AC – AC Converters

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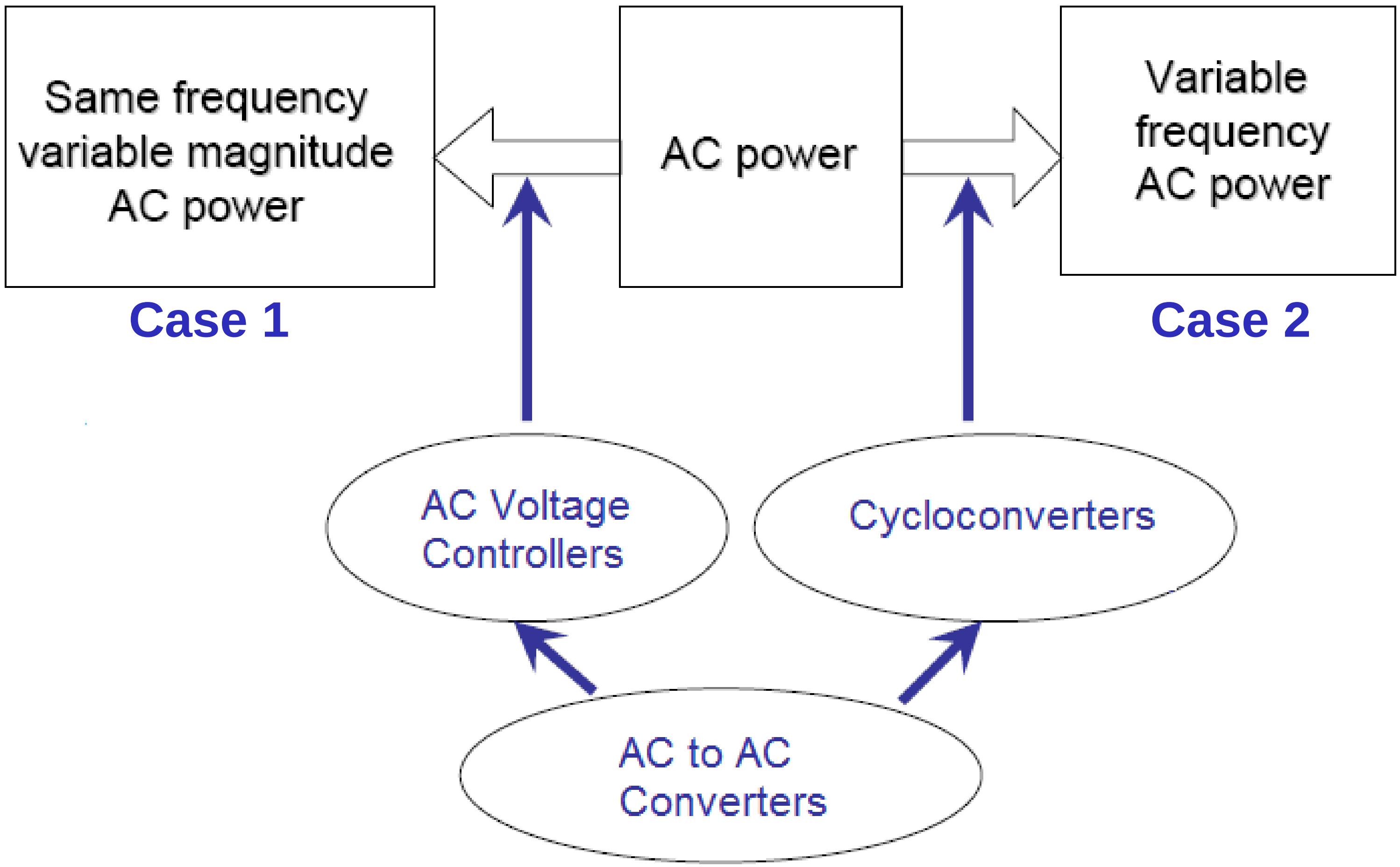
Outline

1. AC Voltage Controllers
   - 1.1 Phase control
     - Resistive load
     - Inductive load
   - 1.2 On-off control
     - Principles
     - Static switches (AC&DC)

2. Cycloconverters
   - 2.1 Basic operation principle
   - 2.2 Single phase system

Classification of AC to AC Converters



✓ Used to obtain a variable ac output voltage from a fixed ac source.

