

AC VOLTAGE CONTROLLERS

6.1 AC voltage controllers

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

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).

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 ' α ' (delay angle), the output RMS voltage across the load can be controlled.

6.2 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.

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).

6.3 Applications of AC Voltage Controllers

The ac voltage controllers can be found in the following applications;

- 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).

6.4 Single Phase Full Wave Ac 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 ' α '.

The RMS value of load voltage can be varied by varying the trigger angle ' α '. The input supply current is alternating in 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 ' α '. Hence the full wave ac voltage controller is also referred to as to a bi-directional controller.

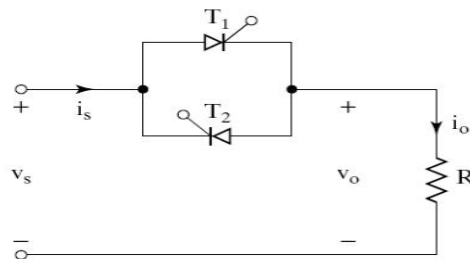


Fig.6.1: Single phase full wave ac voltage controller (Bi-directional Controller) using SCRs

Instead of using two SCR's in parallel, a Triac can be used for full wave ac voltage control.

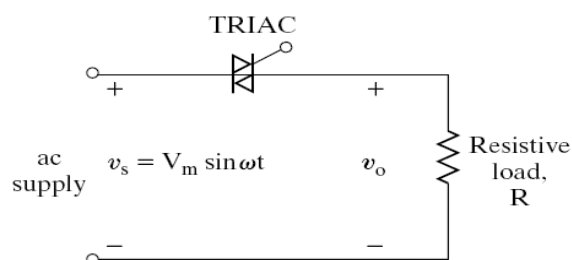


Fig.6.2: Single phase full wave ac voltage controller (Bi-directional Controller) using TRIAC

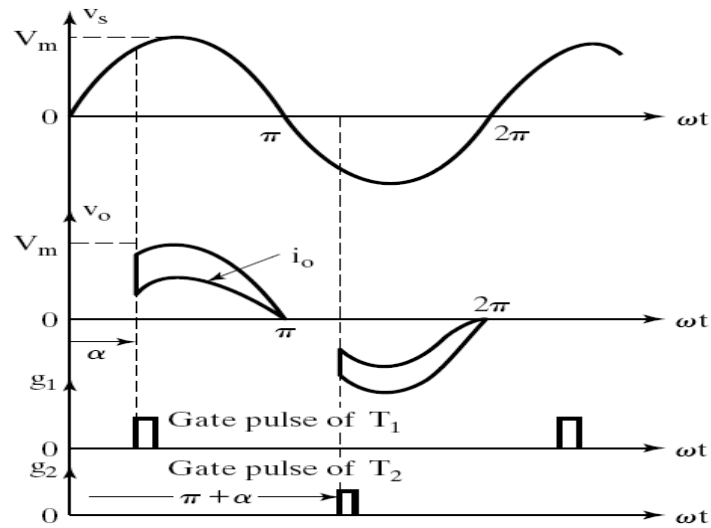


Fig.6.2: Waveforms of single phase full wave ac voltage controller

Input supply voltage

$$v_s = V_m \sin \omega t = \sqrt{2} V_s \sin \omega t ;$$

Output voltage across the load resistor R_L ;

$$v_o = v_L = V_m \sin \omega t ;$$

$$\text{for } \omega t = \alpha \text{ to } \pi \text{ and } \omega t = (\pi + \alpha) \text{ to } 2\pi$$

Output load current

$$i_o = \frac{v_o}{R_L} = \frac{V_m \sin \omega t}{R_L} = I_m \sin \omega t ;$$

$$\text{for } \omega t = \alpha \text{ to } \pi \text{ and } \omega t = (\pi + \alpha) \text{ to } 2\pi$$

The RMS value of output voltage (load voltage) can be found using the expression

$$V_{O(RMS)}^2 = V_{L(RMS)}^2 = \frac{1}{2\pi} \int_0^{2\pi} v_L^2 d(\omega t) ;$$

