Lecture#

4.1 Introduction

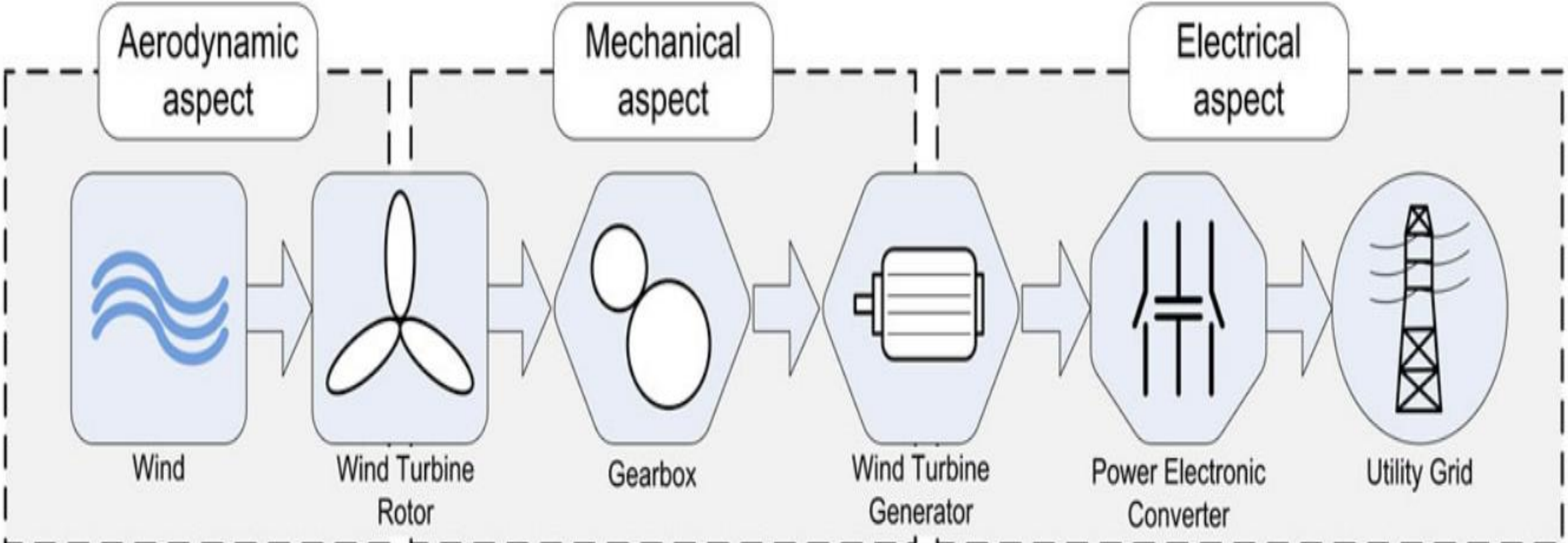
4.2 AC Voltage Controllers (Soft Starters)

4.2.1 Single-phase AC Voltage Controller with R & RL load

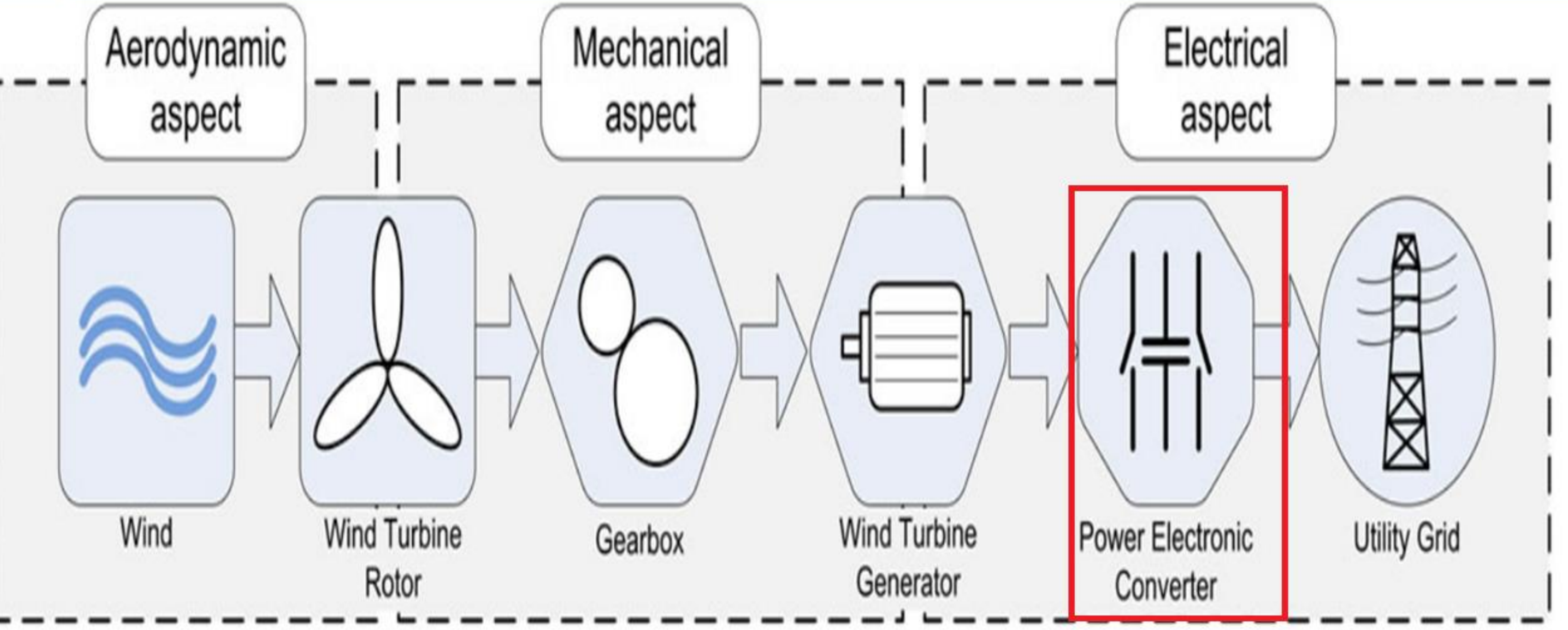
Numericals:4-1 to 4-2

4.1 Introduction

Q. What element is widely used in Wind Energy Conversion Systems (WECS)?



Power converters are widely used in Wind Energy Conversion Systems (WECS).



Q. Only fixed speed WECS required Power converters?

Answer:

- **We use Power converters in both the fixed speed WECS as well as Variable-speed WECS.**

Use of Power converters in fixed Versus Variable-speed WECS

Fixed-speed WECS

- Converters reduce inrush current &
- torque oscillations during system start-up.

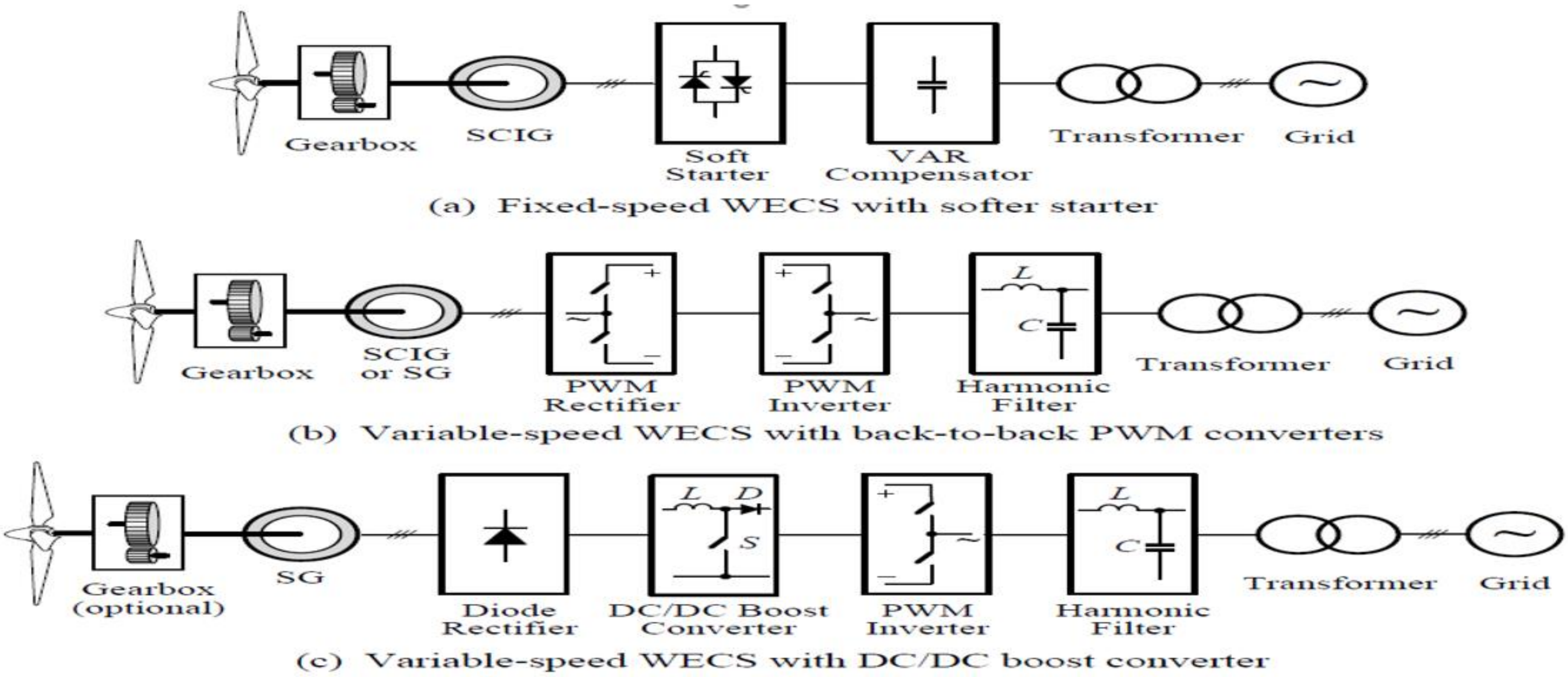
Variable-speed WECS

- Converter control speed/torque of generator &
- active/reactive power to grid.

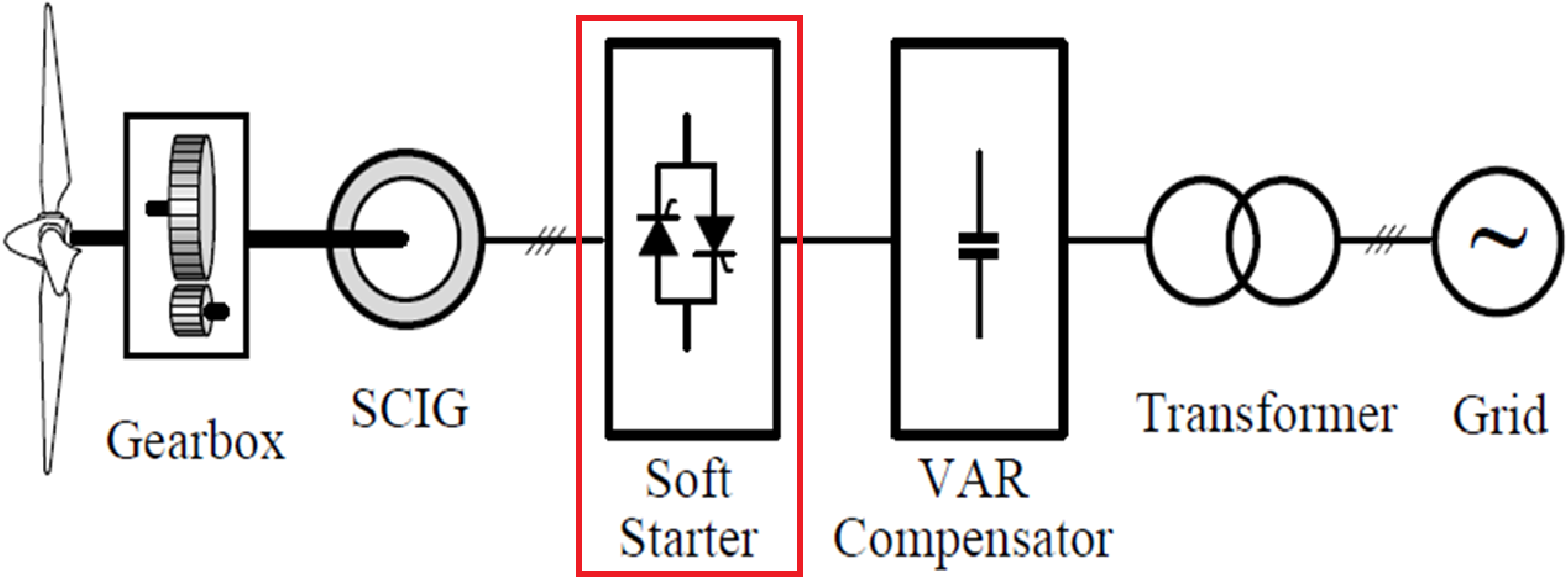
Variety of power converter configurations

- According to **system power ratings & type of wind turbines:**
- a variety of power converter configurations are developed for optimal control of wind energy systems.

3 practical wind energy conversion systems using different power converter topologies.

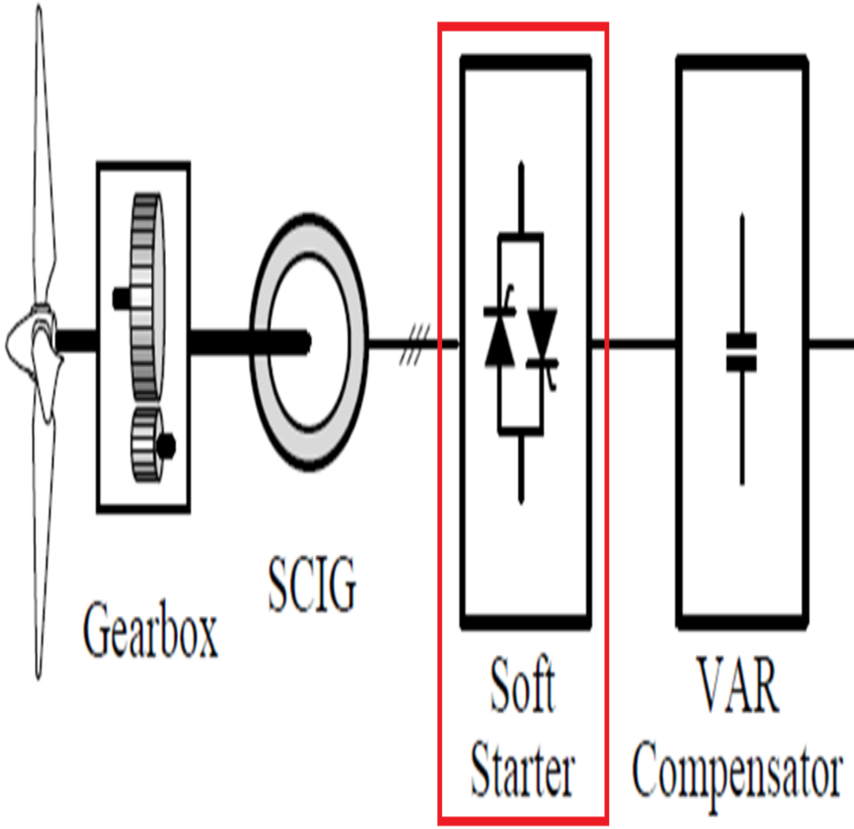


In fixed-speed induction generator based WECS, soft starter reduces **inrush current**, when generator is connected to grid.



(a) Fixed-speed WECS with softer starter

Soft starter is an AC voltage controller using SCR devices, **whose output voltage *Vo* is adjusted such that it increases slowly with time during system start-up[We shall prove the statement mathematically]**