1. AC voltage control

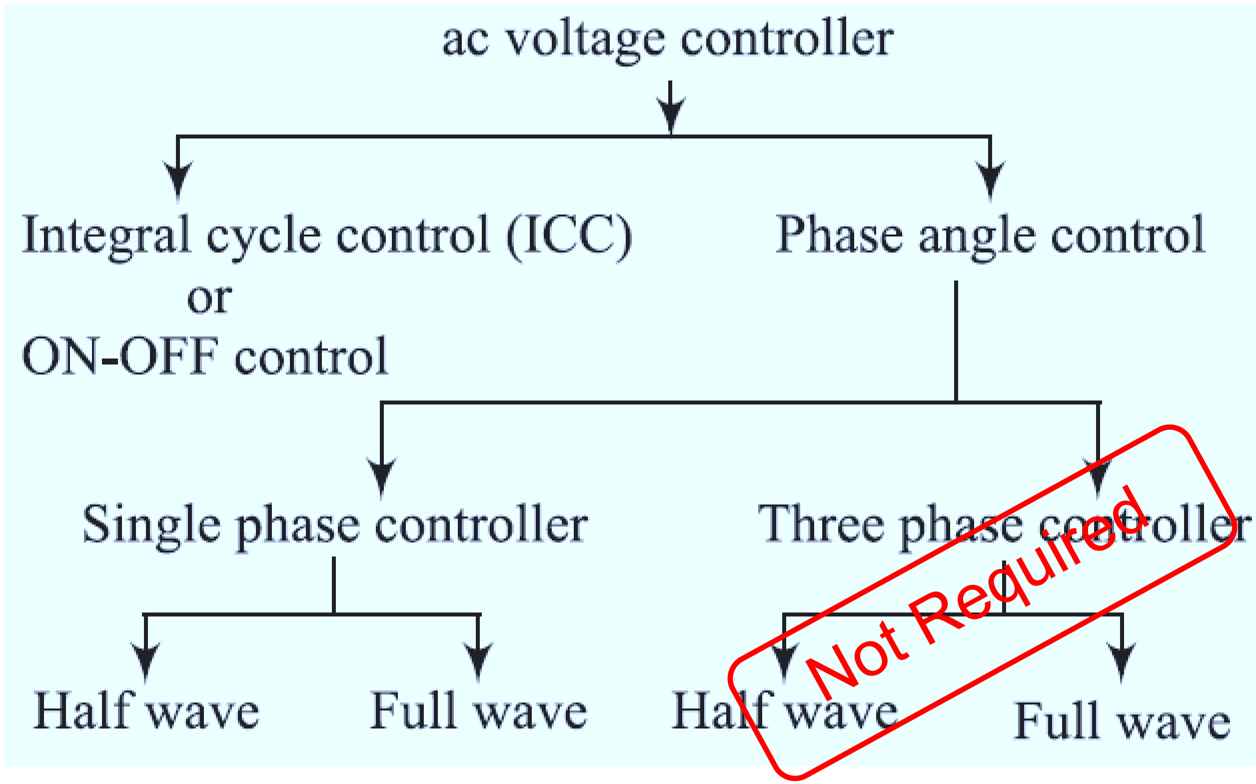
In order to get variable AC voltage from an AC source, two techniques are often used:

