.

5. What are unidirectional controllers? Explain the operation of the same with the help of waveforms and obtain the expression for the RMS value of the output voltage. What are the advantage and disadvantages of unidirectional controllers?

6. What are bi-directional controllers explain the operation of the same with the help of waveforms and obtain the expression for the R<S value of the output voltage. RMS value of thyristor current. What are the advantages of bi-directional controllers?

7. The AC Voltage controller shown below is used for heating a resistive load of 5 Ω and the input voltage Vs = 120 V (rms). The thyristor switch is on for n=125 cycles and is off for m = 75 cycles. Determine the RMS output voltage Vo, the input factor and the average and RMS thyristor current

4.9 Generic Skills / Outcomes

- Discuss the principle of operation of single phase and three phase AC voltage controllers.

4.10 Further Reading

1. **"Thyristorized Power Controllers" -** G. K. Dubey S. R. Doradla, A. Joshi and Rmk Sinha New age international (P) ltd reprint 1999.

2. **"Power Electronics" -** Cynil W. Lander 3rd edition, MGH 2003.