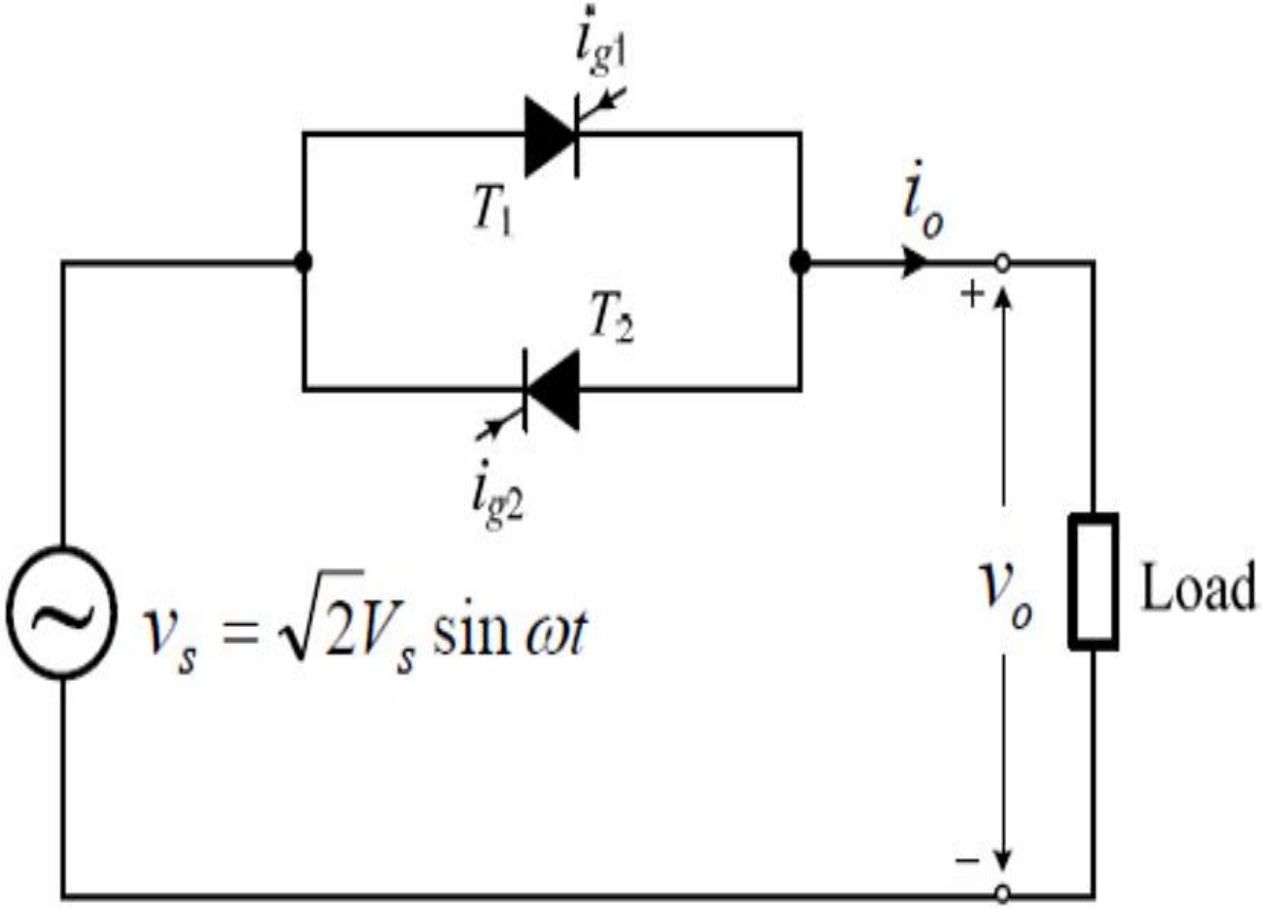
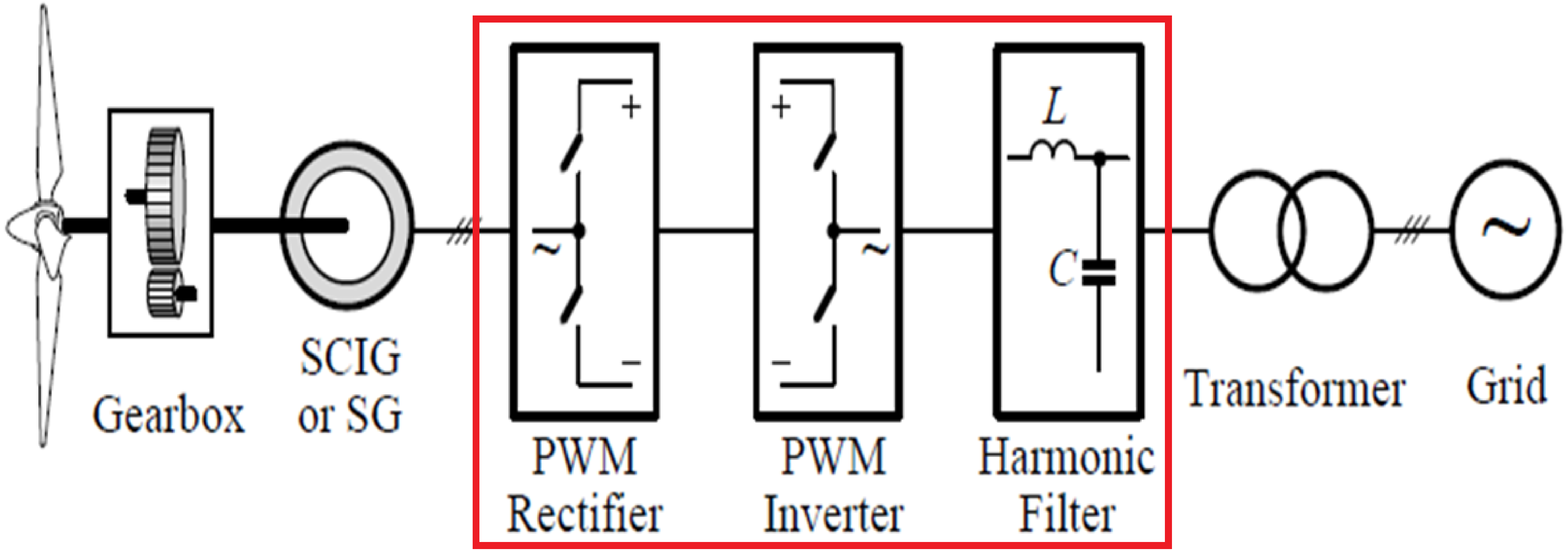
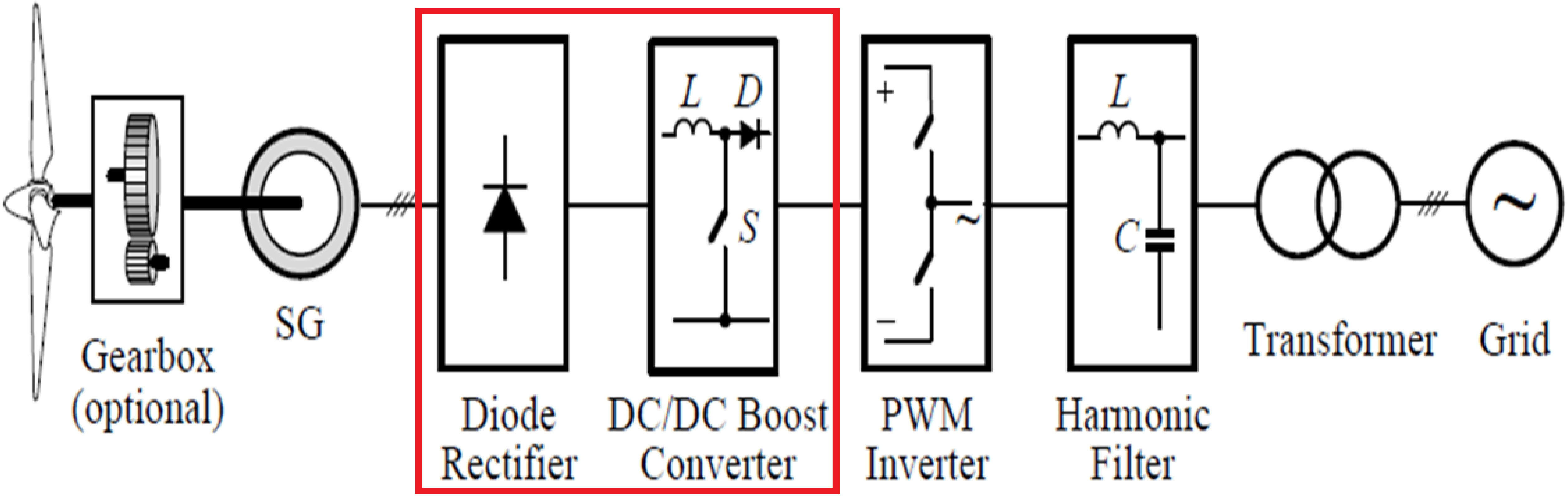


Fig.b shows a variable-speed WECS using Squirrel Cage Induction Generators (SCIG) or Synchronous Generators (SG), where a back-to-back converter configuration with 02 identical PWM converters is used.



(b) Variable-speed WECS with back-to-back PWM converters

Fig. c is also a variable-speed wind energy system only for synchronous generators, where a **low-cost diode rectifier with a DC/DC boost converter** is used instead of PWM rectifier.



(c) Variable-speed WECS with DC/DC boost converter

In this Chapter we shall study:

1. Different power converter topologies for wind energy systems

a) Their operating principles &

b) Switching schemes

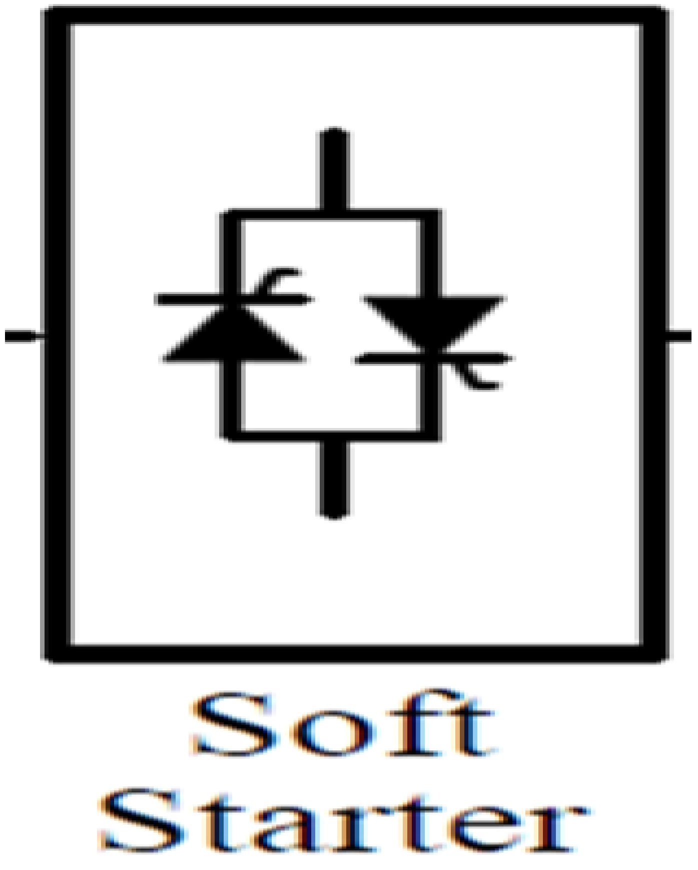
2. These power converters include:

a) AC voltage controllers
b) DC/DC boost converters
c) 2-level voltage source converters
d) 3-level Neutral Point Clamped (NPC) converters &
e) PWM current source converters

3. Finally, control of grid-connected converters.

4.2 AC Voltage Controllers (Soft Starters)

- AC voltage controller is often referred to as soft starter in WECS.



02 main functions of Soft Starters:

- To start wind turbine smoothly with reduced :

1. Inrush current &

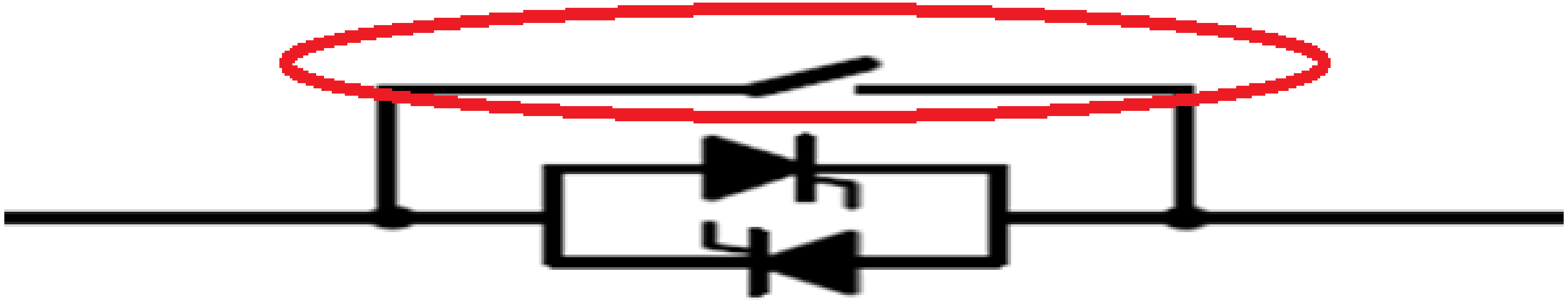
2. Mechanical stress.

Q. After system is started, AC voltage controller should be bypassed or not?

Answer: Yes should be by-passed

Why?

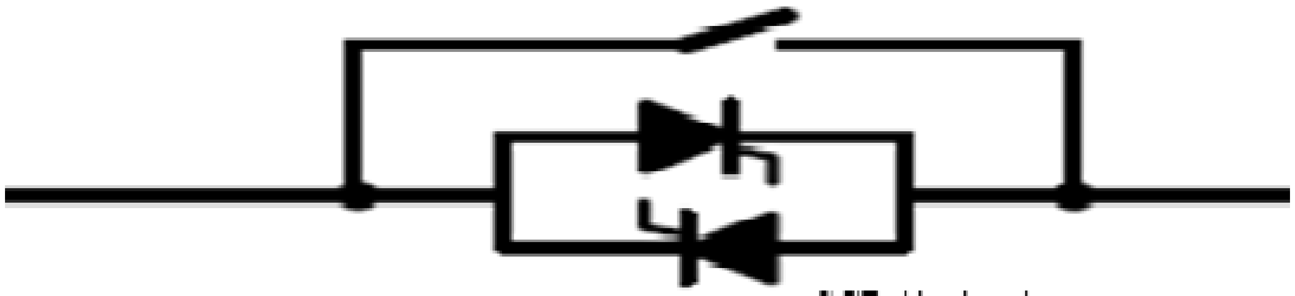
- After system is started, AC voltage controller is usually bypassed (short circuited) by a bypass switch, which eliminates power losses of controller.



Soft Starter

Silicon Control Rectifier(SCR)

- AC voltage controllers in WECS normally use SCR (thyristor) as a switching device.

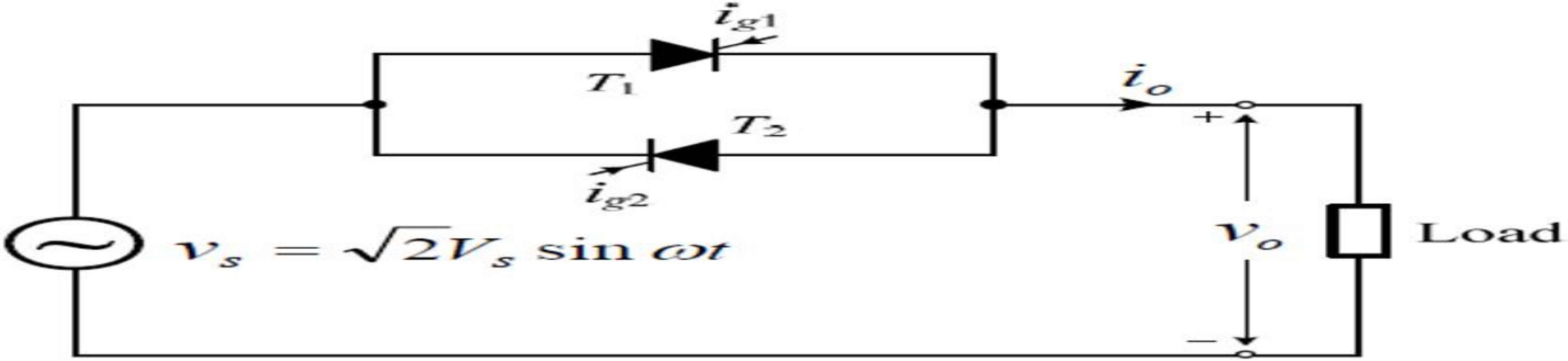


SCR (thyristor)

Adjustment of output voltage of controller (*vo*) through delay (firing) angle(α)

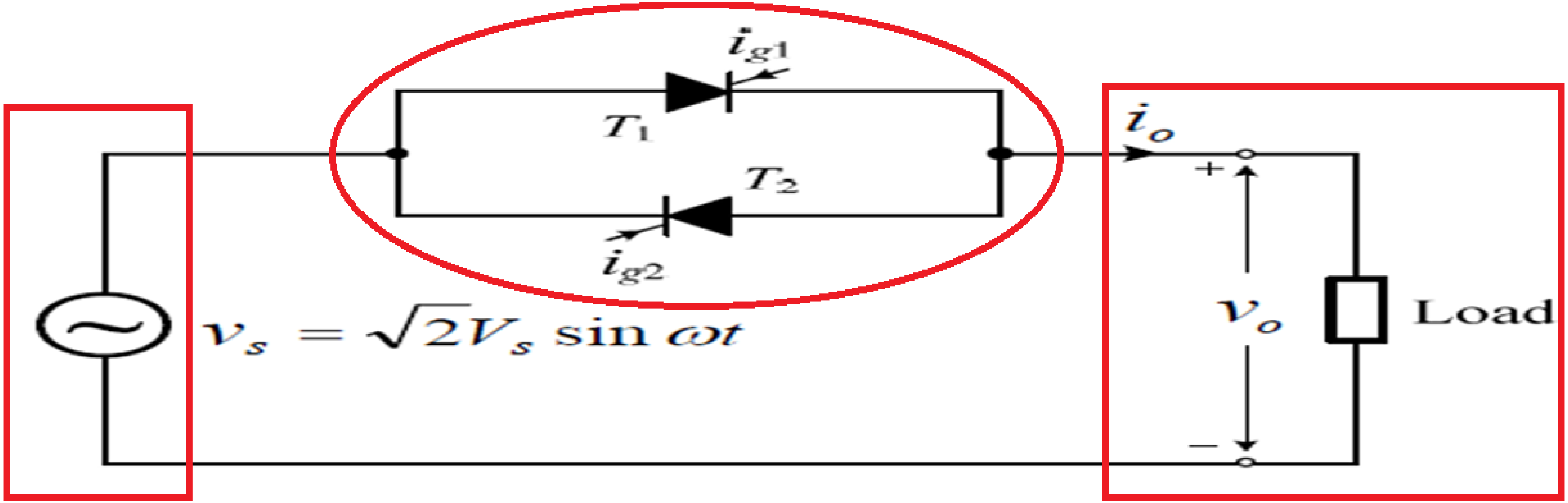
- We shall now prove mathematically that:

“Output voltage of controller(*vo*) can be adjusted from 0 all the way up to its supply voltage(vs), which effectively reduces starting current of system.”