For a full wave ac voltage controller,

$$V_{L(RMS)}^2 = \frac{1}{\pi} \int_0^{\pi} V_m^2 \sin^2 \omega t . d\omega t$$

$$V_{L(RMS)}^2 = \frac{1}{2\pi} \int_0^{2\pi} v_L^2 . d(\omega t) ;$$

$$v_L = v_o = V_m \sin \omega t ; \text{ For } \omega t = \alpha \text{ to } \pi \text{ and } \omega t = (\pi + \alpha) \text{ to } 2\pi$$

Hence,

$$\begin{aligned}
V_{L(RMS)}^2 &= \frac{1}{2\pi} \left[\int_{\alpha}^{\pi} (V_m \sin \omega t)^2 d(\omega t) + \int_{\pi+\alpha}^{2\pi} (V_m \sin \omega t)^2 d(\omega t) \right] \\
&= \frac{1}{2\pi} \left[V_m^2 \int_{\alpha}^{\pi} \sin^2 \omega t d(\omega t) + V_m^2 \int_{\pi+\alpha}^{2\pi} \sin^2 \omega t d(\omega t) \right] \\
&= \frac{V_m^2}{2\pi} \left[\int_{\alpha}^{\pi} \frac{1 - \cos 2\omega t}{2} d(\omega t) + \int_{\pi+\alpha}^{2\pi} \frac{1 - \cos 2\omega t}{2} d(\omega t) \right] \\
&= \frac{V_m^2}{4\pi} \left[2(\pi - \alpha) + \frac{\sin 2\alpha}{2} + \frac{\sin(2\pi + 2\alpha)}{2} \right] \\
&= \frac{V_m^2}{4\pi} \left[2(\pi - \alpha) + \frac{\sin 2\alpha}{2} + \frac{1}{2} (\sin 2\pi \cdot \cos 2\alpha + \cos 2\pi \cdot \sin 2\alpha) \right] \\
&\quad \sin 2\pi = 0 \quad \& \quad \cos 2\pi = 1
\end{aligned}$$

Therefore;

$$\begin{aligned}
V_{L(RMS)}^2 &= \frac{V_m^2}{4\pi} \left[2(\pi - \alpha) + \frac{\sin 2\alpha}{2} + \frac{\sin 2\alpha}{2} \right] \\
V_{L(RMS)}^2 &= \frac{V_m^2}{4\pi} [(2\pi - 2\alpha) + \sin 2\alpha]
\end{aligned}$$

hence;

$$V_{L(RMS)} = \frac{V_m}{2\sqrt{\pi}} \sqrt{[(2\pi - 2\alpha) + \sin 2\alpha]}$$

$$V_{L(RMS)} = V_s \sqrt{\frac{1}{\pi} \left[(\pi - \alpha) + \frac{\sin 2\alpha}{2} \right]} \quad (6.1)$$

Maximum RMS voltage will be applied to the load when $\alpha = 0$, in that case the full sine wave appears across the load. RMS load voltage will be the same as the RMS supply voltage $= \frac{V_m}{\sqrt{2}}$. When α is increased the RMS load voltage decreases.

$$\begin{aligned}
V_{L(RMS)} \Big|_{\alpha=0} &= \frac{V_m}{\sqrt{2}} \sqrt{\frac{1}{\pi} \left[(\pi - 0) + \frac{\sin 2 \times 0}{2} \right]} \\
V_{L(RMS)} \Big|_{\alpha=0} &= \frac{V_m}{\sqrt{2}} = V_{i(RMS)} = V_s \quad (6.2)
\end{aligned}$$

6.5. Single Phase Full Wave Ac Voltage 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 T_1 and T_2 (T_1 and T_2 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 Triac is available for the desired RMS load current and the RMS output voltage ratings.

