Power Electronics II

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Chapter 1
(Part 1)

Single phase AC voltage controllers

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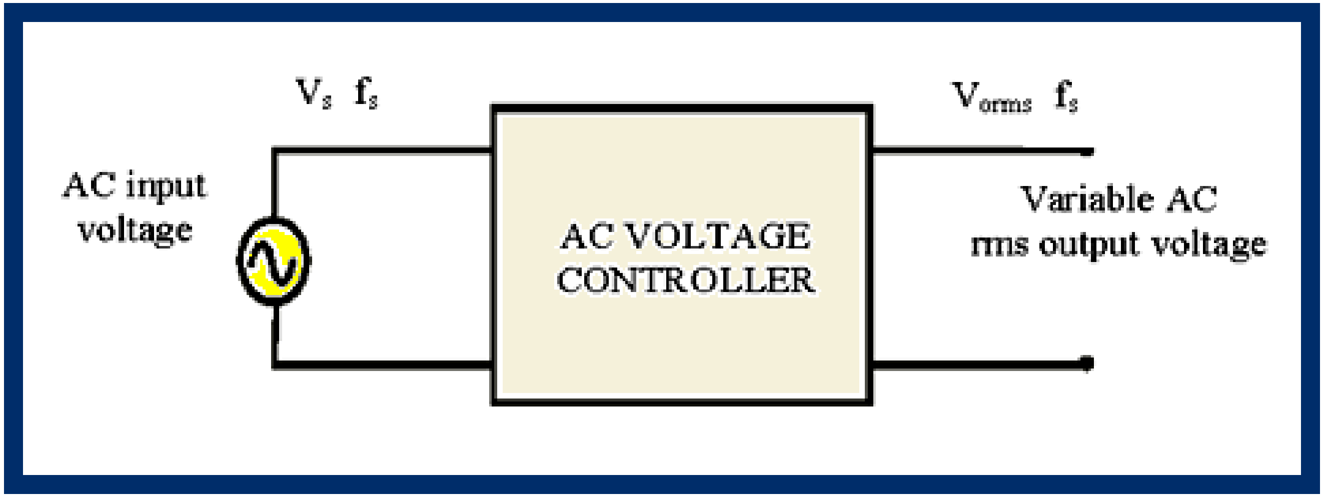
Introduction



- AC voltage controllers are used to control the RMS value of the AC voltage applied to the load circuit at the same frequency.
- AC voltage controller is a type of thyristor power electronics converter which is used to convert a fixed voltage, fixed frequency AC input supply to a variable voltage AC output with fixed frequency.

Types of Thyrsitor control techniques

1- **On-off (integral-cycle) control technique**

The 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 a few input cycles.

2- **Phase angle control technique**

The thyristors are used as switches to connect the load circuit to the input AC supply, for a part of each input half cycle and then is turned off during the remaining part, by controlling the phase (triggering) angle.

Applications of AC Voltage Controllers

(1) Light-dimmer circuits.

(2) Induction heating.

(3) Industrial & household heating.

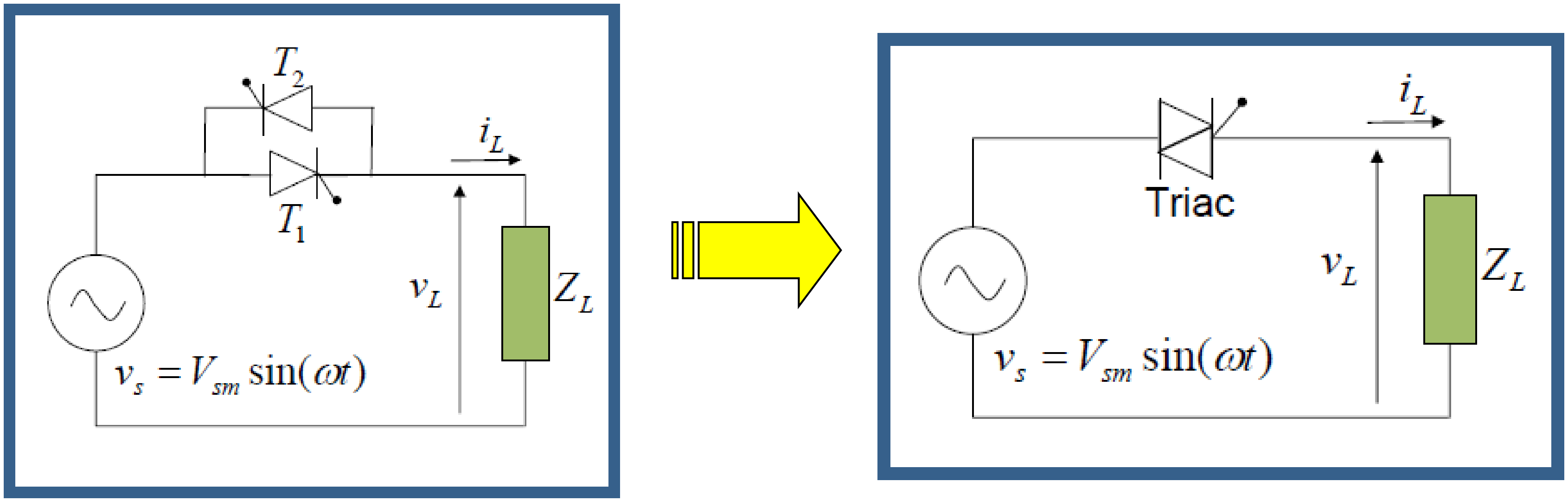
(4) On load Transformer tap changing.