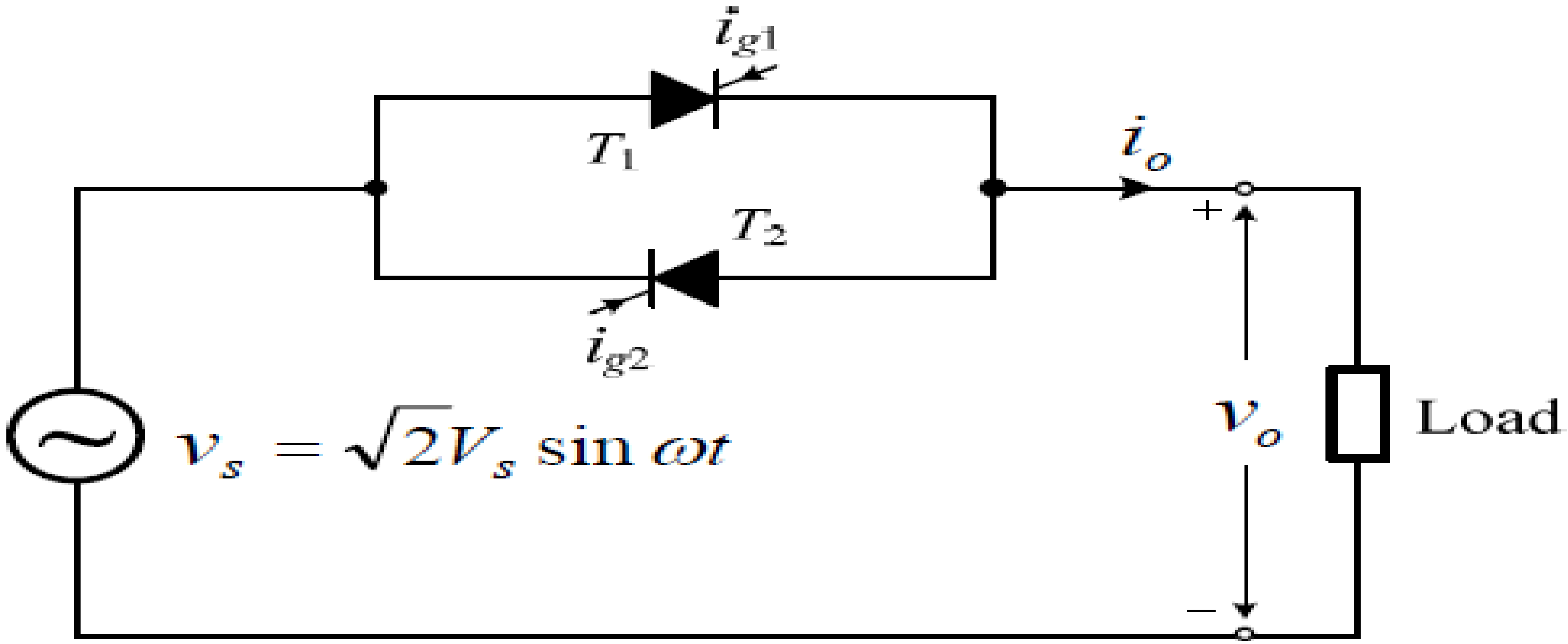


Simplified circuit for a 1-phase AC voltage controller

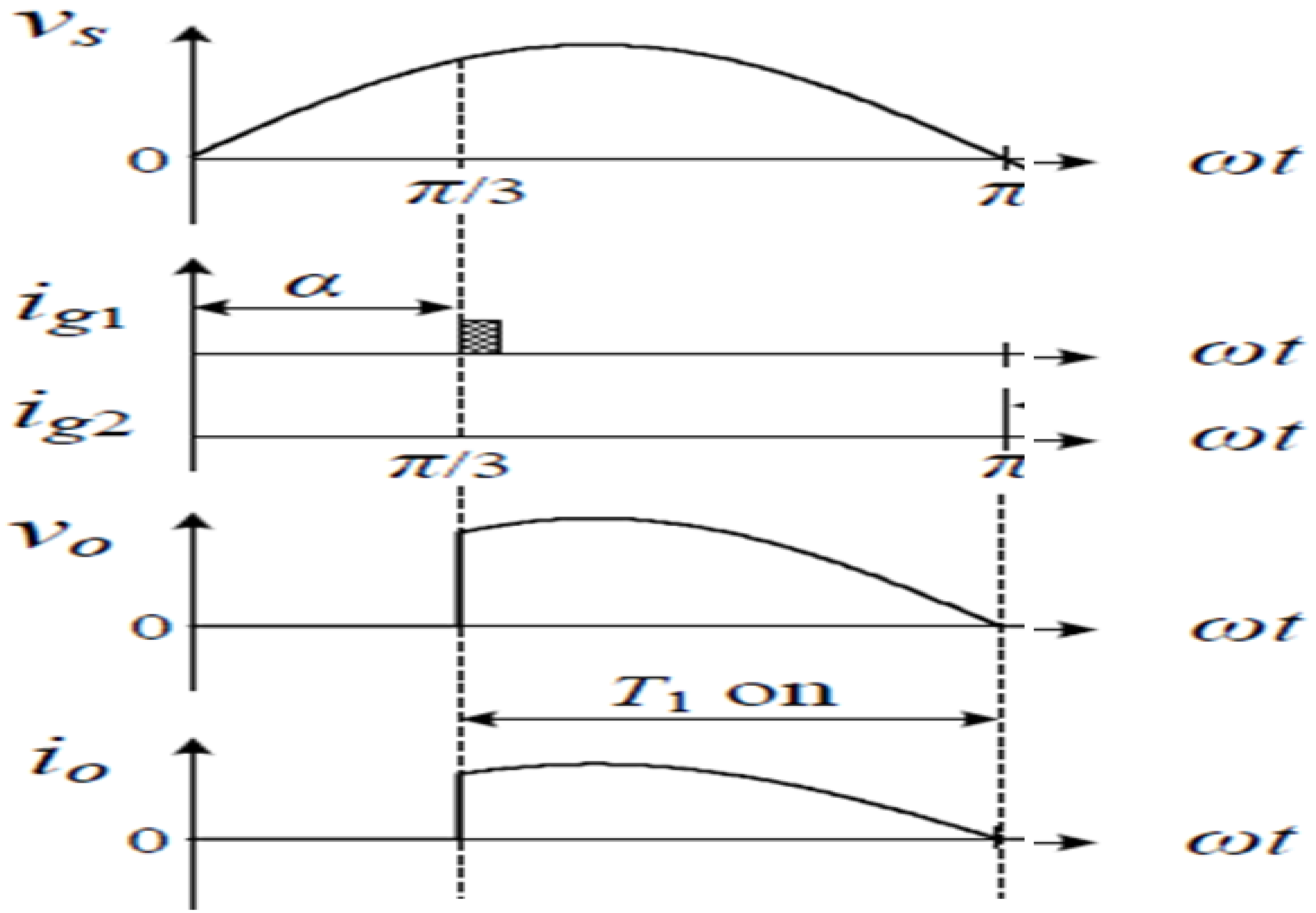
- It is composed of a pair of SCR thyristors,
- connected **in anti-parallel between power supply & load.**

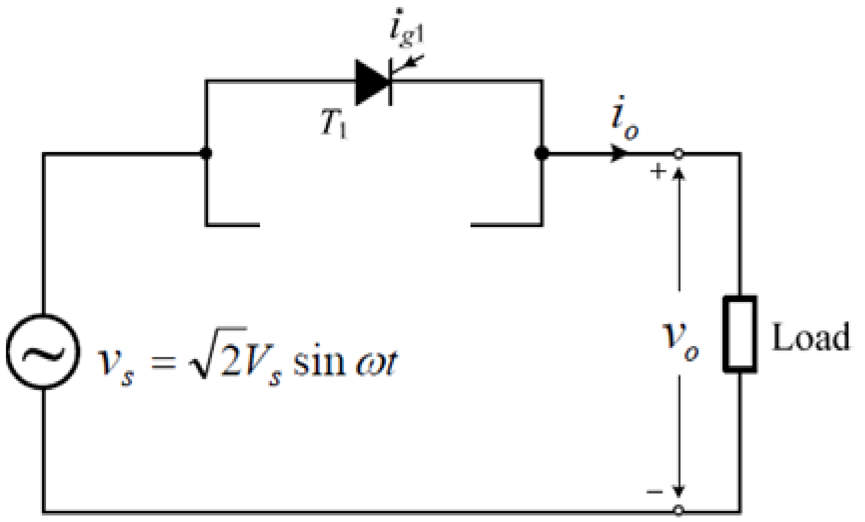


Draw waveforms for gate signals i_{g1} & i_{g2}, output current i_o, & output voltage v_o of controller with a delay angle of $\alpha = \pi/3 = 60^o$ **(assuming a resistive load)?**

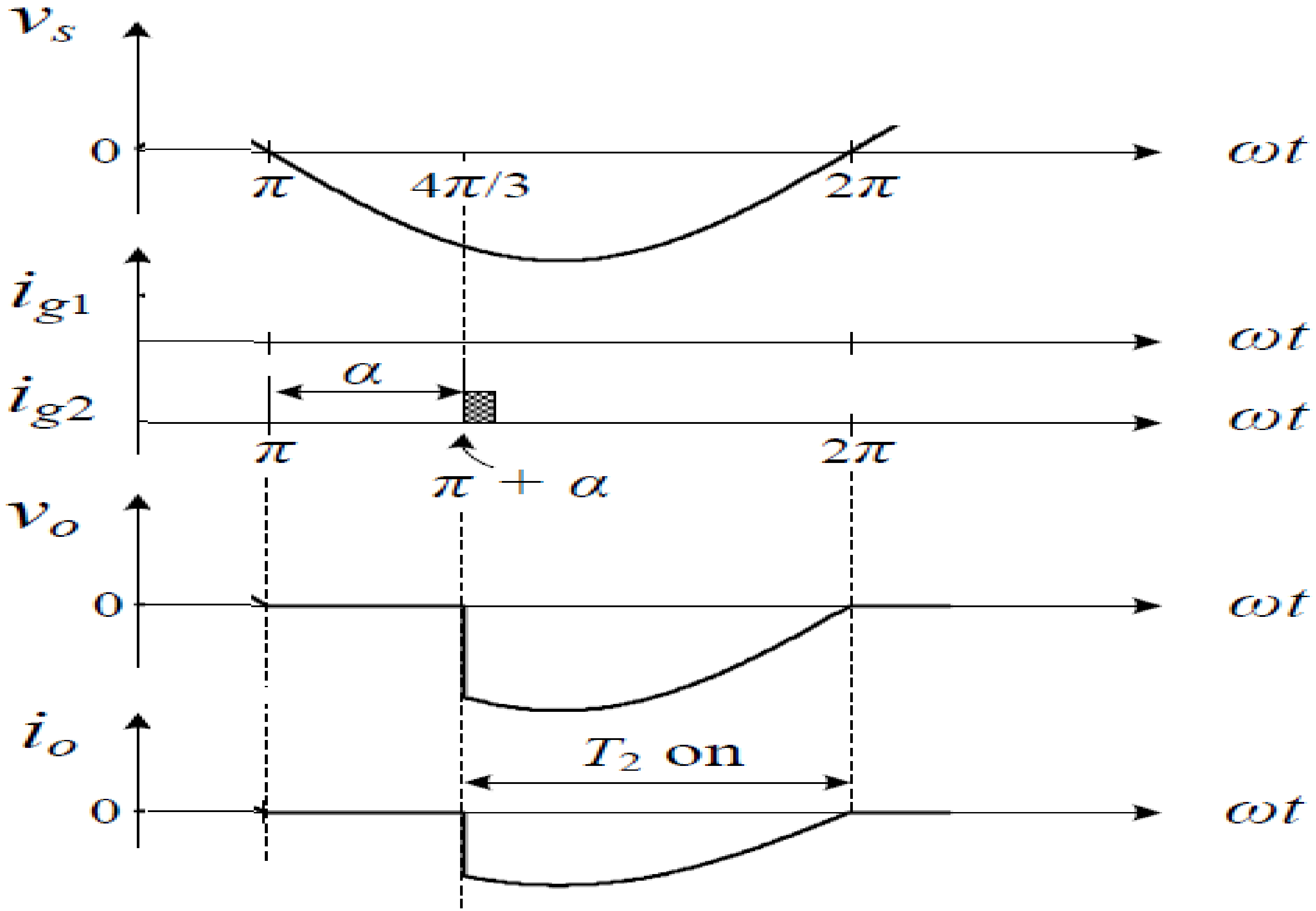


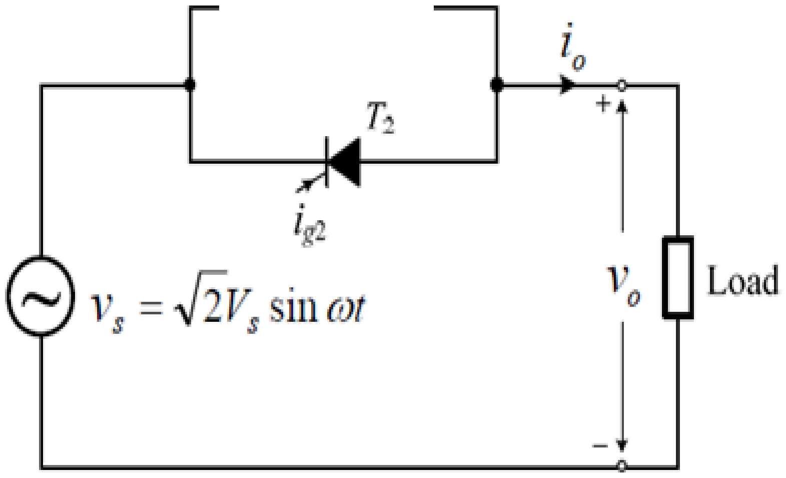
During +ve ½ cycle of power supply(v_s), thyristor T_1 is **turned on** at $\omega t = \alpha = \pi/3 = 60^o$ by i_{g1} & is **turned off** at π when its current falls to 0.



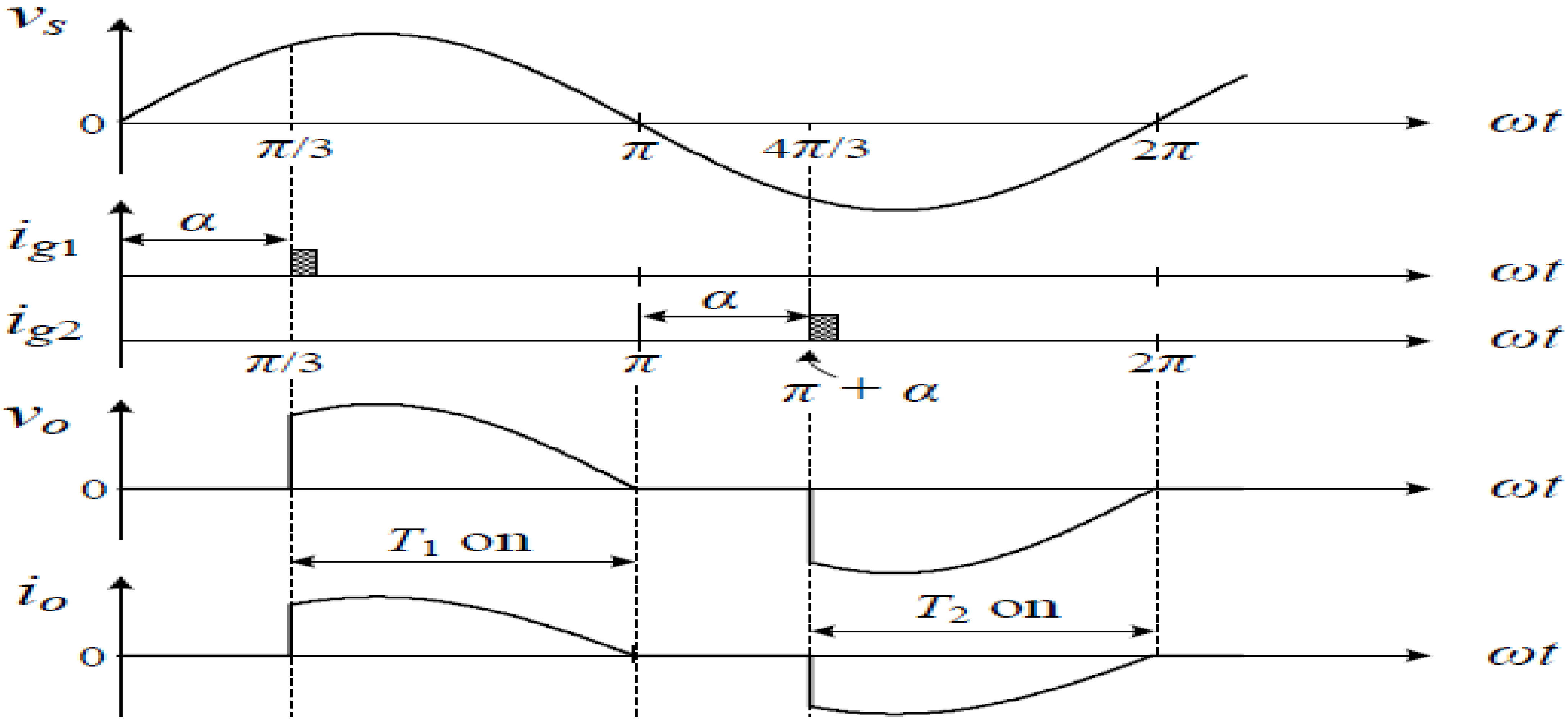


During -ve ½ cycle, thyristor T_2 is triggered on at $\omega t = (\alpha + \pi) = 4\pi/3 = (180+60=240^o)$ & is switched off at $2\pi = 360^o$.

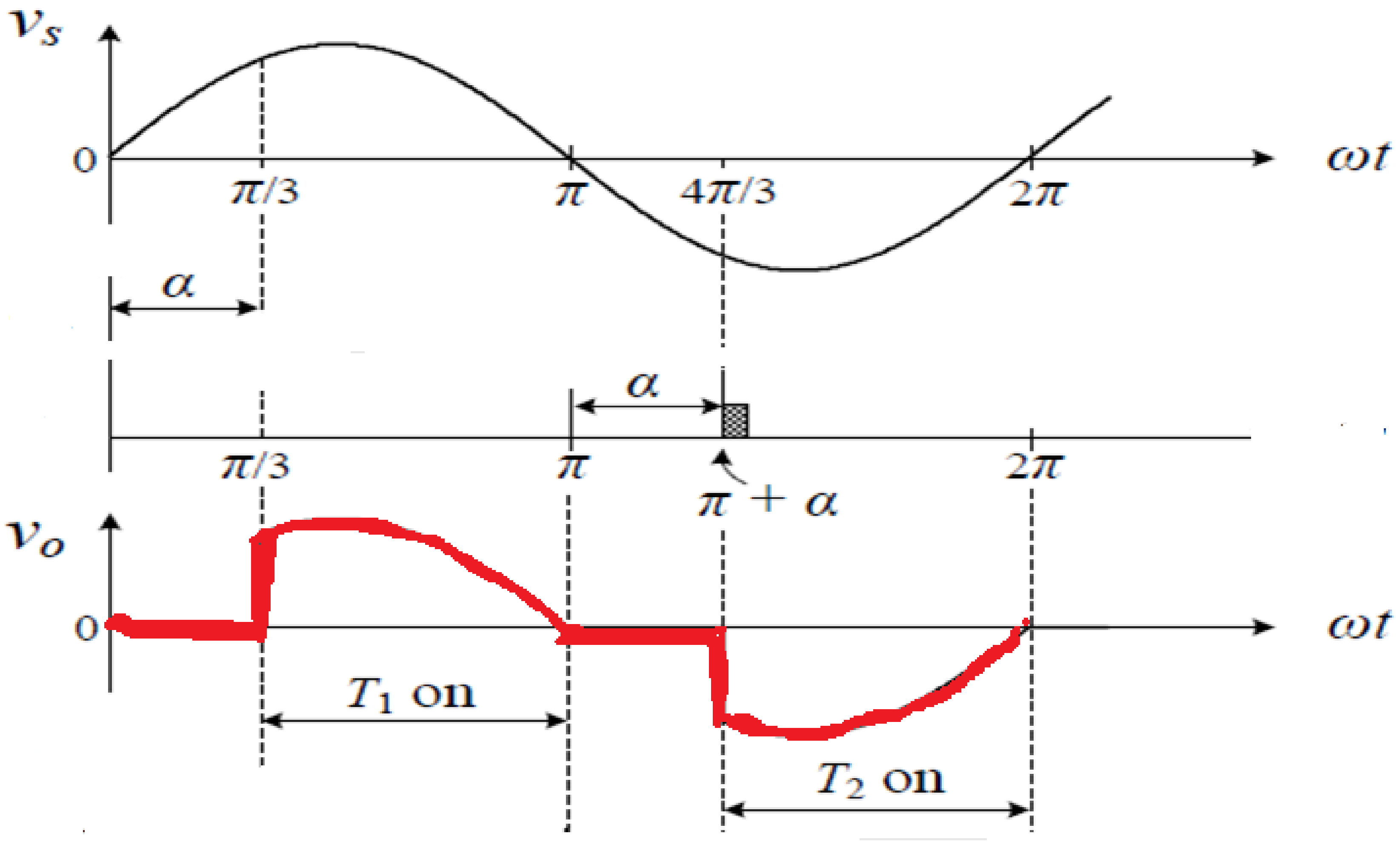


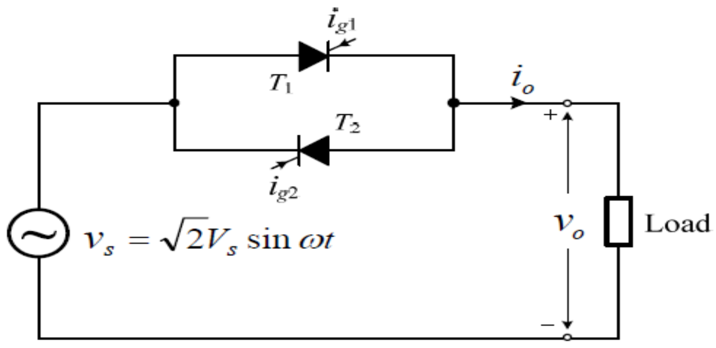


waveforms for gate signals i_{g1} & i_{g2}, output current i_o, & output voltage v_o of controller with a delay angle of $\alpha = \pi/3 = 60^o$



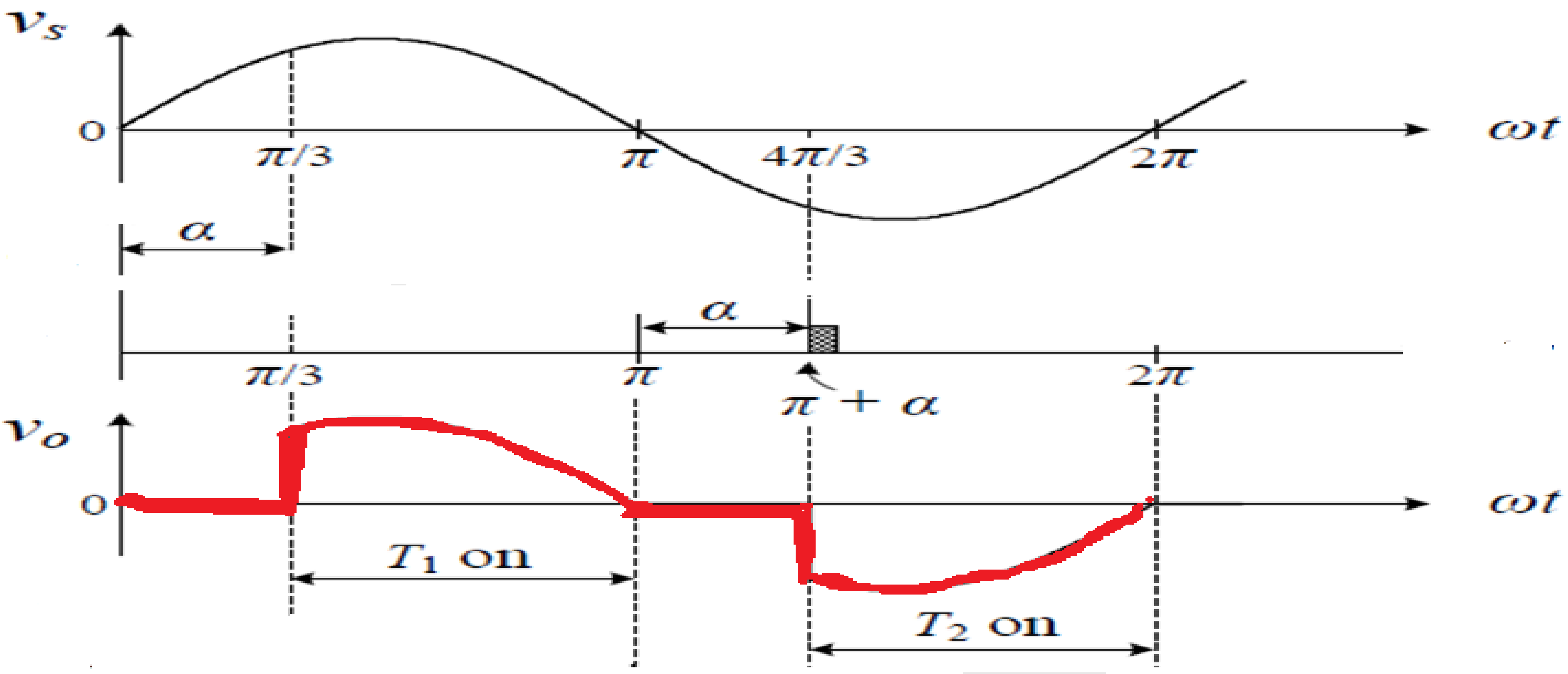
With a resistive load, rms value of output voltage *Vo* can be found by squaring wave, averaging it & then finding square root.