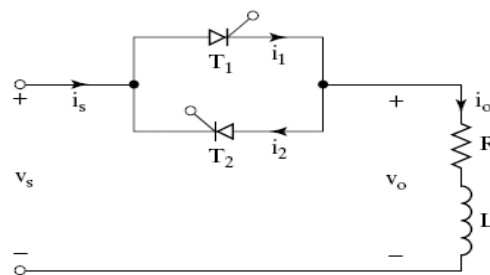


Fig.6.3: Single phase full wave ac voltage controller with RL load

The thyristor T_1 is forward biased during the positive half cycle of input supply. Let us assume that T_1 is triggered at $\omega t = \alpha$, by applying a suitable gate trigger pulse to T_1 during the positive half cycle of input supply. The output voltage across the load follows the input supply voltage when T_1 is ON. The load current i_o flows through the thyristor T_1 and through the load in the downward direction.

This load current pulse flowing through T_1 can be considered as the positive current pulse. Due to the inductance in the load, the load current i_o flowing through T_1 would not fall to zero at $\omega t = \pi$, when the input supply voltage starts to become negative.

The thyristor T_1 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 T_1 falls to zero at $\omega t = \beta$, where β is referred to as the Extinction angle, (the value of ωt) at which the load current falls to zero. The extinction angle β 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 T_1 conducts from $\omega t = \alpha$ to β . The conduction angle of T_1 is $\delta = (\beta - \alpha)$, which depends on the delay angle α and the load impedance angle ϕ . The waveforms of the input supply voltage, the gate trigger pulses of T_1 and T_2 , the thyristor current, the load current and the load voltage waveforms appear as shown in the figure below.

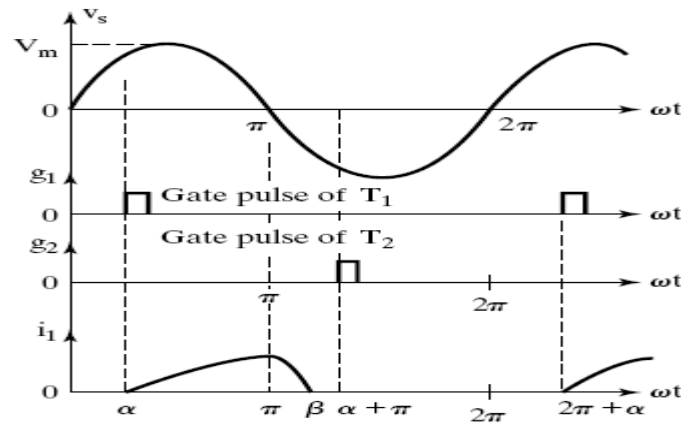


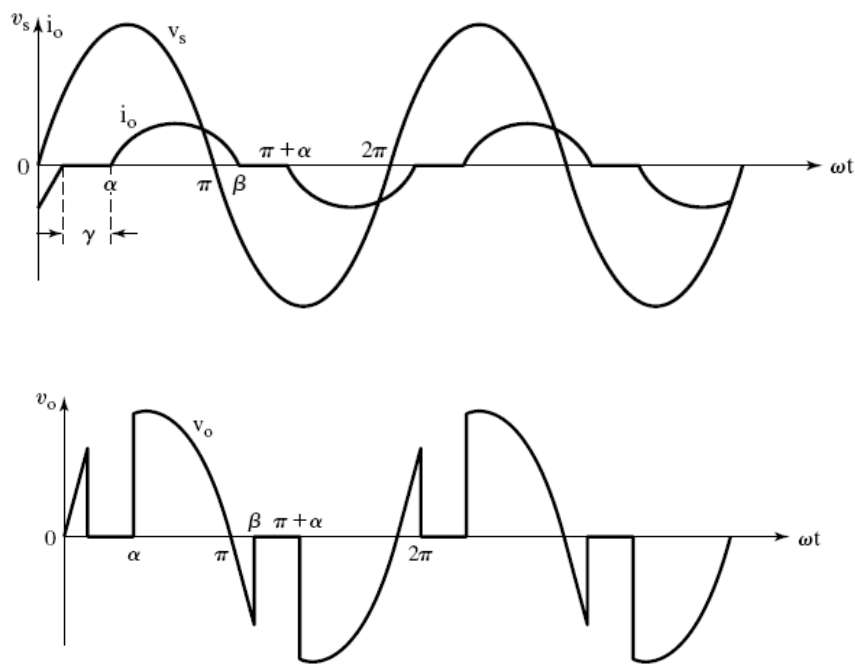
Fig.6.4: Input supply voltage & Thyristor current waveforms