Allows a current flow in both directions

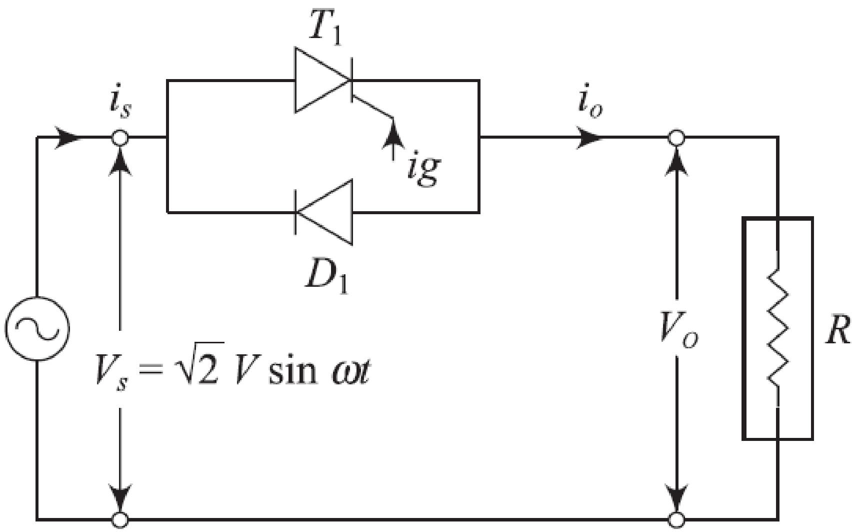
- **Phase control**
  - The strategy is to use anti-parallel connected thyristors or TRIACS (Triode AC Switch).
  - Like AC-DC converters, the firing angle of the devices are controlled.
  - The devices conduct for a portion of each cycle.
- **On-off/integral-cycle control**
  - The devices conduct some cycles in a period of time and then disconnect some cycles.
  - The firing angle of devices is 0. But for some cycles, the firing pulses are turned off.
  - Lower switching losses.