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

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



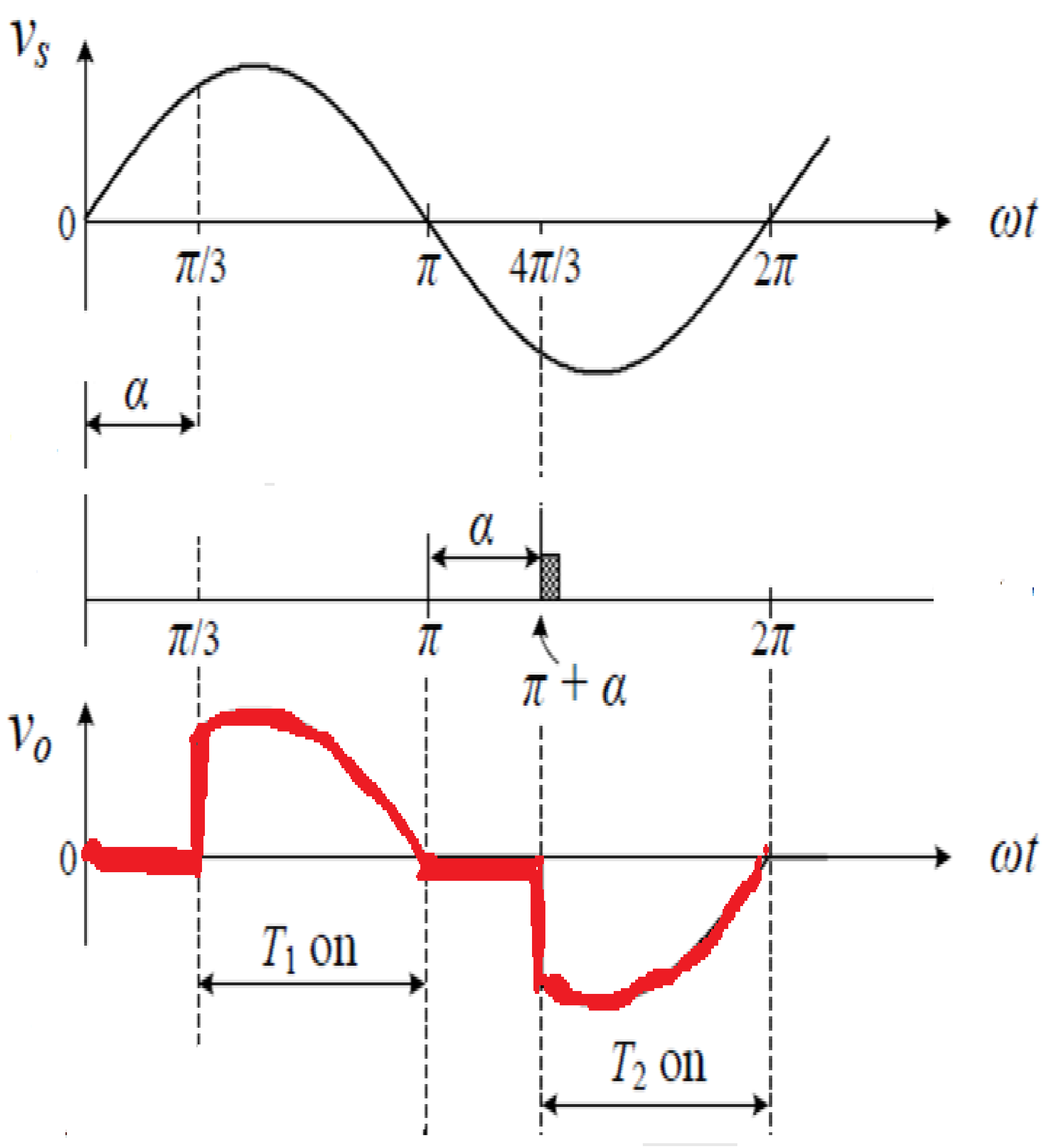
$$V^2_{L(RMS)} = \frac{1}{2\pi}\int_0^{2\pi} v_L^{\,2}.d(\omega t);$$

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

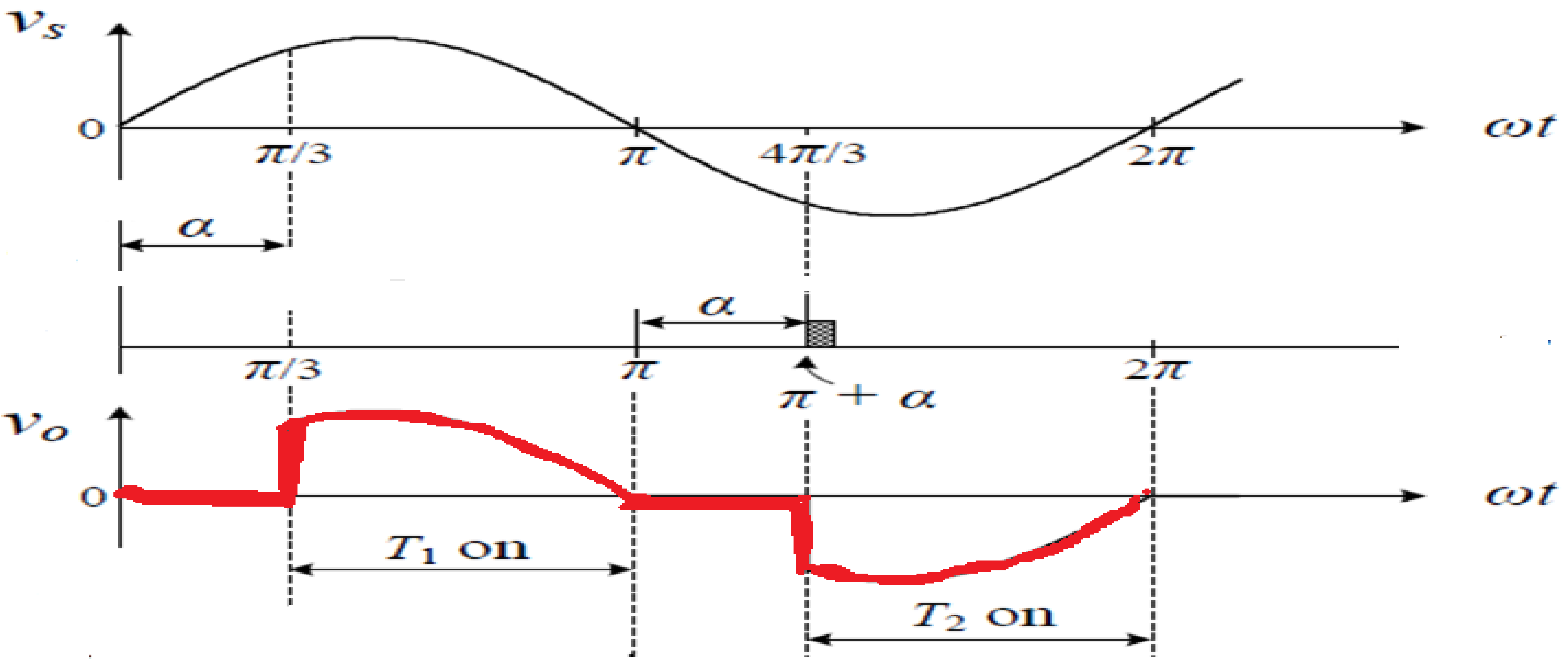
Hence,

$$V^2_{L(RMS)} = \frac{1}{2\pi}\left[\int_\alpha^\pi (V_m \sin\omega t)^2 d(\omega t) + \int_{\pi+\alpha}^{2\pi} (V_m \sin\omega t)^2 d(\omega t)\right]$$

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



Try to evaluate it



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

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

$$=\frac{V_m^{\ 2}}{4\pi}\left[(\omega t)\Big/_{\alpha}^{\pi}+(\omega t)\Big/_{\pi+\alpha}^{2\pi}-\left[\frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi}-\left[\frac{\sin 2\omega t}{2}\right]_{\pi+\alpha}^{2\pi}\right]$$

$$=\frac{V_m^{\ 2}}{4\pi}\left[(\pi-\alpha)+(\pi-\alpha)-\frac{1}{2}(\sin 2\pi-\sin 2\alpha)-\frac{1}{2}(\sin 4\pi-\sin 2(\pi+\alpha))\right]$$

$$=\frac{V_m^{\ 2}}{4\pi}\left[2(\pi-\alpha)-\frac{1}{2}(0-\sin 2\alpha)-\frac{1}{2}(0-\sin 2(\pi+\alpha))\right]$$

$$=\frac{V_m^{\ 2}}{4\pi}\left[2(\pi-\alpha)+\frac{\sin 2\alpha}{2}+\frac{\sin 2(\pi+\alpha)}{2}\right]$$

$$=\frac{V_m^{\ 2}}{4\pi}\left[2(\pi-\alpha)+\frac{\sin 2\alpha}{2}+\frac{\sin(2\pi+2\alpha)}{2}\right]$$

$$=\frac{V_m^{\ 2}}{4\pi}\left[2(\pi-\alpha)+\frac{\sin 2\alpha}{2}+\frac{1}{2}(\sin 2\pi.\cos 2\alpha+\cos 2\pi.\sin 2\alpha)\right]$$

$\sin 2\pi=0$ & $\cos 2\pi=1$

Therefore,

$$V^2_{L(RMS)} = \frac{V_m^{\;2}}{4\pi}\left[2(\pi-\alpha)+\frac{\sin 2\alpha}{2}+\frac{\sin 2\alpha}{2}\right]$$

$$= \frac{V_m^{\;2}}{4\pi}\left[2(\pi-\alpha)+\sin 2\alpha\right]$$

$$V^2{}_{L(RMS)} = \frac{V_m^{\;2}}{4\pi}\left[(2\pi-2\alpha)+\sin 2\alpha\right]$$

Taking the square root, we get

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

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

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

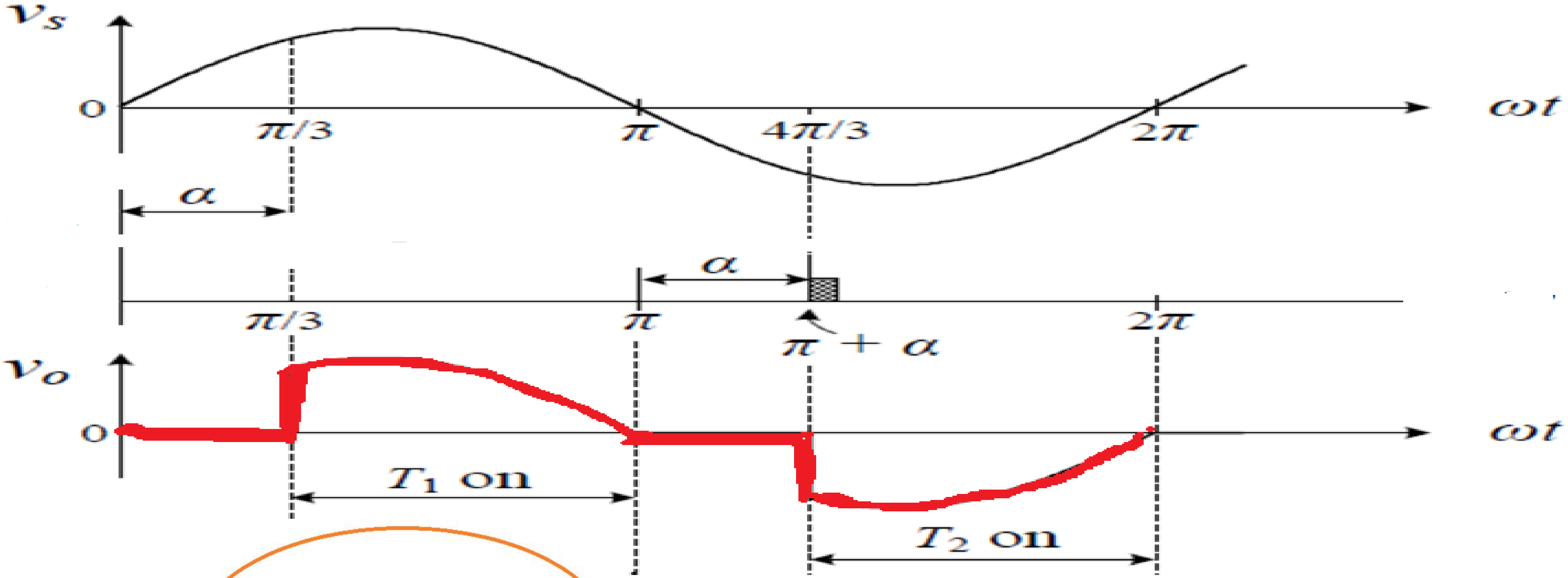
$$V_{L(RMS)} = \frac{V_m}{\sqrt{2}} \sqrt{\frac{1}{2\pi}\left[2\left\{(\pi - \alpha) + \frac{\sin 2\alpha}{2}\right\}\right]}$$

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

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

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

Q. How we can obtain full sin wave across load?



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

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.

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

$$V_{L(RMS)}\Big|_{\alpha=0} = \frac{V_m}{\sqrt{2}} \sqrt{\frac{1}{\pi}\left[(\pi - 0) + \frac{\sin 2\times 0}{2}\right]}$$

$$V_{L(RMS)}\Big|_{\alpha=0} = \frac{V_m}{\sqrt{2}} \sqrt{\frac{1}{\pi}\left[(\pi) + \frac{0}{2}\right]}$$

$$V_{L(RMS)}\Big|_{\alpha=0} = \frac{V_m}{\sqrt{2}} = V_{i(RMS)} = V_S$$

CONTROL CHARACTERISTIC OF SINGLE PHASE FULL-WAVE ACVOLTAGE CONTROLLER WITH RESISTIVE LOAD

Plot RMS output voltage $V_{L(RMS)}$ versus the trigger angle α

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

Plot RMS output voltage $V_{L(RMS)}$ versus trigger angle α

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

The control characteristics

The control characteristic is the plot of RMS output voltage $V_{O(RMS)}$ versus the trigger angle α ; which can be obtained by using the expression for the RMS output voltage of a full-wave ac controller with resistive load.

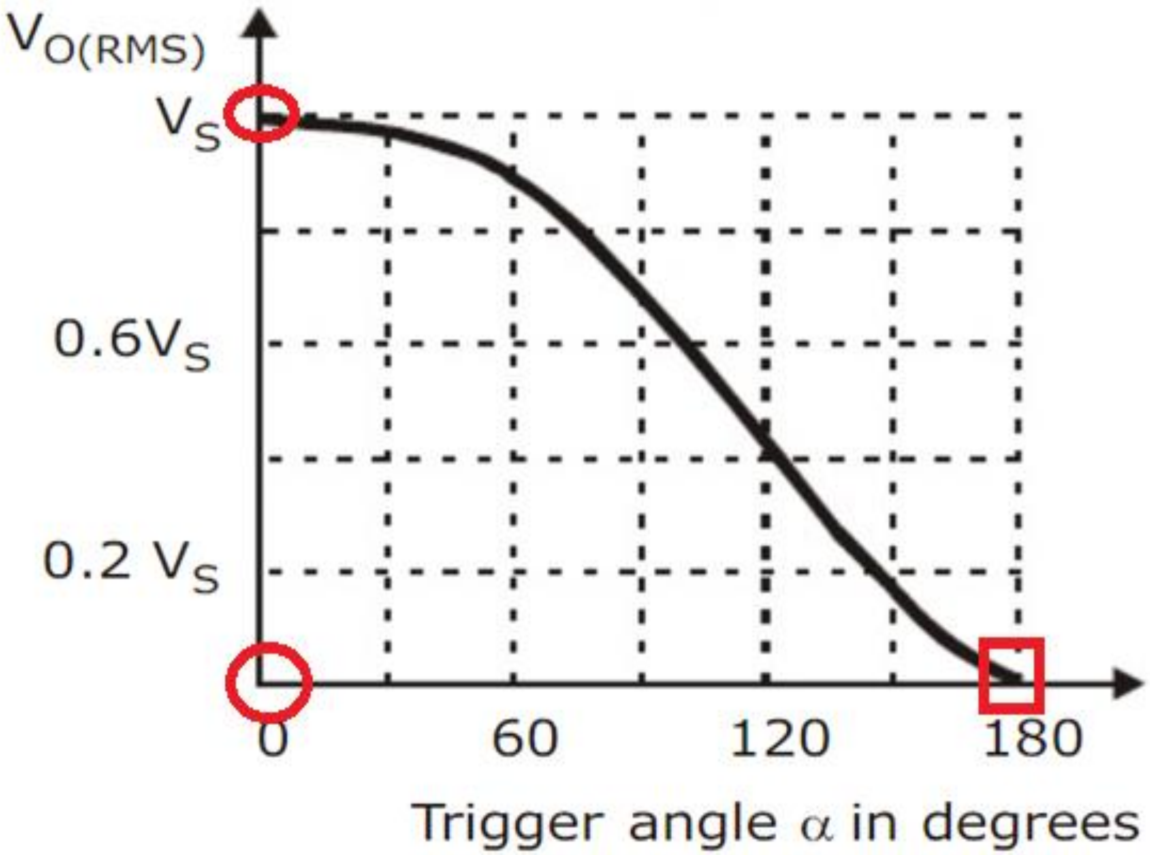
$$V_{O(RMS)} = V_S \sqrt{\frac{1}{\pi}\left[(\pi - \alpha) + \frac{\sin 2\alpha}{2}\right]} \quad ;$$

When α is increased the RMS load voltage decreases.