β is the extinction angle which depends upon the load inductance value.

Waveforms of single phase full wave ac voltage controller with RL load for $\alpha > \phi$.

Discontinuous load current operation occurs for $\alpha > \phi$ and $\beta < (\pi + \alpha)$;

i.e., $(\beta - \alpha) < \pi$, conduction angle $< \pi$.



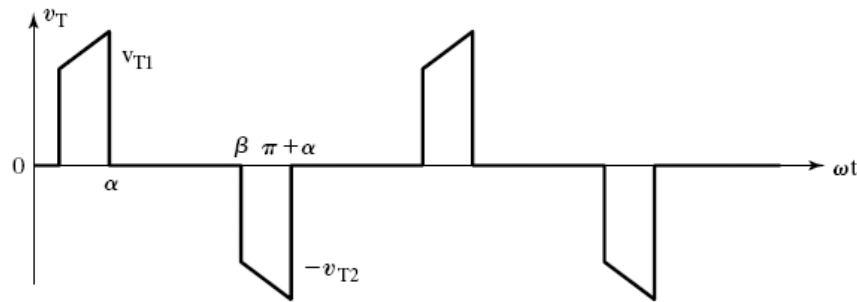


Fig.6.5: Waveforms of Input supply voltage, Load Current, Load Voltage and Thyristor Voltage across T_1

Note

- The RMS value of the output voltage and the load current may be varied by varying the trigger angle α .
- 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 commute, 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 T_1 and T_2 . 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 ϕ .

6.6 Output current of an RL load

During $\omega t = \alpha$ to β when thyristor T_1 conducts and considering sinusoidal input supply voltage we can write the expression for the supply voltage as

$$v_s = V_m \sin \omega t = \text{instantaneous value of the input supply voltage.}$$

Let us assume that the thyristor T_1 is triggered by applying the gating signal to T_1 at $\omega t = \alpha$. The load current which flows through the thyristor T_1 during $\omega t = \alpha$ to β can be found from the equation

$$L \left(\frac{di_o}{dt} \right) + Ri_o = V_m \sin \omega t ;$$

The solution of the above differential equation gives the general expression for the output load current which is of the form

$$i_o = \frac{V_m}{Z} \sin(\omega t - \phi) + A_1 e^{\frac{-t}{\tau}} ;$$

Where $V_m = \sqrt{2}V_s$ = maximum or peak value of input supply voltage.

$$Z = \sqrt{R^2 + (\omega L)^2} = \text{Load impedance.}$$

$$\phi = \tan^{-1} \left(\frac{\omega L}{R} \right) = \text{Load impedance angle (power factor angle of load).}$$

$$\tau = \frac{L}{R} = \text{Load circuit time constant.}$$

Therefore the general expression for the output load current is given by the equation

$$i_o = \frac{V_m}{Z} \sin(\omega t - \phi) + A_1 e^{\frac{-R}{L} t} ; \quad (6.3)$$