(5) Speed control of induction motors (single-phase and poly-phase).

ON-OFF
Control Technique

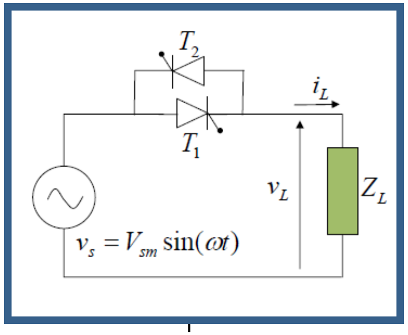
ON-OFF Control Technique

- The basic principle of ON-OFF (Integral-Cycle) control technique is explained with reference to a single-phase full-wave AC voltage controller circuit



- The thyristor switches (T_1 and T_2) 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 (t_{on}).
- The thyristor switches (T_1 and T_2) are turned off by blocking the gate trigger pulses for 'm' number of input cycles during the time interval (t_{off}).

Waveforms of the ON-OFF control technique



- Thyristors are turned ON at the voltage zero crossings of the input supply.

- Thyristors are turned ON during (t_{on}) for two input cycles.
  n = two input cycles

- Thyristors are turned OFF during (t_{off}) for one input cycle.
  m = one input cycle

- The thyristor (T_1) is turned on at the beginning of each positive half cycle by applying the gate triggering pulses during the ON time (t_{on}).

- The thyristor (T_2) is turned on at the beginning of each negative half cycle, by applying triggering pulse to the gate of (T_2), during (t_{on}).

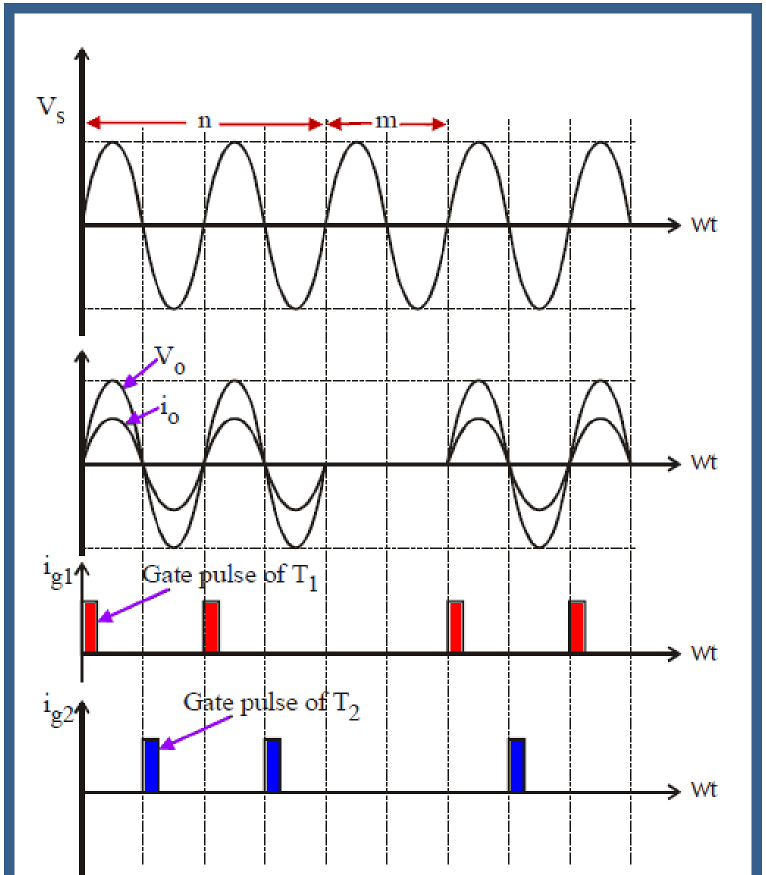
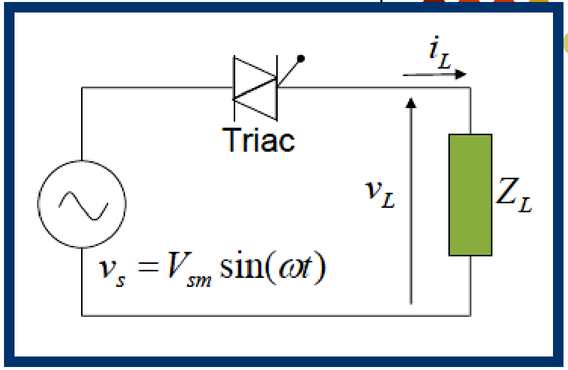


Fig.: Waveforms

ON-OFF control analysis



For a sine wave input supply voltage,

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

V_S =RMS value of input ac supply $= \frac{V_m}{\sqrt{2}}$ = RMS phase supply voltage.