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

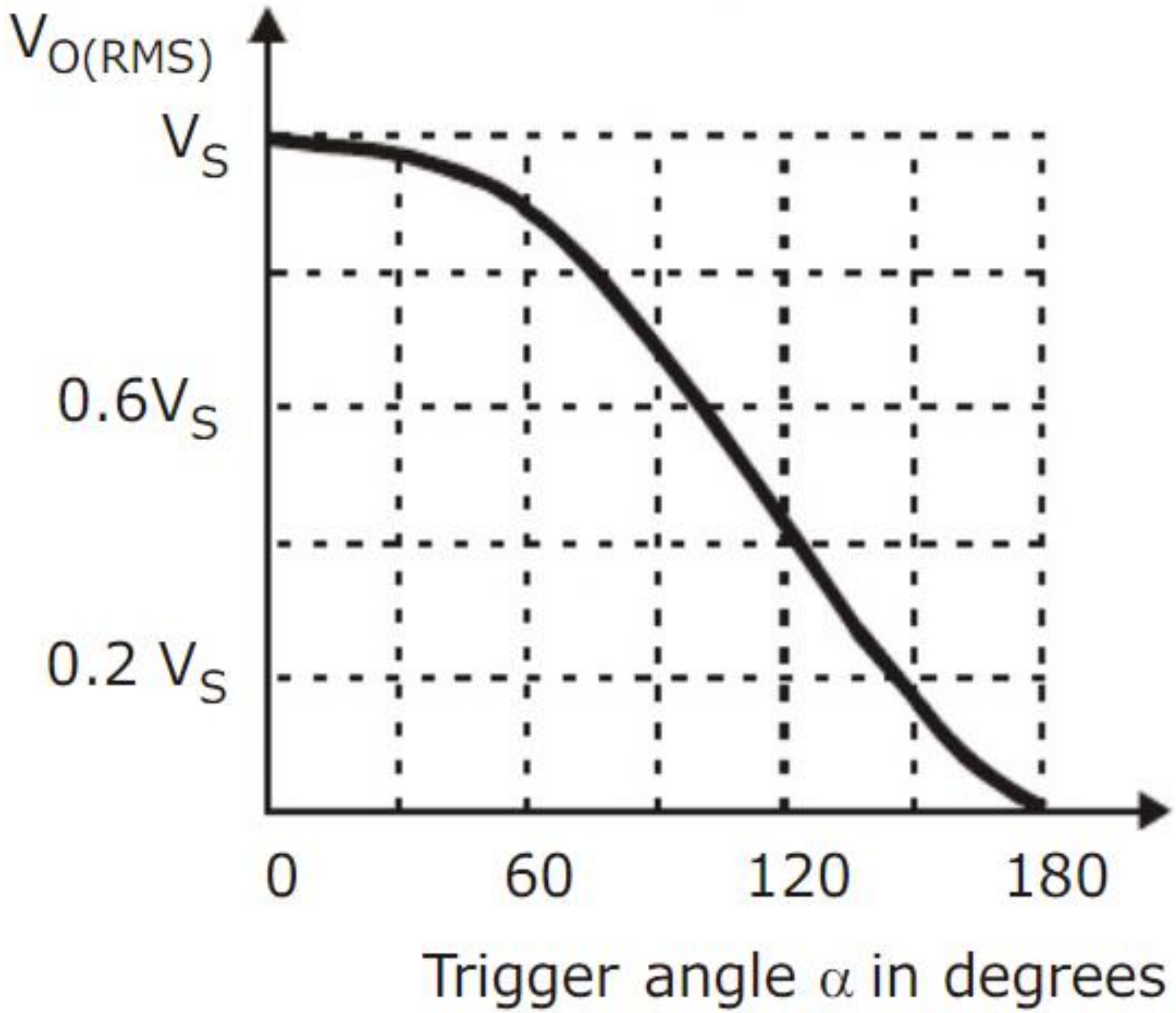
$$V_{L(RMS)} = V_S \sqrt{\frac{1}{\pi}\left[(\pi - \alpha) + \frac{\sin 2\alpha}{2}\right]}$$

Trigger angle α in degrees	Trigger angle α in radians	$V_{O(RMS)}$	%
0	0	V_S	100% V_S
30^0	$\pi/6$; $(1\pi/6)$	0.985477 V_S	98.54% V_S
60^0	$\pi/3$; $(2\pi/6)$	0.896938 V_S	89.69% V_S
90^0	$\pi/2$; $(3\pi/6)$	0.7071 V_S	70.7% V_S
120^0	$2\pi/3$; $(4\pi/6)$	0.44215 V_S	44.21% V_S
150^0	$5\pi/6$; $(5\pi/6)$	0.1698 V_S	16.98% V_S
180^0	π ; $(6\pi/6)$	0 V_S	0 V_S



Plot of RMS output voltage $V_{L(RMS)}$ versus trigger angle α

- We can notice from figure, that we obtain a much better output control characteristic by using a single phase full wave ac voltage controller.
- **RMS output voltage can be varied from a maximum of 100%Vs at α=0 to a minimum of "0" at α=180º.**
- Thus we get a full range output voltage control by using a single phase full wave ac voltage controller.
- **Hence, mathematically proved.**



Lets watch a video

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LEARN AND GROW

Numericals

A single-phase full-wave AC voltage controller with resistive load

4-1 (Solved Problem) A single-phase full-wave AC voltage controller in Fig. 4.2-1 has an input voltage of 220 V (rms), 50 Hz and a load resistance of 10 Ω. The converter operates at a firing angle of 45°. Assuming that the converter is ideal, calculate/answer the following:

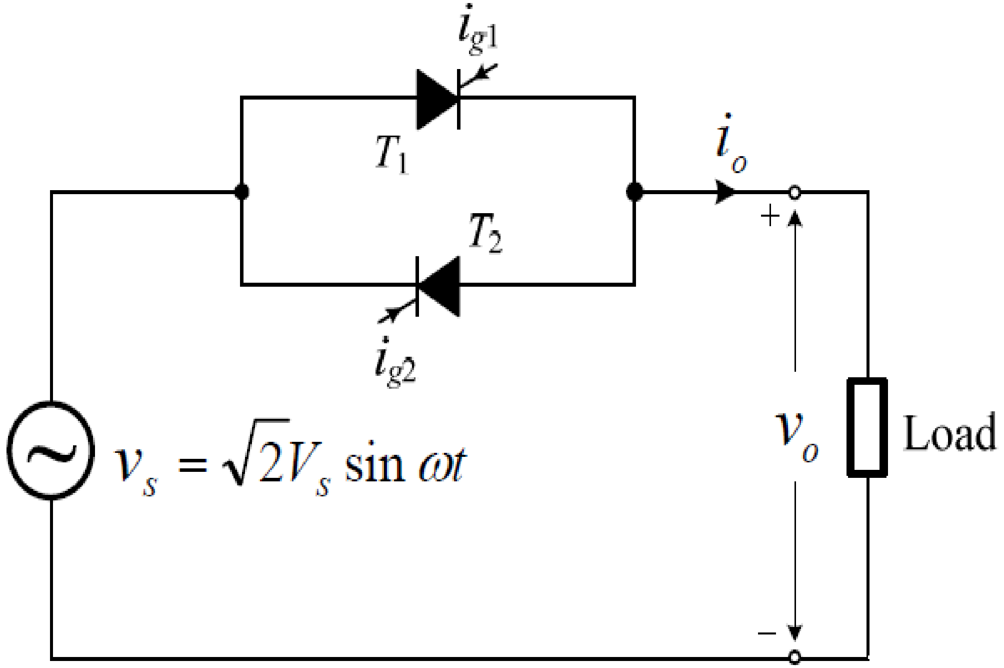
a) the rms output voltage and current,

b) the load apparent, active and reactive powers,

c) the rms input and thyristor currents,

d) the apparent, active, reactive powers and input power factor, and

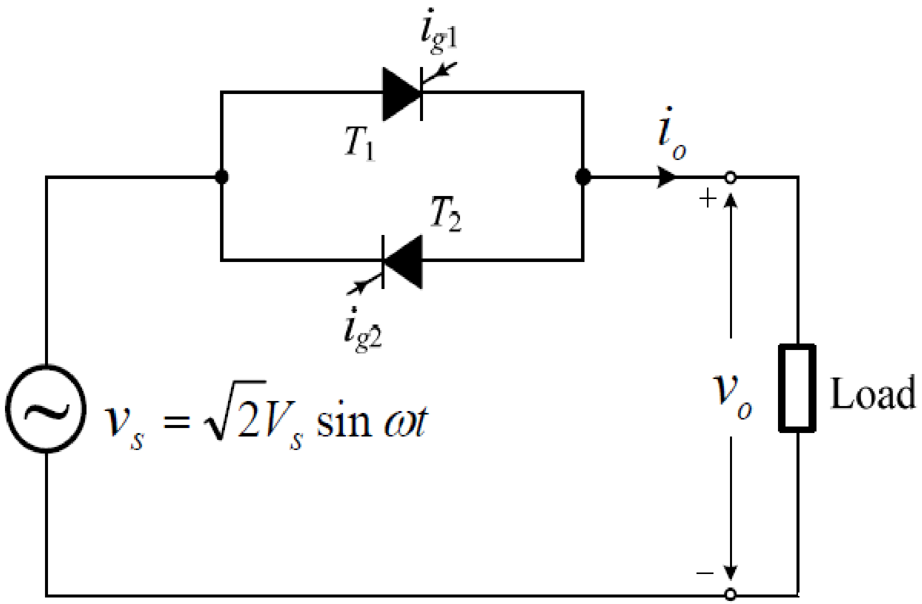
e) draw the waveforms for $v_s, i_{g1}, i_{g2}, v_o, i_o, i_{T1}$ and i_{T2}.



Solution:

a) The output voltage: $V_o = V_s\left(1-\frac{\alpha}{\pi}+\frac{\sin 2\alpha}{2\pi}\right)^{1/2} = 220\left(1-\frac{\pi/4}{\pi}+\frac{\sin 2(\pi/4)}{2\pi}\right)^{1/2} = 209.77\text{ V (rms)}$ (α is in radians)

The output current: $I_o = \frac{V_o}{R} = \frac{209.77}{10} = 20.977\text{ A (rms)}$

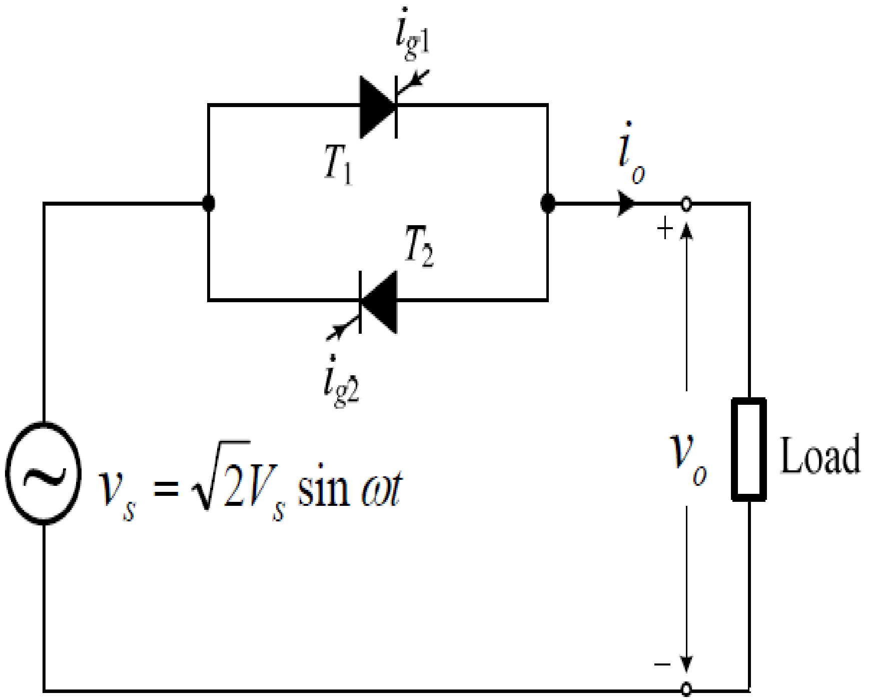


b) The load apparent power: $S_o = V_o \times I_o = 209.77 \times 20.977 = 4400.3\text{ VA}$

The load active power: $P_o = I_o^2 \times R = 20.977^2 \times 10 = 4400.3\text{ W}$

c) The input current: $I_s = I_o = 20.977\text{ A (rms)}$ (ideal converter, no losses)

The thyristor currents: $I_{T1} = I_{T2} = \frac{I_o}{\sqrt{2}} = \frac{20.977}{\sqrt{2}} = 14.833\text{ A (rms)}$ (each thyristor carries half the load current)



d) The input apparent power: $S_s = V_s \times I_s = 220 \times 20.977 = 4614.9$ VA

The input active power: $P_s = P_o = 4400.31$ W

The input reactive power: $Q_s = \sqrt{S_s^2 - P_s^2} = \sqrt{4614.92^2 - 4400.31^2} = 1390.9$ VAR

$$Q_s = S_s \times \sin\varphi_s = V_s \times I_s \times \sin\varphi_s = 220 \times 20.977 \times 0.3014 = 1390.9 \text{ VAR}$$

The input power factor: $PF_s = \dfrac{P_s}{S_s} = \dfrac{4400.3}{4614.9} = 0.9535$

4-2 A single-phase full-wave AC voltage controller with an input voltage of 120 V (rms) and 60 Hz feeds a 1.0kW/120V resistive load. Repeat Problem P4-1 for a firing angle of 60°.

Answers:

a) $R = 14.4\,\Omega$, $V_o = 107.63$ V, $I_o = 7.48$ A

b) $S_o = 804.5$ VA, $P_o = 804.5$ W, $Q_o = 0$ VAR

c) $I_s = 7.48$ A, $I_{T1} = I_{T2} = 5.285$ A

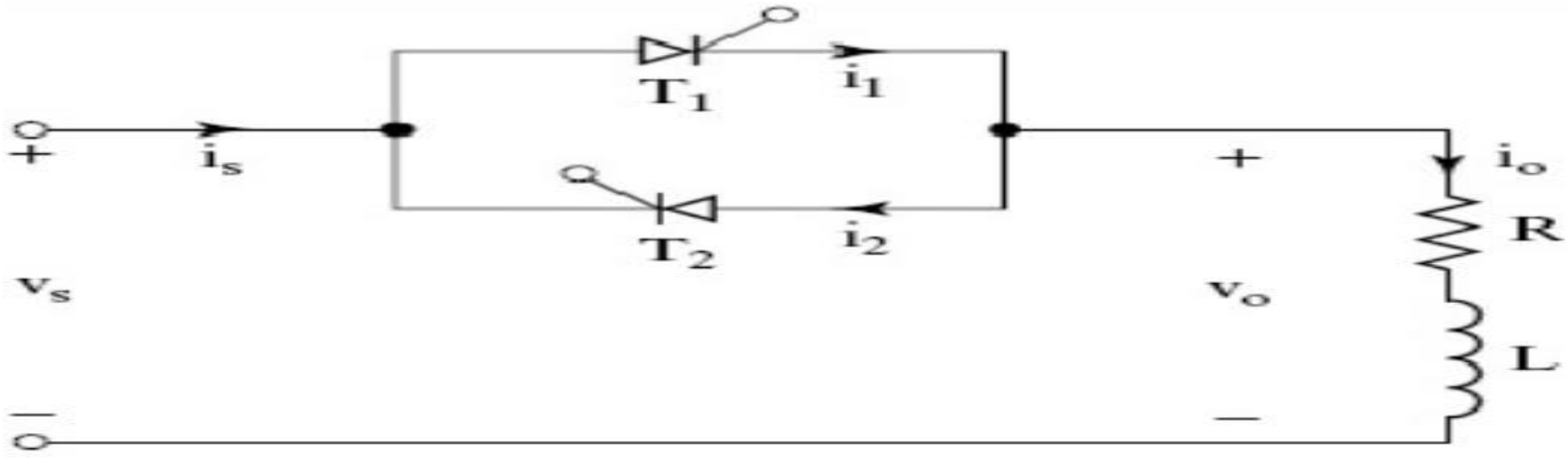
d) $S_s = 896.94$ VA, $P_s = 804.5$ W, $Q_s = 396.59$ VAR, $PF_s = 0.8969$ (lag)

1-PHASE FULL WAVE AC VOLTAGE CONTROLLER (BIDIRECTIONAL CONTROLLER) WITH RL LOAD

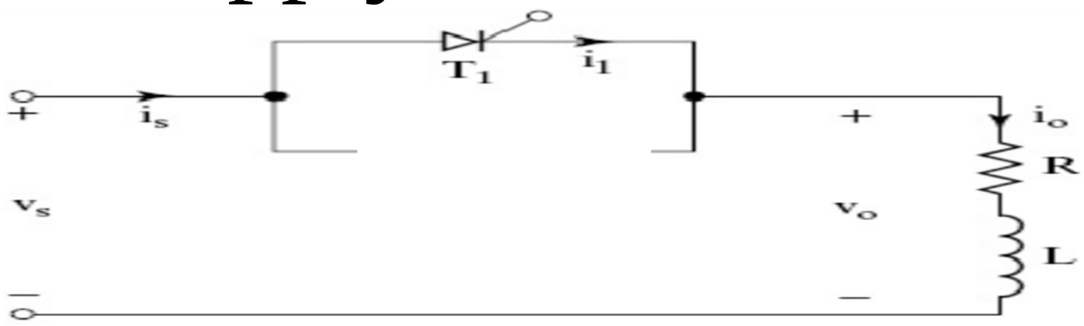
- In practice most of the loads are of RL type.
- For example: If we consider a single phase full wave ac voltage controller controlling the speed of a single phase ac induction motor, the load which is the induction motor winding is an RL type of load,
- where R represents the motor winding resistance and L represents the motor winding inductance.