The value of the constant A_1 can be determined from the initial condition. i.e. initial value of load current $i_o = 0$, at $\omega t = \alpha$. Hence from the equation for i_o equating i_o to zero and substituting $\omega t = \alpha$,

we get

$$i_o = 0 = \frac{V_m}{Z} \sin(\alpha - \phi) + A_1 e^{\frac{-R}{L} t}$$

Therefore

$$A_1 e^{\frac{-R}{L} t} = \frac{-V_m}{Z} \sin(\alpha - \phi)$$

$$A_1 = \frac{1}{e^{\frac{-R}{L} t}} \left[\frac{-V_m}{Z} \sin(\alpha - \phi) \right]$$

$$A_1 = e^{\frac{+R}{L} t} \left[\frac{-V_m}{Z} \sin(\alpha - \phi) \right]$$

$$A_1 = e^{\frac{R(\omega t)}{\omega L}} \left[\frac{-V_m}{Z} \sin(\alpha - \phi) \right]$$

By substituting $\omega t = \alpha$, we get the value of constant A_1 as

$$A_1 = e^{\frac{R(\alpha)}{\omega L}} \left[\frac{-V_m}{Z} \sin(\alpha - \phi) \right]$$

Substituting the value of constant A_1 from the equation (6.3) into the expression for i_o , we obtain

$$i_o = \frac{V_m}{Z} \sin(\omega t - \phi) + e^{\frac{-R}{L}t} e^{\frac{R(\alpha)}{\omega L}} \left[\frac{-V_m}{Z} \sin(\alpha - \phi) \right] ;$$

$$i_o = \frac{V_m}{Z} \sin(\omega t - \phi) + e^{\frac{-R}{\omega L}(\omega t - \alpha)} \left[\frac{-V_m}{Z} \sin(\alpha - \phi) \right]$$

Therefore we obtain the final expression for the inductive load current of a single phase full wave ac voltage controller with RL load as

$$i_o = \frac{V_m}{Z} \left[\sin(\omega t - \phi) - \sin(\alpha - \phi) e^{\frac{-R}{\omega L}(\omega t - \alpha)} \right] ; \quad \text{Where } \alpha \leq \omega t \leq \beta . \quad (6.4)$$

The above expression also represents the thyristor current i_{T1} , during the conduction time interval of thyristor T_1 from $\omega t = \alpha$ to β .

To Calculate Extinction Angle β

The extinction angle β , which is the value of ωt at which the load current i_o falls to zero and T_1 is turned off can be estimated by using the condition that $i_o = 0$, at $\omega t = \beta$. By using the above expression for the output load current, we can write;

$$i_o = 0 = \frac{V_m}{Z} \left[\sin(\beta - \phi) - \sin(\alpha - \phi) e^{\frac{-R}{\omega L}(\beta - \alpha)} \right]$$

As $\frac{V_m}{Z} \neq 0$ we can write $\left[\sin(\beta - \phi) - \sin(\alpha - \phi) e^{\frac{-R}{\omega L}(\beta - \alpha)} \right] = 0$

Therefore; we obtain the expression; $\sin(\beta - \phi) = \sin(\alpha - \phi) e^{\frac{-R}{\omega L}(\beta - \alpha)}$

The extinction angle β can be determined from this transcendental equation by using the iterative method of solution (trial and error method). After β is calculated, we can determine the thyristor conduction angle $\delta = (\beta - \alpha)$. β is the extinction angle which depends upon the load inductance value. Conduction angle δ increases as α is decreased for a known value of β .

For $\delta < \pi$ radians, i.e., for $(\beta - \alpha) < \pi$ radians, for $(\pi + \alpha) > \beta$ the load current waveform appears as a discontinuous current waveform as shown in the figure. The output load current remains at zero during $\omega t = \beta$ to $(\pi + \alpha)$. This is referred to as discontinuous load current operation which occurs for $\beta < (\pi + \alpha)$

When the trigger angle α is decreased and made equal to the load impedance angle ϕ i.e., when $\alpha = \phi$ we obtain from the expression for $\sin(\beta - \phi)$,

$$\sin(\beta - \phi) = 0 ; \text{ Therefore } (\beta - \phi) = \pi \text{ radians.}$$

Extinction angle $\beta = (\pi + \phi) = (\pi + \alpha)$; for the case when $\alpha = \phi$

Conduction angle $\delta = (\beta - \alpha) = \pi \text{ radians} = 180^\circ$; for the case when $\alpha = \phi$

Each thyristor conducts for 180° (π radians) . T_1 conducts from $\omega t = \phi$ to $(\pi + \phi)$ and provides a positive load current. T_2 conducts from $(\pi + \phi)$ to $(2\pi + \phi)$ and provides a negative load current. Hence we obtain a continuous load current and the output voltage waveform appears as a continuous sine wave identical to the input supply voltage waveform for trigger angle $\alpha \leq \phi$ and the control on the output is lost.