If the input ac supply is connected to load for 'n' number of input cycles and disconnected for 'm' number of input cycles, then

$$t_{ON} = n \times T$$

$$t_{OFF} = m \times T$$

Where $T = \frac{1}{f}$ = input cycle time (time period)

f = input supply frequency

t_{ON} = controller on time

t_{OFF} = controller off time

T_O = Output time period

$$T_O = (t_{ON} + t_{OFF}) = (nT + mT)$$

RMS values of output (load) quantities

The rms value of the load voltage

$$V_o = \left[\frac{n}{2\pi(n+m)} \int_0^{2\pi} V_m^2 \sin^2 \omega t . d(\omega t) \right]^{0.5}$$

$$\text{Output RMS voltage } V_{O(RMS)} = V_{i(RMS)} \sqrt{\frac{t_{ON}}{T_O}} = V_S \sqrt{\frac{t_{ON}}{T_O}}$$

Where $V_{i(RMS)}$ is the RMS input supply voltage = V_S

$$\frac{t_{ON}}{T_O} = \frac{t_{ON}}{t_{ON} + t_{OFF}} = \frac{nT}{nT + mT} = \frac{n}{(n+m)} = \text{duty cycle}$$

$$V_{O(RMS)} = V_S \sqrt{\frac{n}{(m+n)}} = V_S \sqrt{k}$$

The rms value of the load current

$$I_o = \frac{V_o}{Z_L}$$

(For a resistive load $Z_L = R_L$

$$I_O = \frac{V_O}{R_L}$$

The rms value of the load power

$V_O = V_S \sqrt{k}$

$$P_o = I_o^2 \times R_L = \frac{V_O^2}{R_L} = \frac{K \times V_s^2}{R_L}$$

Input power factor

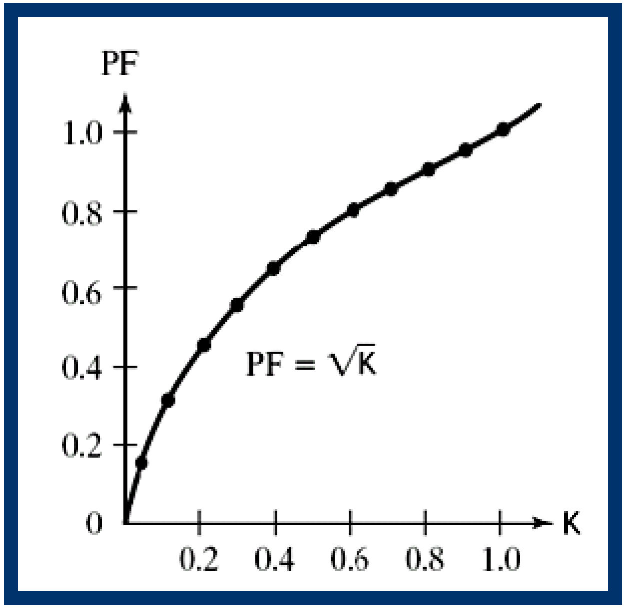
$$PF = \frac{P_O}{VA} = \frac{\text{output load power}}{\text{input supply volt amperes}} = \frac{P_O}{V_S I_S}$$

$V_O = V_S\sqrt{k}$

The input supply current is same as the load current $I_{in} = I_O = I_L$

$$PF = V_o/V_s = \sqrt{K}$$

The rms output voltage and PF vary with $\sqrt{K}$



It can be seen that the PF is poor at the low values of K.

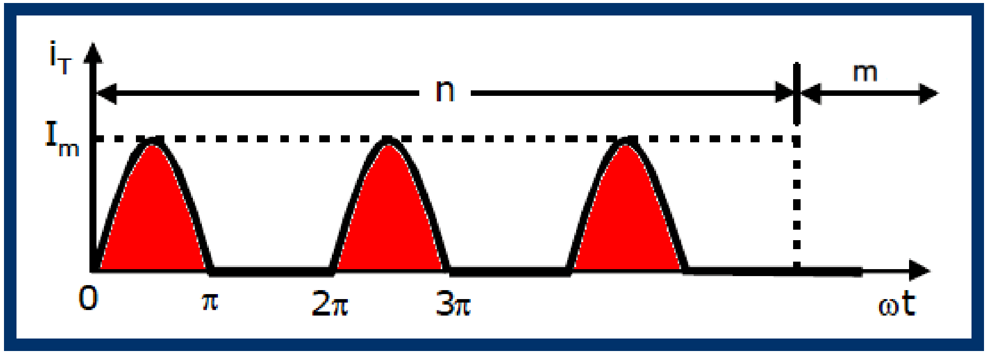
The values of thyristor currents

The average value of thyristor current

Consider the waveform of the thyristor current

$$I_{T(av)} = \frac{n}{2\pi(m+n)} \int_0^{\pi} I_m \sin \omega t \, d(\omega t)$$

$$I_{T(av)} = \frac{K I_m}{\pi}$$



$$\text{where } I_m = \frac{V_m}{R_L} \quad \text{(maximum thyristor current)}$$

The rms value of thyristor current

$$I_{T(rms)} = \left[\frac{n}{2\pi(n+m)} \int_0^{\pi} I_m^2 \sin^2 \omega t \, . d(\omega t) \right]^{0.5} \Rightarrow I_{T(rms)} = \frac{I_m}{2} \sqrt{K}$$

Ex .1: A single-phase full-wave AC voltage controller, is operating using ON/OFF control technique, has a supply voltage of 230V (rms), 50Hz, and a load resistance of 50Ω. The controller is on for 30 cycles and off for 40 cycles.