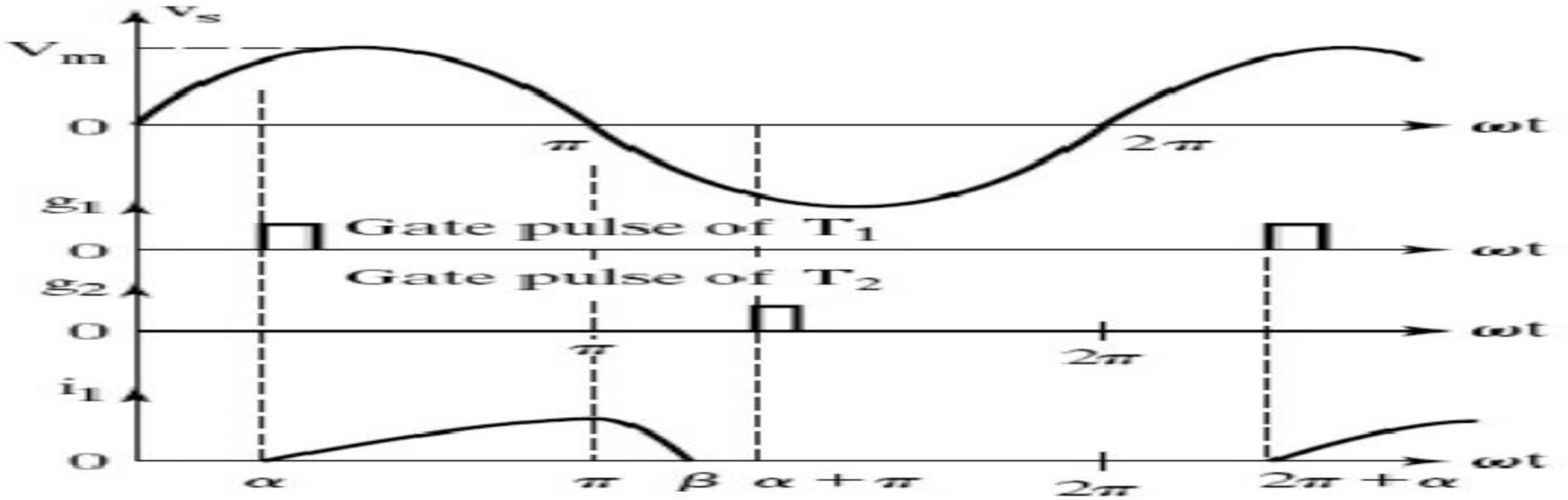
Configuration of 1-phase full wave ac voltage controller with RL load

- A 1-phase full wave ac voltage controller circuit (bidirectional controller) with an RL load using 2 thyristors (T1 & T2) connected **in anti-parallel between power supply & load.**



Thyristor T_1 is forward biased during +ve 1/2 cycle of input supply Vs.

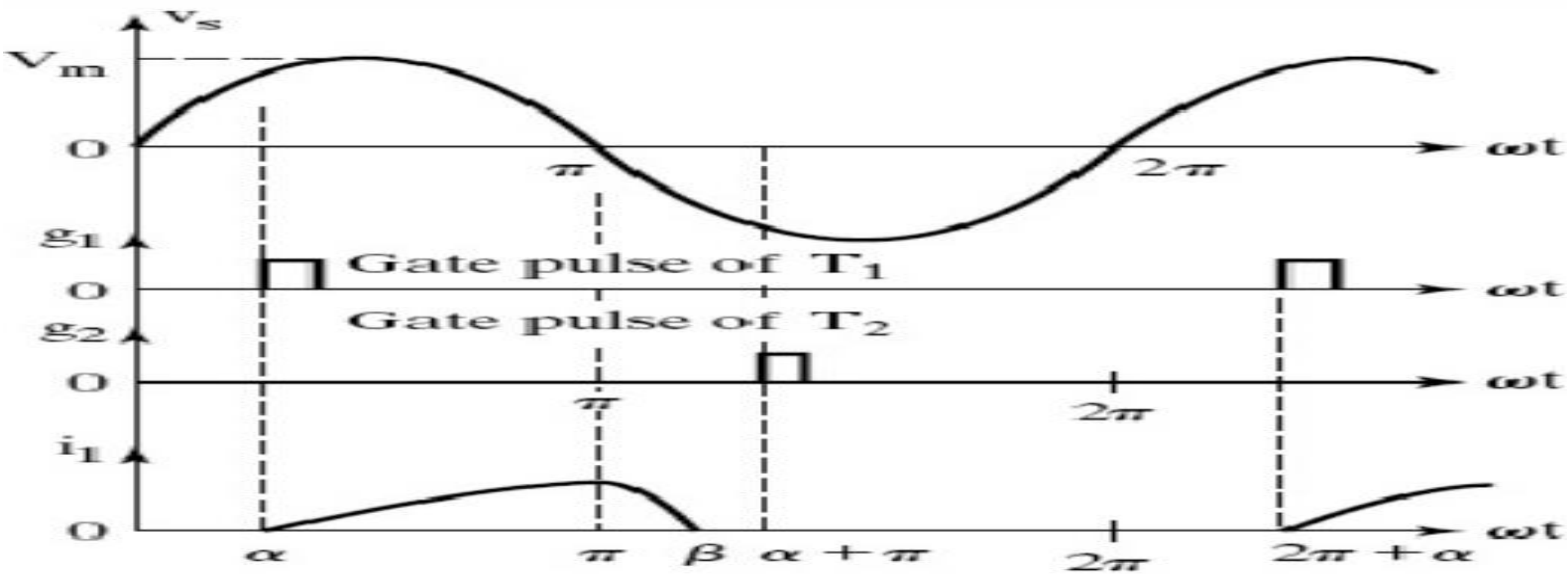


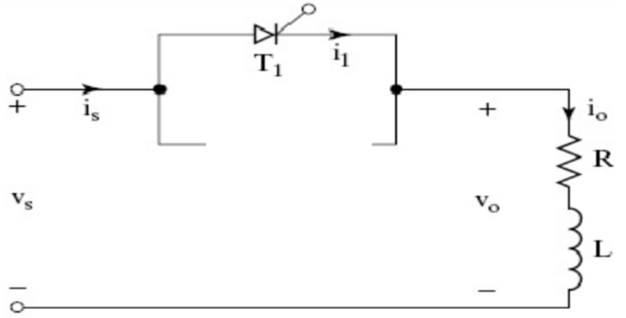


.

T1 is triggered at ωt=α by applying a suitable gate trigger pulse to T1 during the +ve 1/2 cycle of input supply Vs.

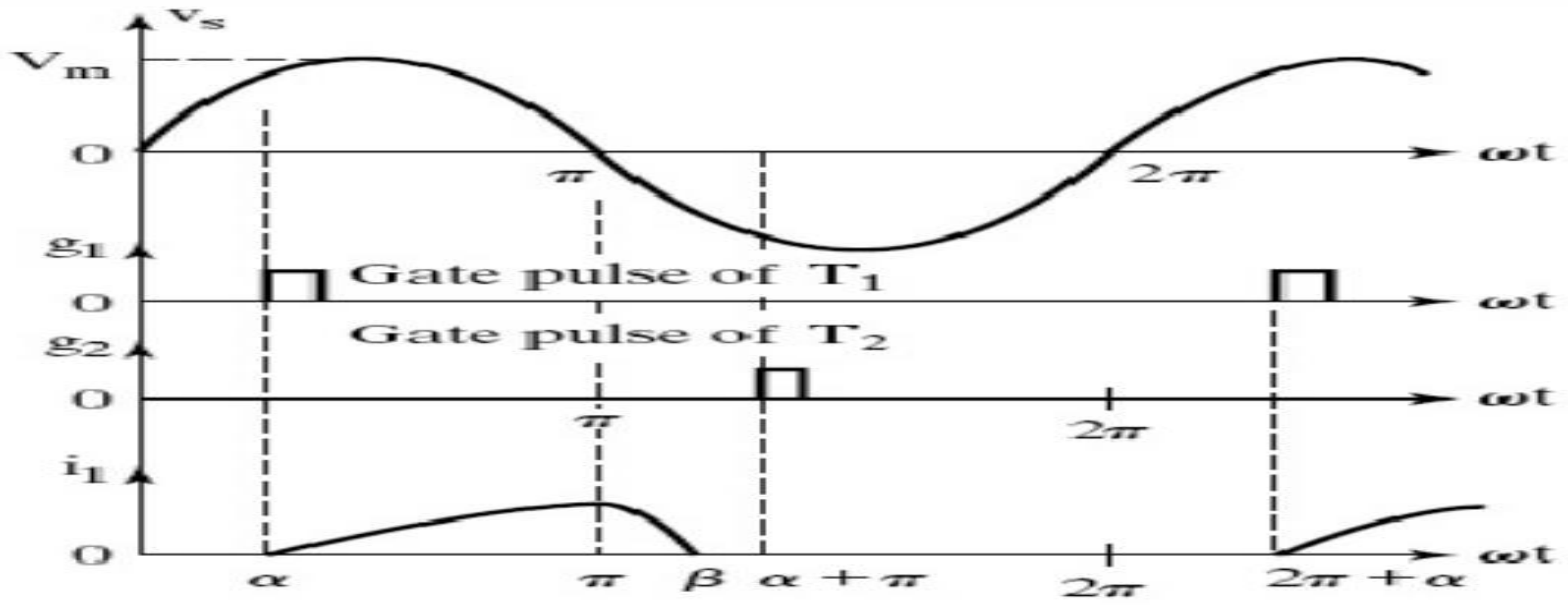
- Output voltage across load follows input supply voltage *vs* when T_1 is ON. Load current i_o flows through thyristor T_1 and through load in downward direction.

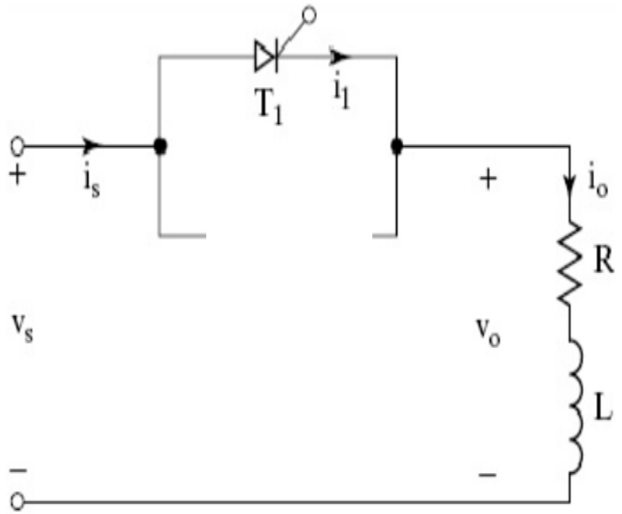




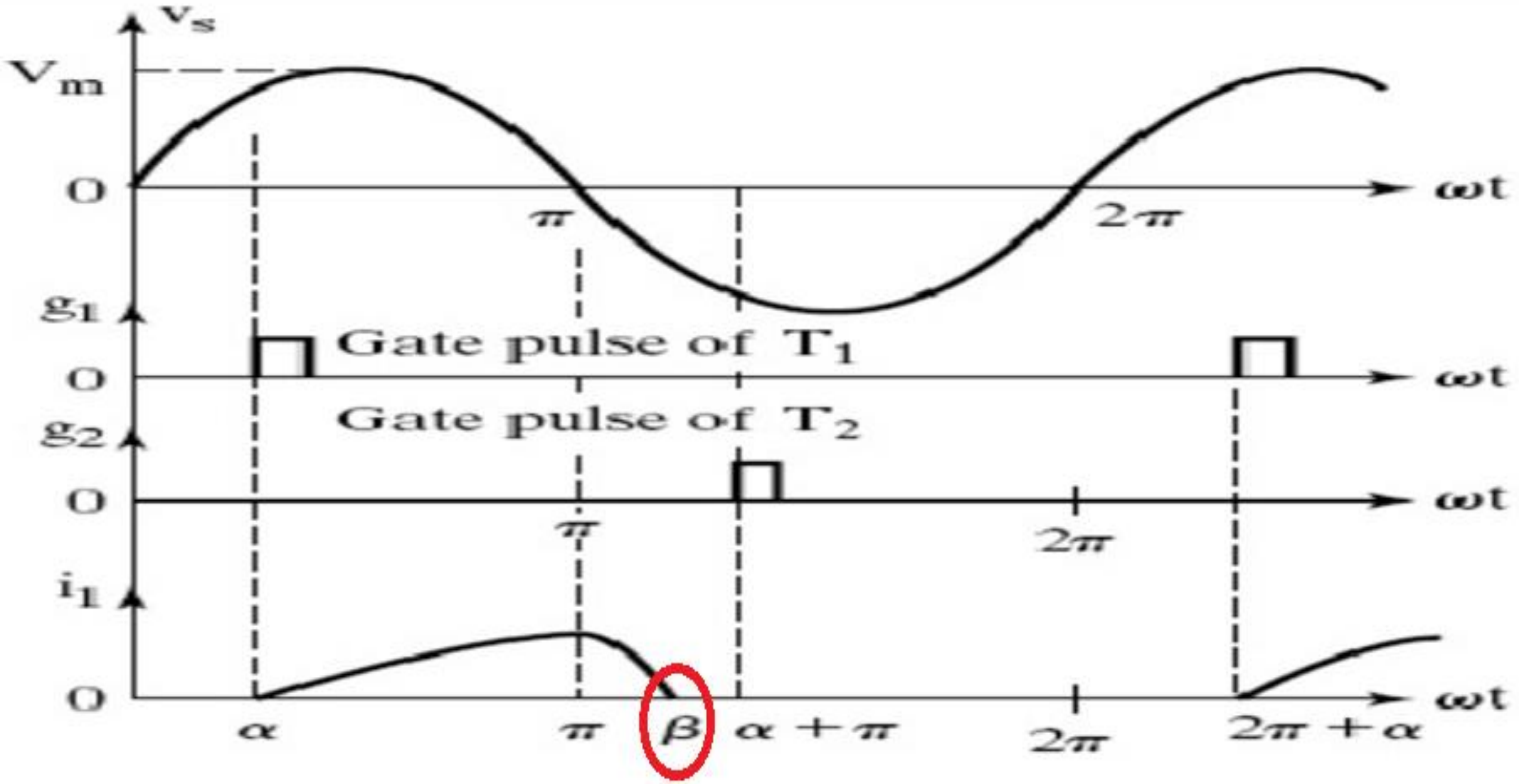
This load current pulse flowing through T1 can be considered as +ve current pulse.

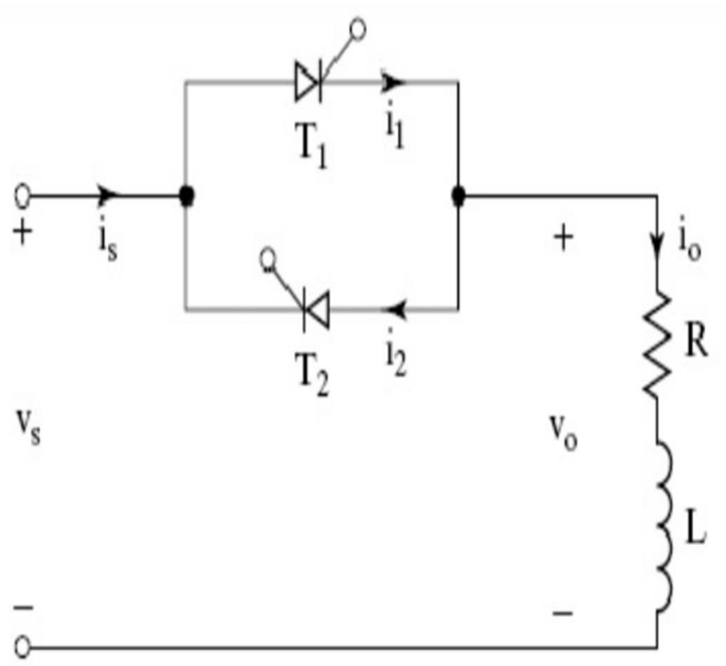
- Due to inductance in load, load current i_o flowing through T1 would not fall to 0 at $\omega t=\pi$ when input supply voltage starts to become -ve.





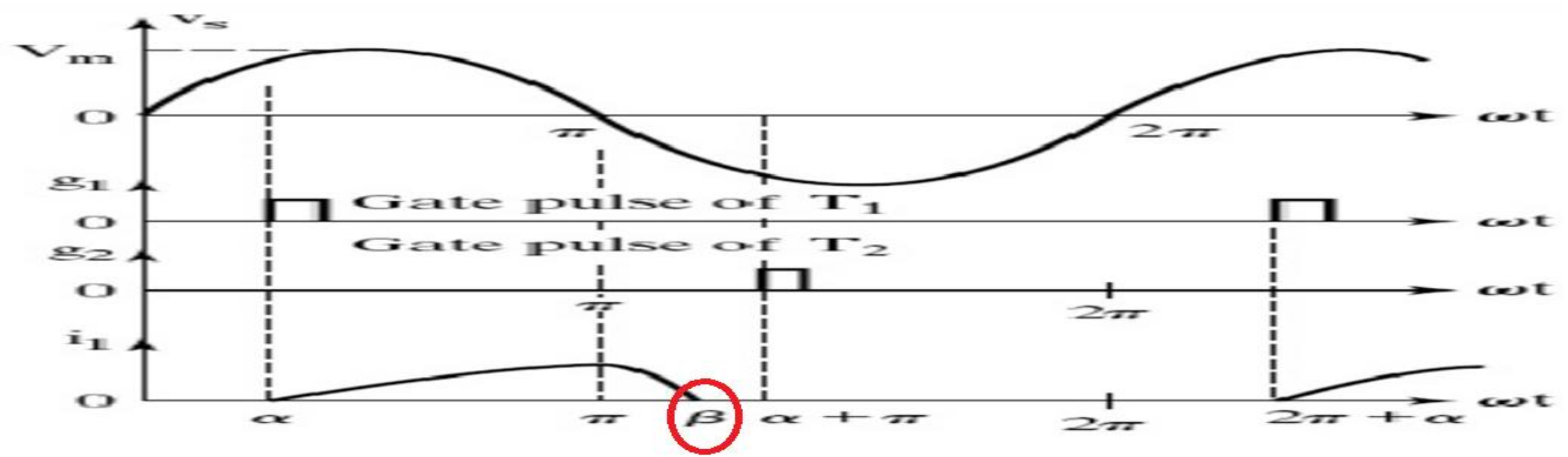
Thyristor T1 will continue to conduct load current until all inductive energy stored in load inductor L is completely utilized & load current through T1 falls to 0 at ωt=β



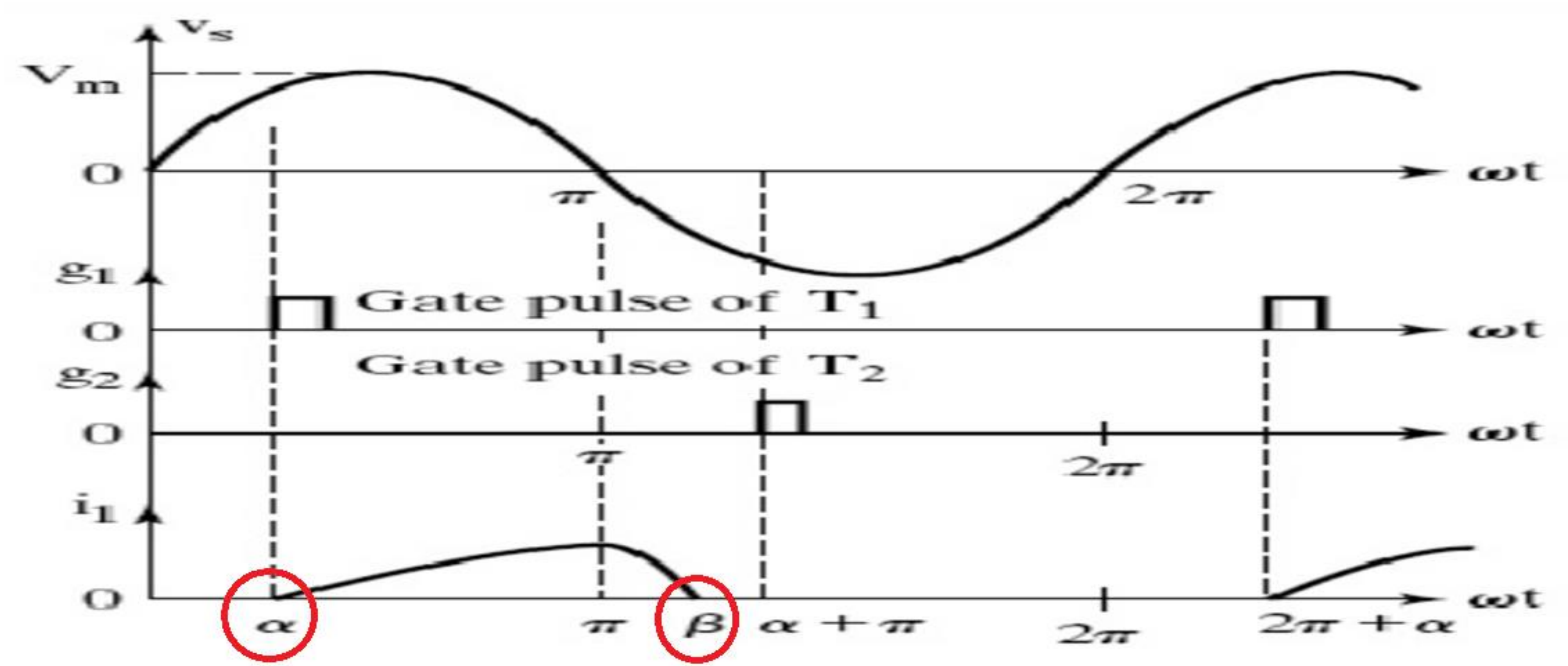


Where β is referred to as Extinction angle, (value of ωt) at which load current falls to 0.