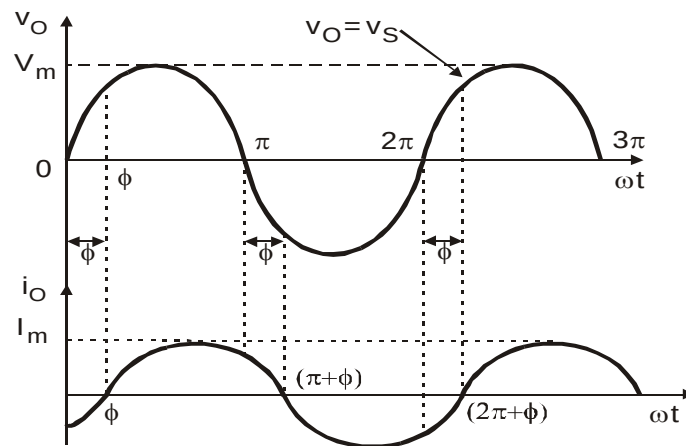


Fig.6.6: Output voltage and output current waveforms for a single phase full wave ac voltage controller with RL load for $\alpha \leq \phi$

Thus we observe that for trigger angle $\alpha \leq \phi$, the load current tends to flow continuously and we have continuous load current operation, without any break in the load current waveform and we obtain output voltage waveform which is a continuous sinusoidal waveform identical to the input supply voltage waveform. We loose the control on the output voltage for $\alpha \leq \phi$ as the output voltage becomes equal to the input supply voltage and thus we obtain

$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}} = V_s ; \text{ for } \alpha \leq \phi$$

Hence,

$$\text{RMS output voltage} = \text{RMS input supply voltage for } \alpha \leq \phi$$

6.7 Output Voltage of an RL load

The expression of $V_{O(RMS)}$ output voltage of the AC voltage controller with RL load is;

$$V_{O(RMS)} = \left[\frac{1}{\pi} \int_{\alpha}^{\beta} V_m^2 \sin^2 \omega t \cdot d(\omega t) \right]^{\frac{1}{2}} \quad (6.5)$$

Output $v_o = V_m \sin \omega t$, for $\omega t = \alpha$ to β , when T_1 is ON.

$$\begin{aligned} V_{O(RMS)} &= \left[\frac{V_m^2}{\pi} \int_{\alpha}^{\beta} \frac{(1 - \cos 2\omega t)}{2} d(\omega t) \right]^{\frac{1}{2}} \\ V_{O(RMS)} &= \left[\frac{V_m^2}{2\pi} \left\{ (\omega t) \Big|_{\alpha}^{\beta} - \left(\frac{\sin 2\omega t}{2} \right) \Big|_{\alpha}^{\beta} \right\} \right]^{\frac{1}{2}} \\ V_{O(RMS)} &= \frac{V_m}{\sqrt{2}} \left[\frac{1}{\pi} \left\{ (\beta - \alpha) + \frac{\sin 2\alpha}{2} - \frac{\sin 2\beta}{2} \right\} \right]^{\frac{1}{2}} \end{aligned} \quad (6.6)$$

The RMS output voltage across the load can be varied by changing the trigger angle α .

For a purely resistive load $L = 0$, therefore load power factor angle $\phi = 0$.

$$\phi = \tan^{-1} \left(\frac{\omega L}{R} \right) = 0 \quad ; \text{Extinction angle} \quad \beta = \pi \text{ radians} = 180^\circ$$