Calculate:

(1) the on and off time intervals, (2) the rms output voltage.

(3) the input PF. (4) the average and rms thyristor currents.

Solution

$V_s = 230\ V \qquad f_s = 50Hz \qquad R_L = 50\Omega \qquad n = 30 \qquad m = 40$

$V_m = \sqrt{2}(230) = 325.3\ V \qquad T_s = \frac{1}{f_s} = \frac{1}{50} = 0.02sec = 20\ ms$

1. $t_{on} = n \times T_s = 30 \times 20\,ms = 600\,ms = \boxed{0.6sec}$

$t_{off} = m \times T_s = 40 \times 20\,ms = 800ms = \boxed{0.8sec}$

2. Duty cycle (K) $= \frac{n}{n+m} = \frac{30}{30+40} = 0.4286$

The rms output voltage $V_o = V_s\sqrt{K} = 230 \times \sqrt{0.4285} = \boxed{150.58\ V}$

3. $I_o = \frac{V_o}{R_L} = \frac{150.58}{50} = 3.012\ A$

$P_o = I_o^2 \times R_L = 3.012^2 \times 50 = 453.49\ W$

$VA = V_s I_o = 230 \times 3.012 = 692.76$

$PF = \frac{P_o}{V_S I_S} = \frac{453.49}{692.76} = 0.655$ or, $PF = \sqrt{K} = \sqrt{0.4285} = \boxed{0.655}$

4. $I_m = V_m / R_L = 325.3 / 50 = 6.506\ A$

The average thyristor current

$$I_{T(av)} = \frac{KI_m}{\pi} = \frac{0.4285 \times 6.505}{\pi} = \boxed{0.9\ A}$$

The rms thyristor current

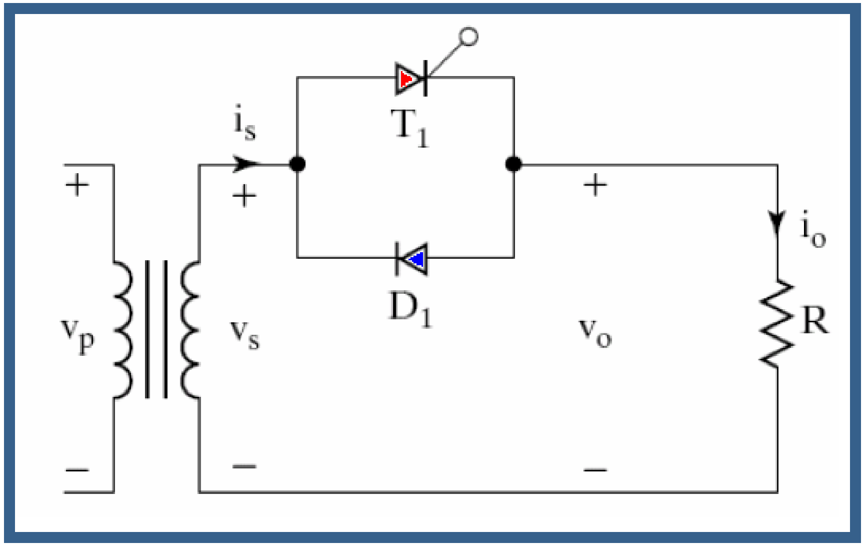
$$I_{T(rms)} = \frac{I_m}{2}\sqrt{K} = \frac{6.505 \times \sqrt{0.4285}}{2} = \boxed{2.13\ A}$$

Phase-Angle Control Technique

Types of AC Voltage Controllers

1) Single-phase half-wave (unidirectional) AC voltage controller.
2) Single-phase full-wave (bidirectional) AC voltage controller.
3) Three-phase half-wave (unidirectional) AC voltage controller.
4) Three-phase full-wave (bidirectional) AC voltage controller.