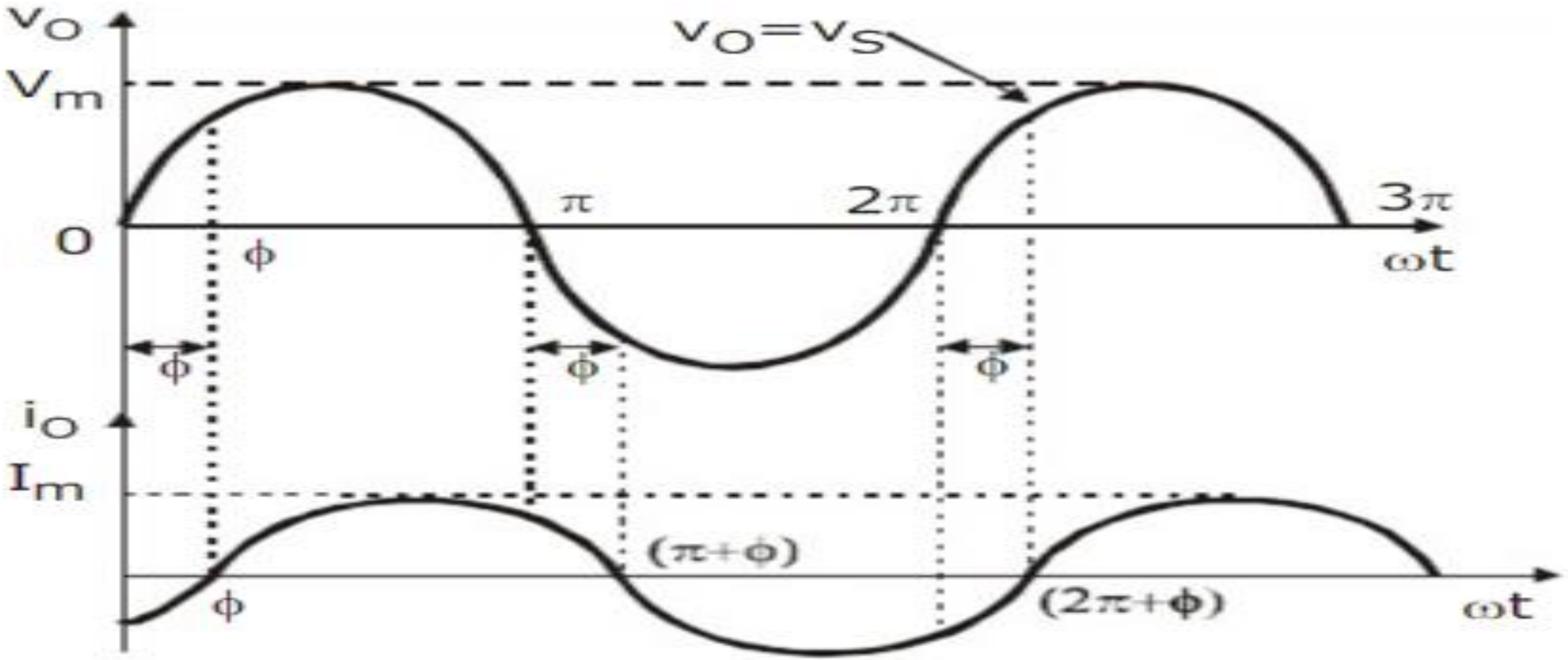
- Extinction angle β is measured from point of beginning of +ve ½ cycle of input supply to point where load current falls to 0. β depends upon load inductance value.



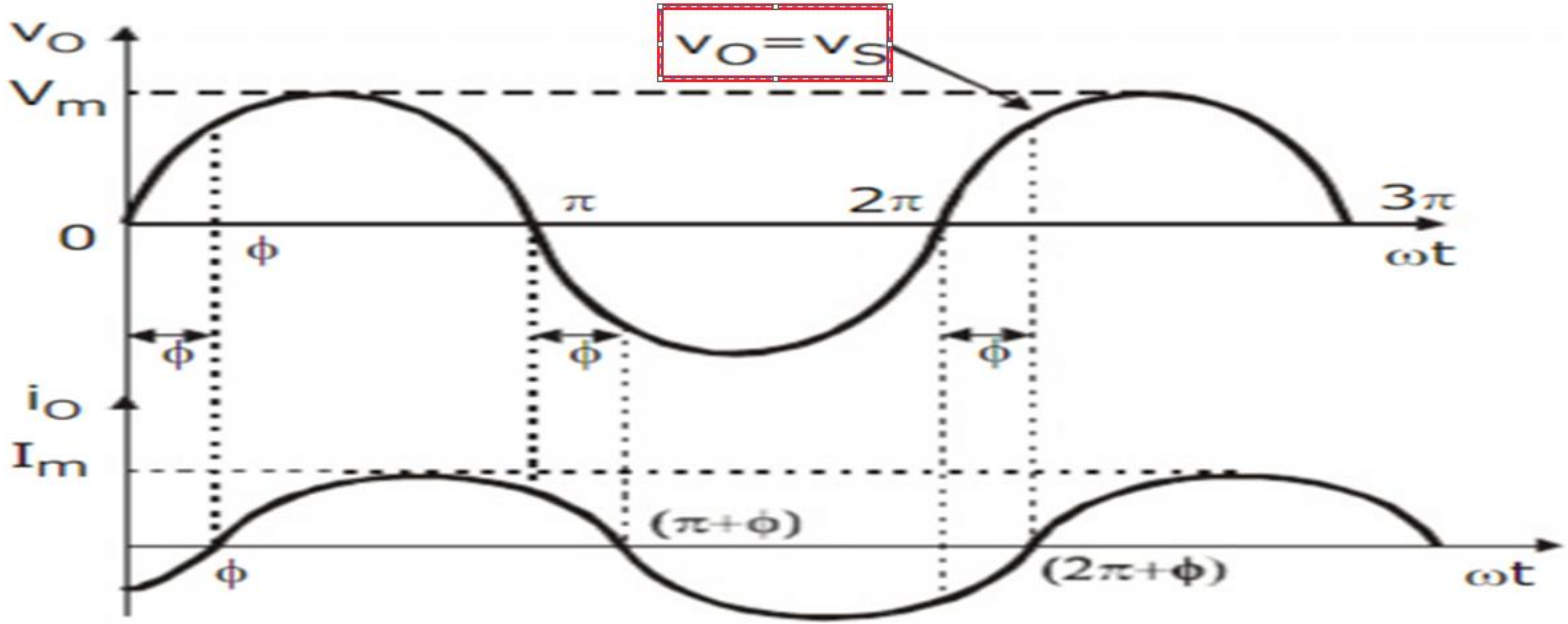
Thyristor T_1 conducts from $\omega t=\alpha$ to β. Conduction angle of T_1 is $\delta=(\beta-\alpha)$,which depends on delay angle α & load impedance angle φ



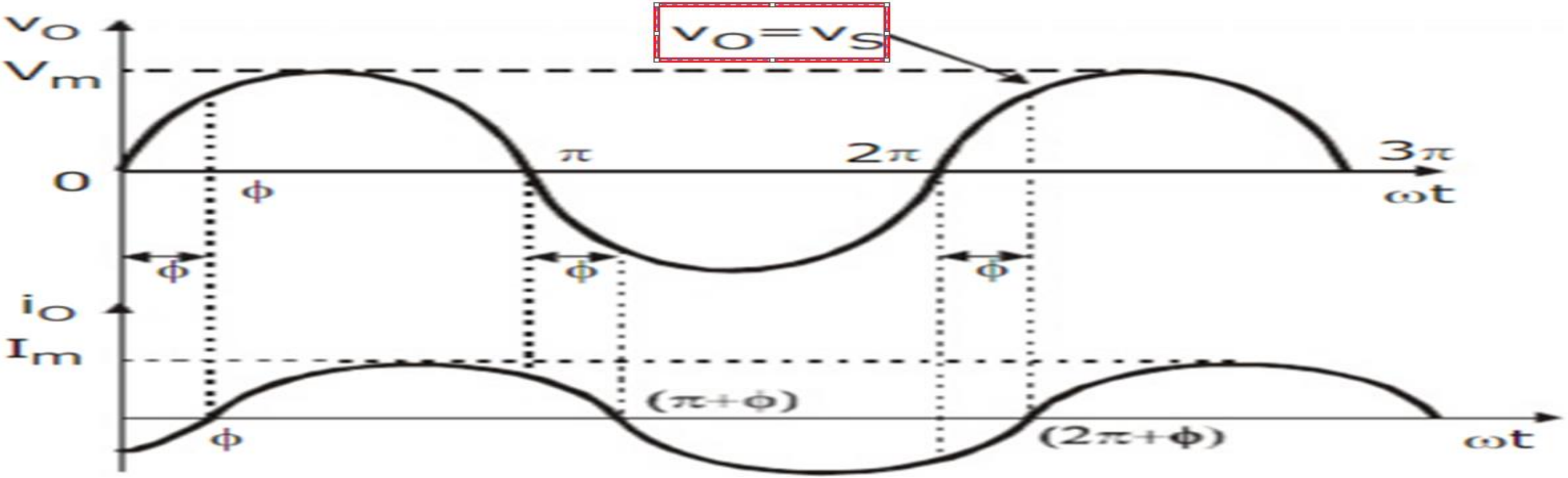
For trigger angle $\alpha \leq \phi$ load current tends to flow continuously, without any break in load current waveform



we obtain output voltage waveform which is a continuous sinusoidal waveform identical to input supply voltage waveform



We loose control on output voltage for $\alpha<\phi$ as output voltage becomes equal to input supply voltage.



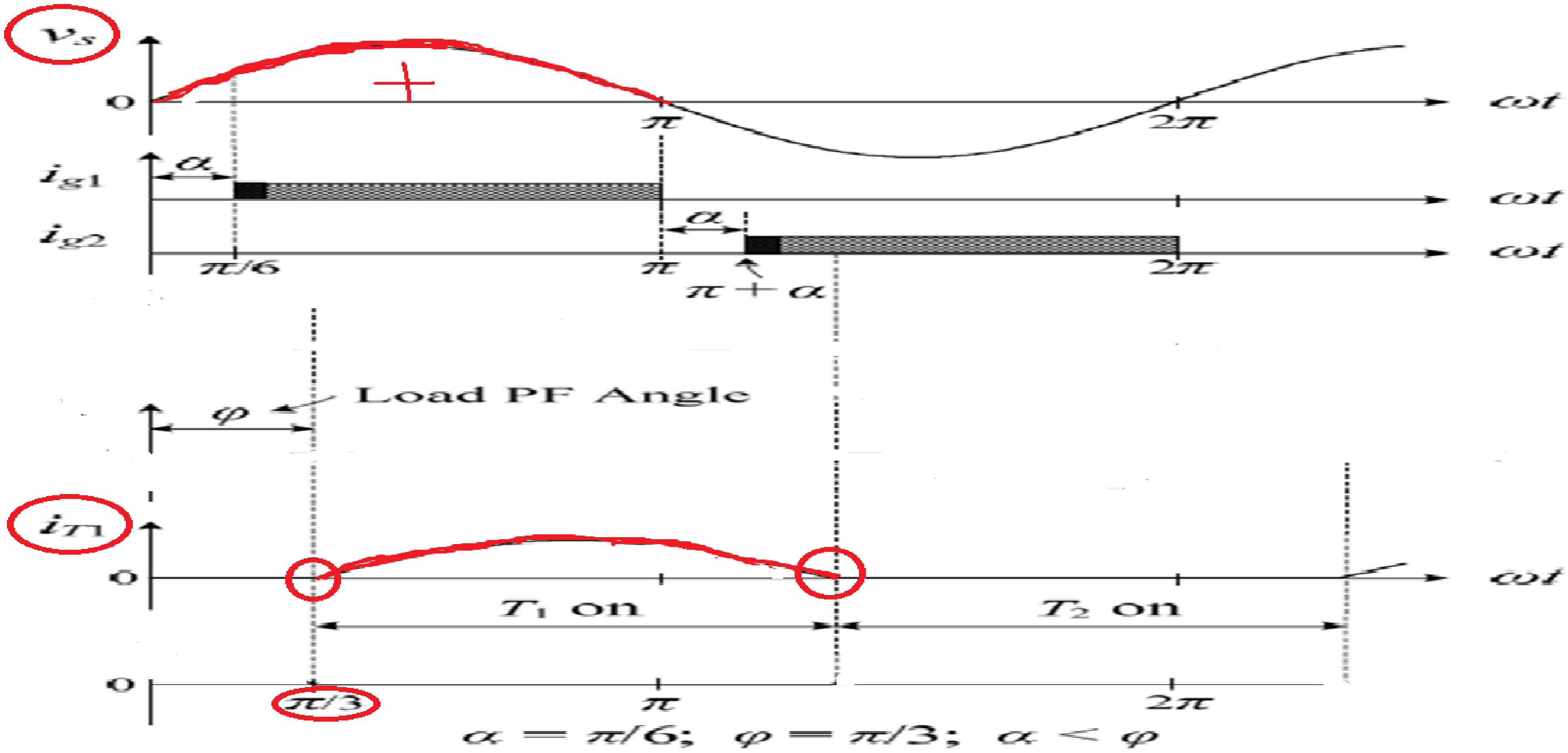
$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}} = V_S \quad ; \text{ for } \alpha \le \phi$$

Hence,

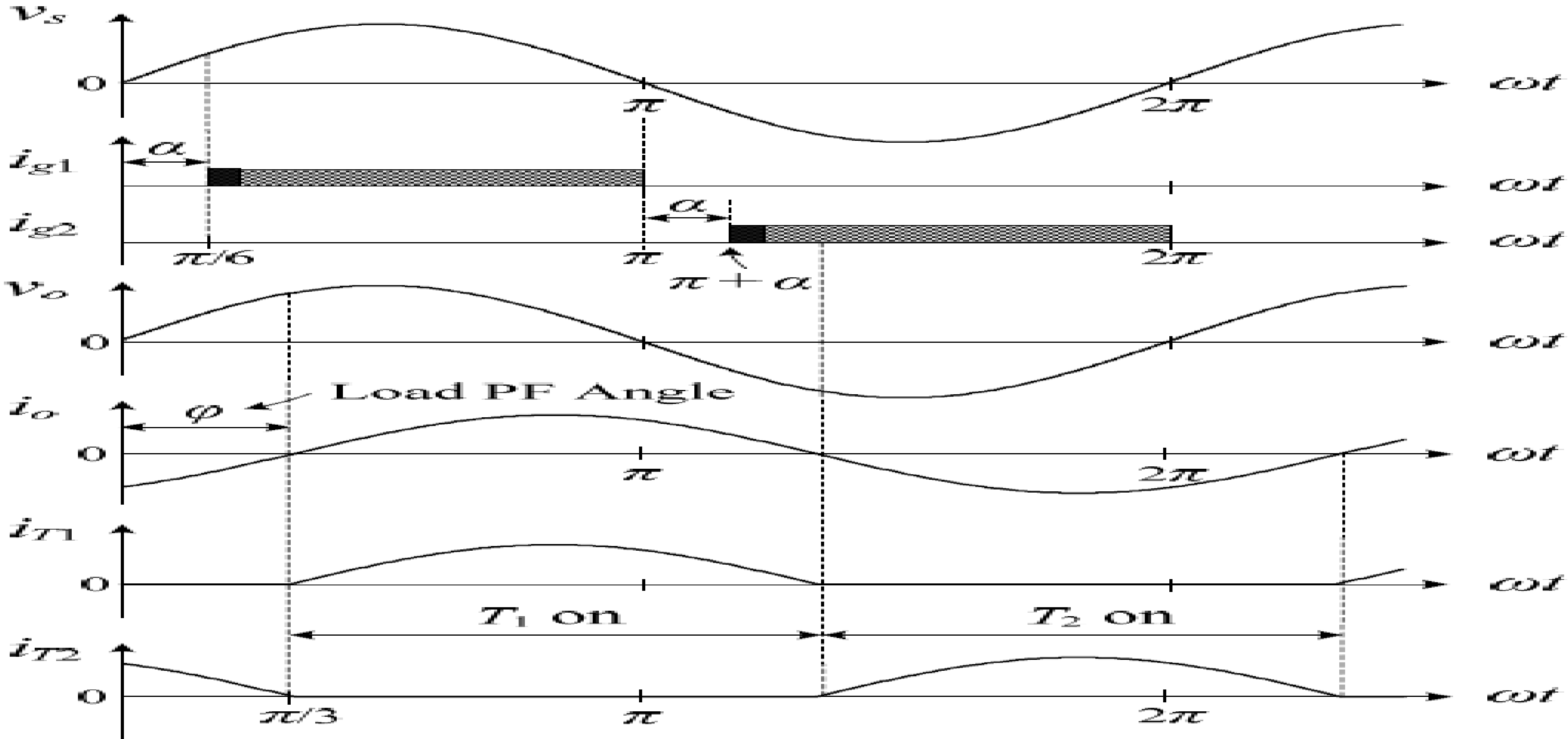
RMS output voltage =RMS input supply voltage for $\alpha \le \phi$

When delay angle $\alpha<$ load power factor angle φ?

In Fig. load power factor angle $\varphi = \pi/3 = 60^{o}$ & delay angle $\alpha = \pi/6 = 30^{o}$. During +ve ½ cycle of supply voltage *vs*, thyristor T_1 conducts for a certain period of time.