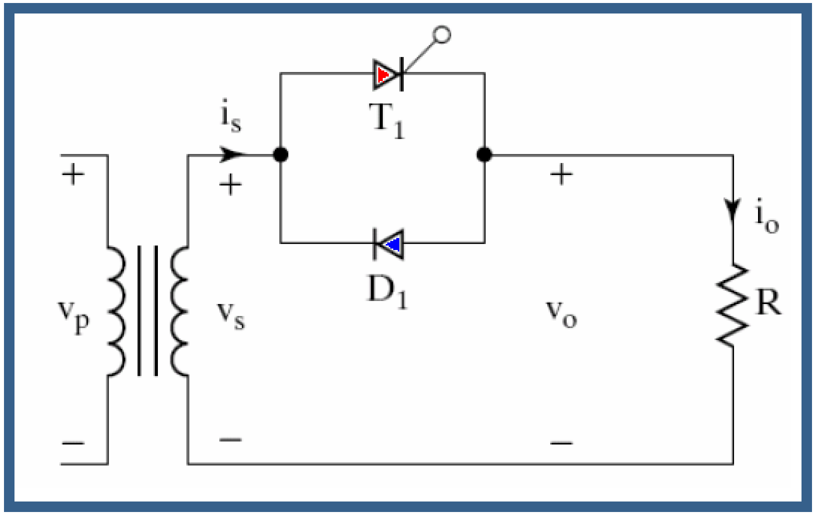
Principle of AC Phase Control



- The basic principle of ac phase control technique is explained with reference to a single phase half wave ac voltage controller (unidirectional controller).
- The aim is to get a variable rms load voltage, with the same supply frequency.
- The half-wave AC controller uses one thyristor and one diode which is connected anti-parallel across the thyristor.

Single-phase half-wave AC voltage controllers

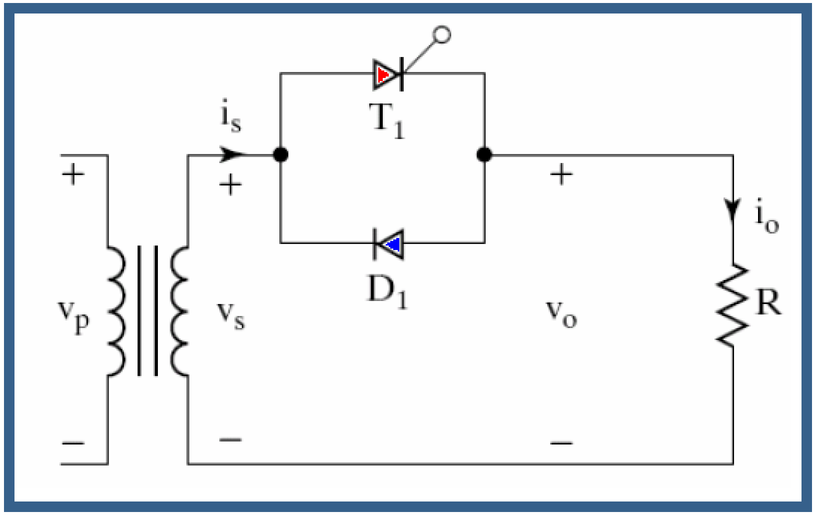
Single-phase half-wave AC voltage controllers

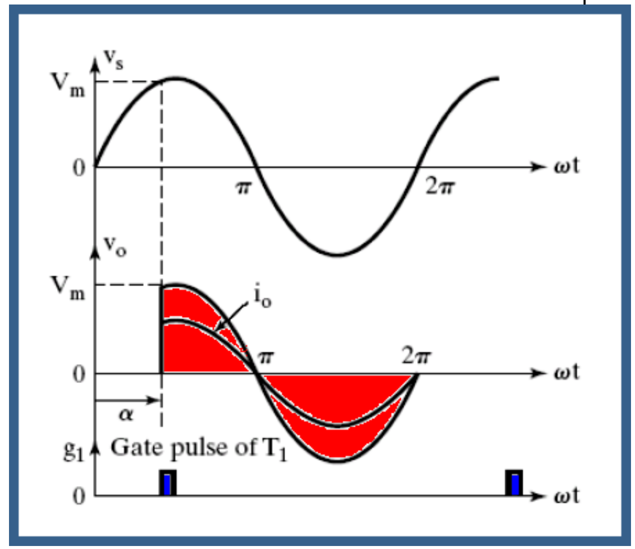


Unidirectional Control

- The output voltage and the output power flow to the load is controlled by varying the triggering angle (α).
- The thyristor (T_1) is forward biased during the positive half cycle of the AC supply. it can be triggered and conduct by applying a suitable gate triggering pulse only during the positive half cycle of the AC supply.

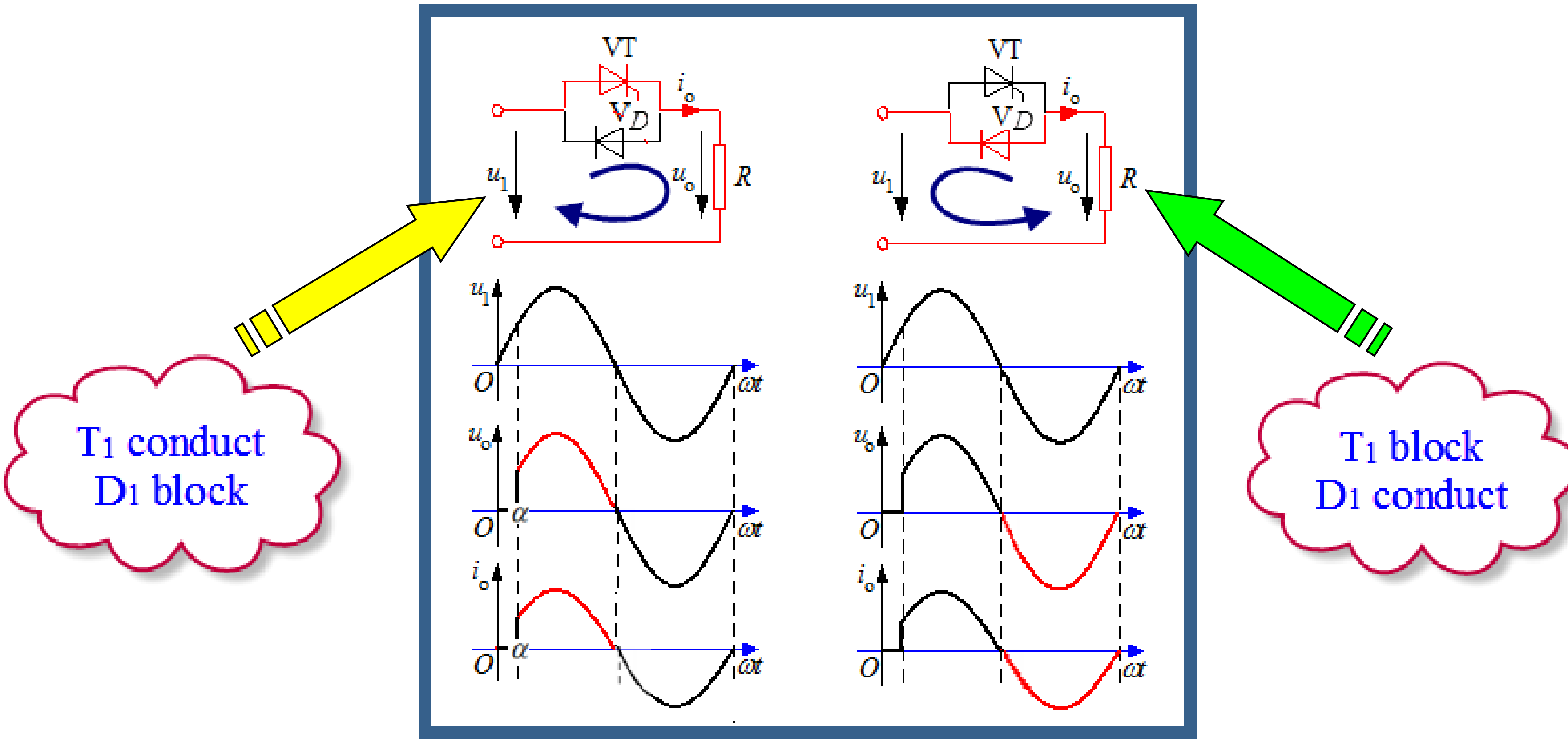
Single-phase half-wave AC voltage controllers





- When the thyristor (T_1) is turned-on, the supply voltage appears across the load from $\omega t = \alpha$ to $\omega t = \pi$.
- The diode (D_1) becomes forward biased and hence turns ON when the supply voltage and also the load current decreases to zero at $\omega t = \pi$.
- The load current flows in the opposite direction during $\omega t = \pi$ to 2π and the negative half cycle of supply voltage appears across the load.

Single-phase half-wave AC voltage controllers



Analysis of single-phase half-wave AC voltage controller

Input AC Supply Voltage across the Transformer Secondary Winding

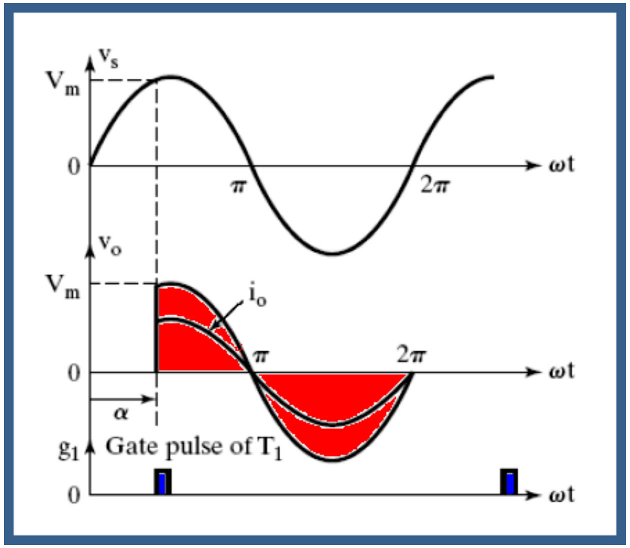
$$v_s = V_m \sin \omega t$$

Where $V_s = \dfrac{V_m}{\sqrt{2}}$ is the rms value of the secondary voltage.