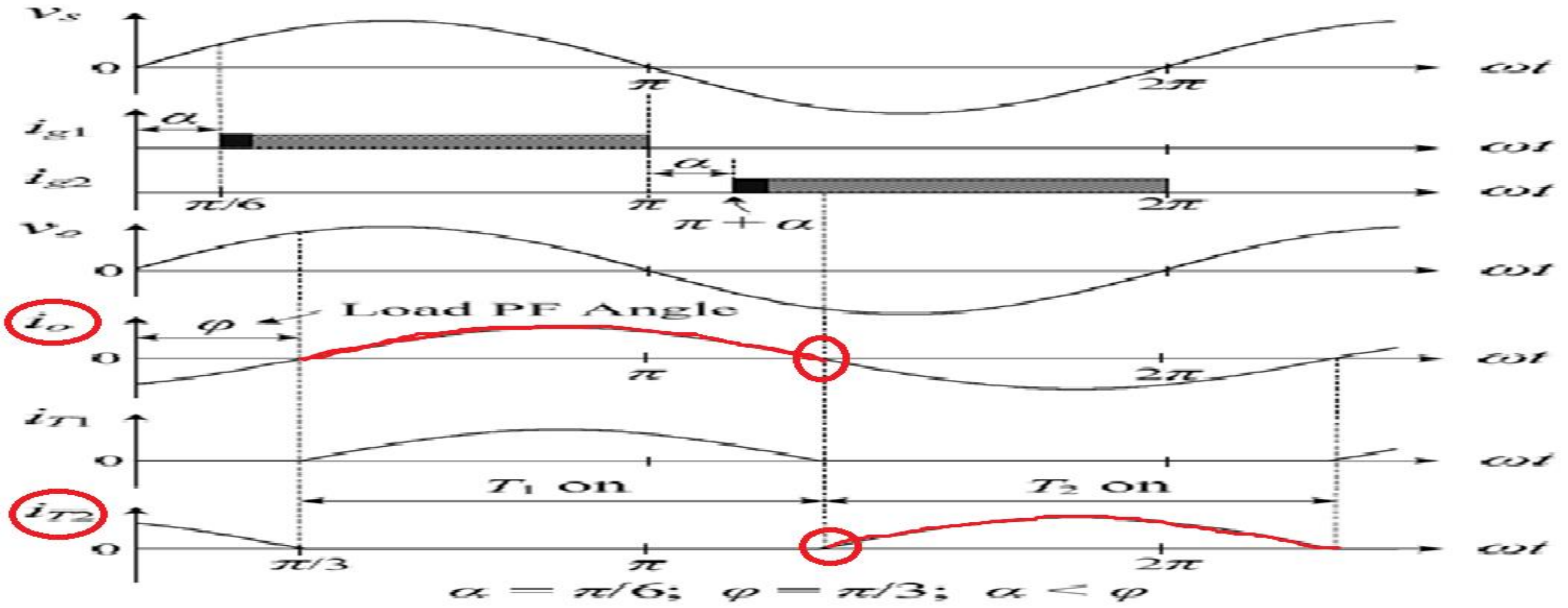
When gate signal for T_2 arrives at $\omega t = \pi + \alpha$, T_2 will not be turned on since load current i_o is still +ve due to inductive load & thus T_1 remains conducting.



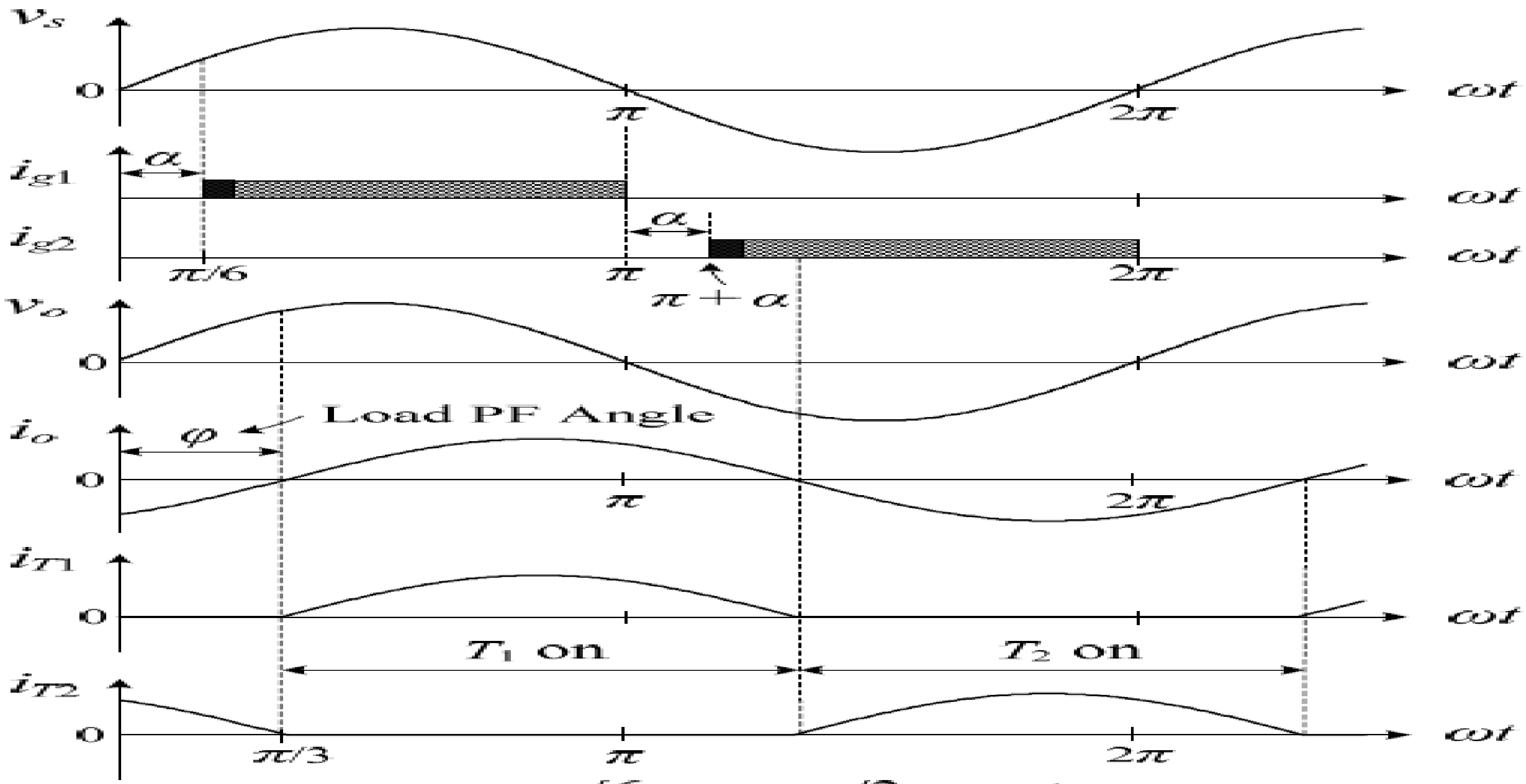
$\alpha = \pi/6; \ \varphi = \pi/3; \ \alpha < \varphi$

T_2 will be turned on only when i_o=0 & becomes -ve provided that gate current ig_2 for T_2 is still there. When T_2 is turned on, T_1 is reverse biased, & thus turned off.

- Both $T1$ & $T2$ conduct 180° alternatively per fundamental-frequency cycle & thus output voltage vo is equal to supply voltage vs. i.e vo= vs

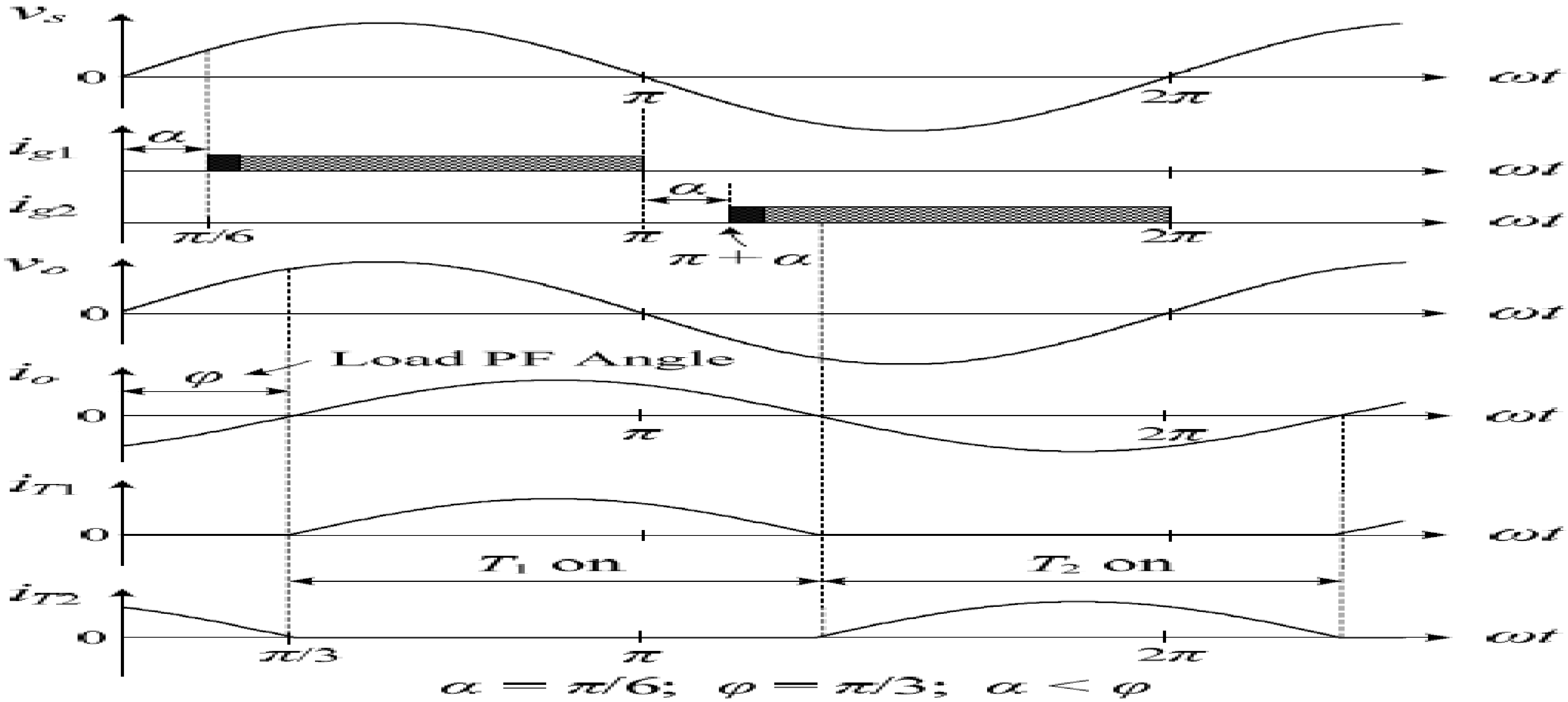


It is also noted that with an inductive load, continuous gating with extended duration, such as i_{g1} and i_{g2} in Fig., should be used.



$\alpha = \pi/6; \ \ \varphi = \pi/3; \ \ \alpha < \varphi$

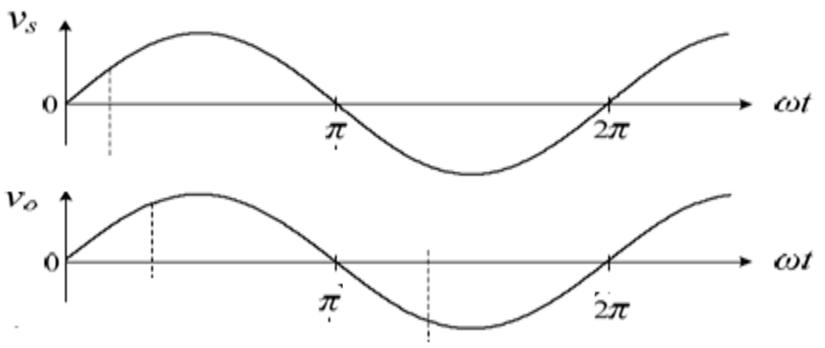
If gate signals are of short duration, controller will not operate properly. e.g with a short gating pulse ig_2 like one shown with a solid block in figure, T_2 will not be turned on during -ve cycle of supply voltage.



For a pure inductive load, rms value of output voltage v_o of controller can be calculated by

$$V_o = \begin{cases} V_s & \text{for } 0 \le \alpha < \pi/2 \\ V_s\left(2 - \dfrac{2\alpha}{\pi} + \dfrac{\sin 2\alpha}{\pi}\right)^{1/2} & \text{for } \pi/2 \le \alpha \le \pi \end{cases}$$

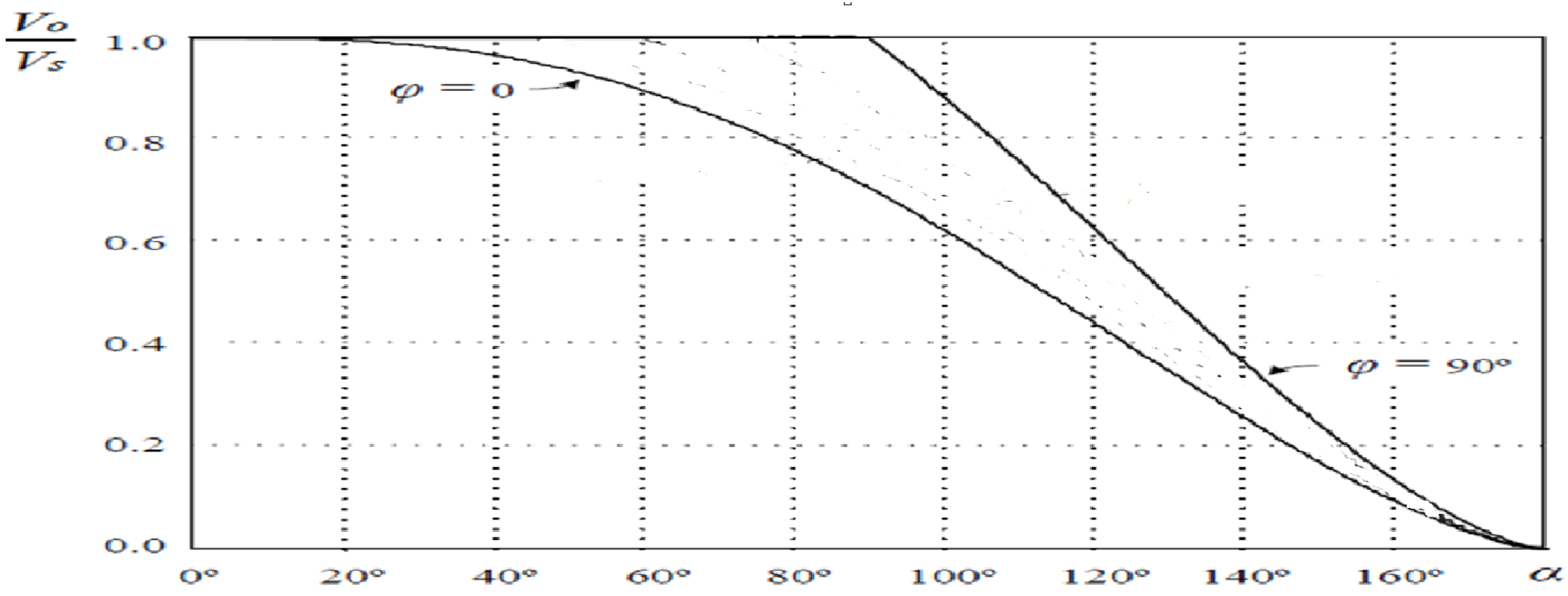
where Vo is equal to Vs for $0 \le \alpha < \pi/2$



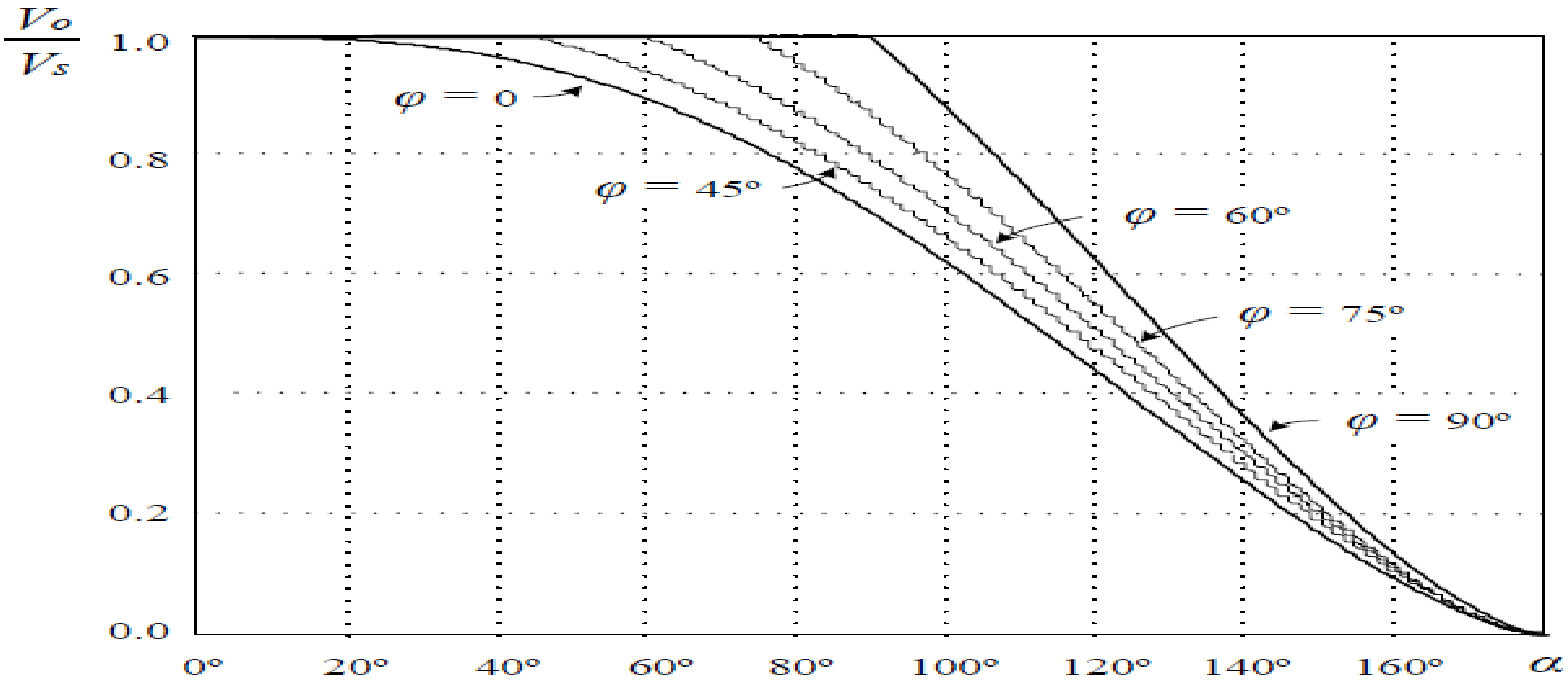
Relationship between voltage ratio *Vo*/ *Vs* & delay angle α with a (i)pure resistive (φ = 0) (ii) pure inductive (φ = 90º) load

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

$$\frac{V_o}{V_s} = \begin{cases} 1 & for \quad 0 \le \alpha < \frac{\pi}{2} \\ \sqrt{(2 - \frac{2\alpha}{\pi} + \frac{\sin 2\alpha}{\pi})} & for \quad \frac{\pi}{2} \le \alpha \le \pi \end{cases}$$



Other curves for load power factor angle of φ=45º, 60º & 75º are obtained by computer simulation.



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