Output Load Voltage

$v_o = v_L = 0$ ⇒ for $\omega t = 0$ to α

$v_o = v_L = V_m \sin \omega t$ ⇒ for $\omega t = \alpha$ to 2π

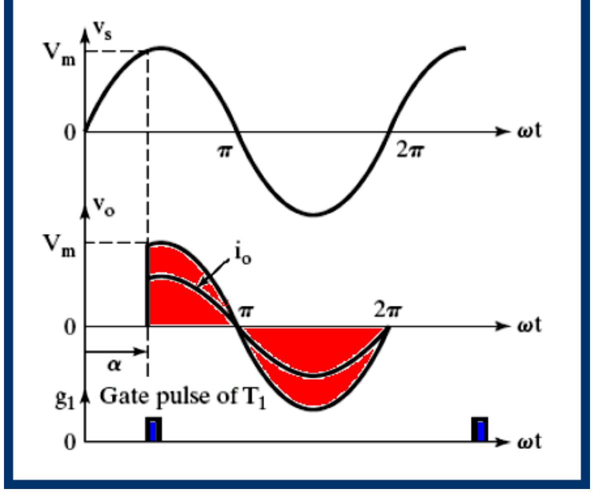


Output Load Current

$i_o = i_L = 0$ ⇒ $\omega t = 0$ to α

$i_o = i_L = \dfrac{v_o}{R_L} = \dfrac{V_m \sin \omega t}{R_L}$ ⇒ for $\omega t = \alpha$ to 2π

Analysis of single-phase half-wave AC voltage controller



RMS OUTPUT VOLTAGE $V_{O(RMS)}$

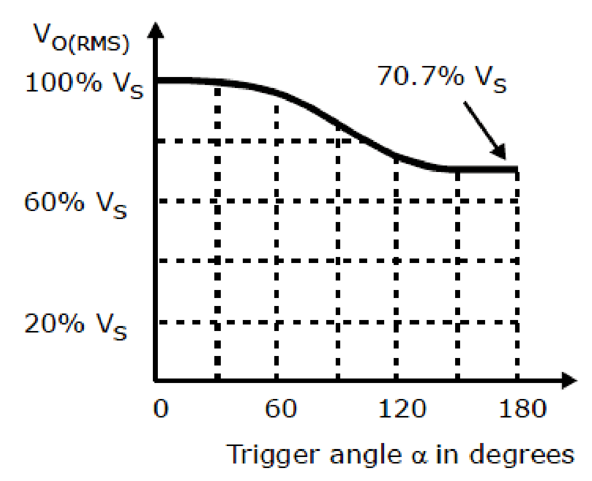
$$V_o = \sqrt{\frac{1}{2\pi}\left[\int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t.d(\omega t) + \int_{\pi}^{2\pi} (-V_m^2)\sin^2 \omega t.d(\omega t)\right]}$$

$$V_o = V_S\sqrt{\frac{1}{2\pi}\left[(2\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]}$$

$\therefore V_S = \frac{V_m}{\sqrt{2}}$ = RMS value of input supply voltage

The rms output voltage (Vo) across the load is controlled by changing (α)

The range of the rms output voltage is from 100% Vs to 70.7% of Vs when we vary the triggering angle α from zero to 180 degrees.



Analysis of single-phase half-wave AC voltage controller

Input power factor

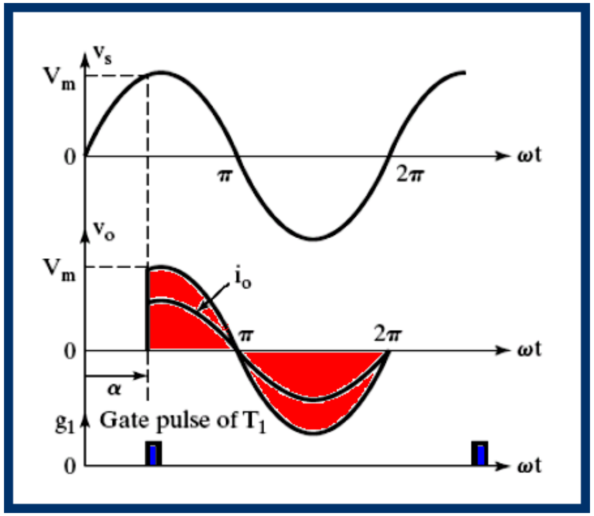
$$PF = \frac{P_o}{V_s I_s} = \frac{V_o}{V_s} = \sqrt{\frac{1}{2\pi}\left[(2\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]}$$

$$V_o = V_s\sqrt{\frac{1}{2\pi}\left[(2\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]}$$

The average (DC) output voltage

$$V_{dc} = \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} V_m \sin\omega t.d(\omega t) + \int_{\pi}^{2\pi} (-V_m)\sin\omega t.d(\omega t)\right]$$

$$V_{dc} = \frac{V_m}{2\pi}[\cos\alpha - 1]$$



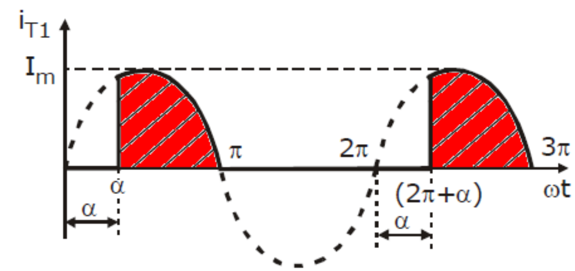
Analysis of single-phase half-wave AC voltage controller

Average Thyristor Currents $I_{T(Avg)}$

Referring to the thyristor current waveform of a single phase half-wave ac voltage controller circuit, we can calculate the average thyristor current $I_{T(Avg)}$ as

$$I_{T(Avg)} = \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} I_m \sin\omega t.d(\omega t)\right] = \frac{I_m}{2\pi}\left[\left(-\cos\omega t\right)\Big/_{\alpha}^{\pi}\right]$$

$$= \frac{I_m}{2\pi}\left[-\cos(\pi)+\cos\alpha\right] = \frac{I_m}{2\pi}\left[1+\cos\alpha\right]$$



Thyristor Current Waveform

$$I_{T(Avg)} = \frac{I_m}{2\pi}\left[1+\cos\alpha\right]$$

Where, $I_m = \frac{V_m}{R_L}$ = Peak thyristor current = Peak load current.

RMS Thyristor Current $I_{T(RMS)}$

$$I_{T(RMS)} = \sqrt{\frac{1}{2\pi}\left[\int_{\alpha}^{\pi} I_m^2 \sin^2\omega t.d(\omega t)\right]} = \sqrt{\frac{I_m^2}{2\pi}\left[\int_{\alpha}^{\pi} \frac{(1-\cos 2\omega t)}{2}.d(\omega t)\right]}$$

$$I_{T(RMS)} = \frac{I_m}{\sqrt{2}}\sqrt{\frac{1}{2\pi}\left[(\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]}$$

Disadvantages of single-phase half-wave AC voltage controller

1- 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.

2- 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 V_s at a trigger angle $\alpha = 0$ to a low of 70.7% of V_s at $\alpha = \pi$ Radians .

3- 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.

- This type of AC voltage controller is not generally used in industrial applications because of these drawbacks. It may only be used in resistive loads.

Ex .2: A single-phase half-wave AC voltage controller has a load resistance of 50 Ω, AC supply voltage is 230V RMS at 50Hz. The supply transformer has a turns ratio of 1:1. If the thyristor is triggered at $\alpha = 60°$.

Calculate:

1. the rms value of output voltage.
2. the output power.
3. the average value of load current.
4. the input power factor.
5. the average and rms values of thyristor current.

Solution

$V_p = V_s = 230V \quad f_S = 50Hz \quad R_L = 50\Omega \quad \frac{V_P}{V_S} = \frac{N_P}{N_S} = 1 \quad \alpha = 60° = \pi/3 \text{ radians}$

1 RMS Value of Output (Load) Voltage $V_{O(RMS)}$

$$V_O = V_S \sqrt{\frac{1}{2\pi}\left[(2\pi - \alpha) + \frac{\sin 2\alpha}{2}\right]}$$

$$V_O = V_S \sqrt{\frac{1}{2\pi}\left[(2\pi - \alpha)\right] + \frac{\sin 2\alpha}{2}} = 230\sqrt{\frac{1}{2\pi}\left[\left(2\pi - \frac{\pi}{3}\right)\right] + \frac{\sin 120^0}{2}} = 230\sqrt{\frac{1}{2\pi}[5.669]}$$

$$V_O = 230 \times 0.94986 = 218.4696\ V \approx \boxed{218.47\ V}$$

2 RMS Load Current $I_{O(RMS)}$

$$I_O = \frac{V_O}{R_L} = \frac{218.46966}{50} = \boxed{4.36939\ Amps}$$

3 Output Load Power P_O

$$P_O = I_O^2 \times R_L = (4.36939)^2 \times 50 = \boxed{954.5799\ Watts}$$

$$P_O = 0.9545799\ KW$$

4 Input Power Factor

$$PF = \frac{P_O}{V_S \times I_S}$$

V_S = RMS secondary supply voltage = 230V.

I_S = RMS secondary supply current = RMS load current. $\therefore I_S = I_O = 4.36939\ Amps$

$$\therefore PF = \frac{954.5799\ \text{W}}{(230 \times 4.36939)\ \text{W}} = \boxed{0.9498}$$

5 Average & RMS Thyristor Currents

average thyristor current $I_{T(Avg)}$

$$I_{T(Avg)} = \frac{I_m}{2\pi}[1+\cos\alpha]$$

Where, $I_m = \frac{V_m}{R_L}$ = Peak thyristor current = Peak load current.

$$I_m = \frac{\sqrt{2}\times 230}{50} = 6.505382 \text{ Amps}$$

$$I_{T(Avg)} = \frac{V_m}{2\pi R_L}[1+\cos\alpha] = \frac{\sqrt{2}\times 230}{2\pi\times 50}\left[1+\cos\left(60^0\right)\right] = \frac{\sqrt{2}\times 230}{100\pi}[1+0.5] = \boxed{1.5530 \text{ Amps}}$$

RMS thyristor current $I_{T(RMS)}$

$$I_{T(RMS)} = \frac{I_m}{\sqrt{2}}\sqrt{\frac{1}{2\pi}\left[(\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]}$$

$$I_{T(RMS)} = \frac{6.50538}{\sqrt{2}}\sqrt{\frac{1}{2\pi}\left[\left(\pi-\frac{\pi}{3}\right)+\frac{\sin\left(120^0\right)}{2}\right]} = 4.6\sqrt{\frac{1}{2\pi}\left[\left(\frac{2\pi}{3}\right)+\frac{0.8660254}{2}\right]} = 4.6\times 0.6342 = \boxed{2.91746A}$$