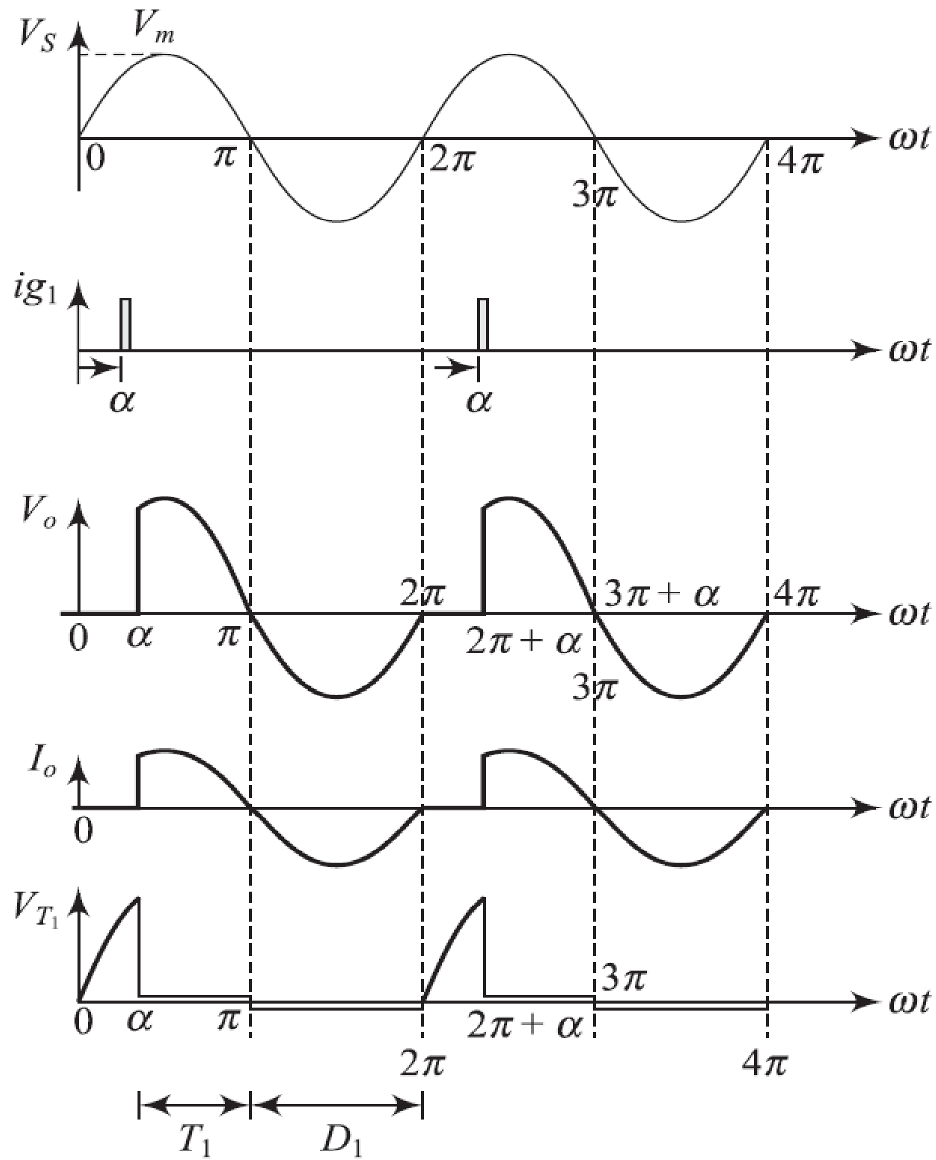
1. AC voltage control

The control strategies of AC voltage controllers are: 1) ON-OFF control or Integral cycle control, 2) Phase control.



1.1 Phase control (1-phase, half-wave–R Load)





- When T1 is forward biased during positive half-cycle, it is turned ON at a firing angle α.
- Negative half-cycle forward biases the diode D1 ($\omega t = \pi \rightarrow 2\pi$).
- Only positive half-cycle can be controlled, negative half-cycle cannot be controlled. (1-phase unidirectional voltage controller)

1.1 Phase control (1-phase, half-wave–R Load)

- The average value of output voltage, $V_o = \frac{1}{2\pi}\int_{\alpha}^{2\pi} V_m \sin \omega t \, dt = \frac{V_m}{2\pi}(\cos\alpha - 1)$

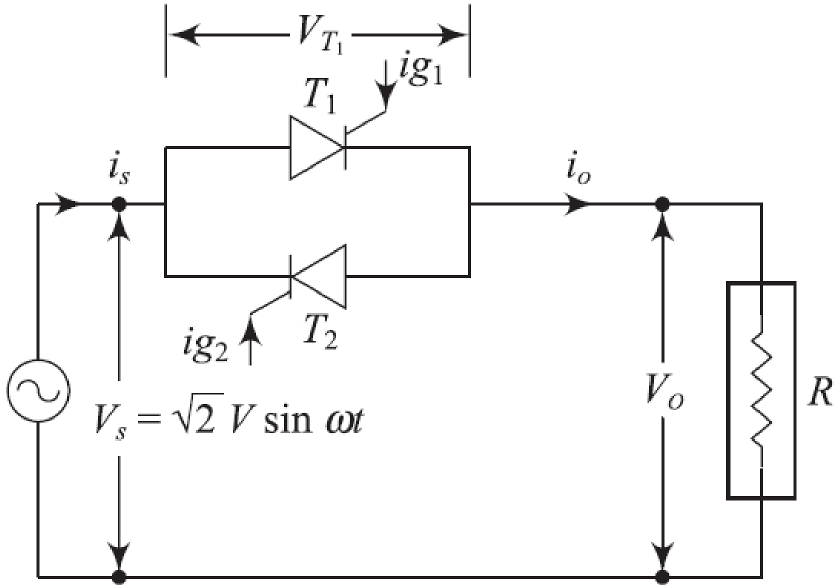
It is clear from the above expression that average output voltage can be controlled from 0 to $\frac{-V_m}{\pi}$.

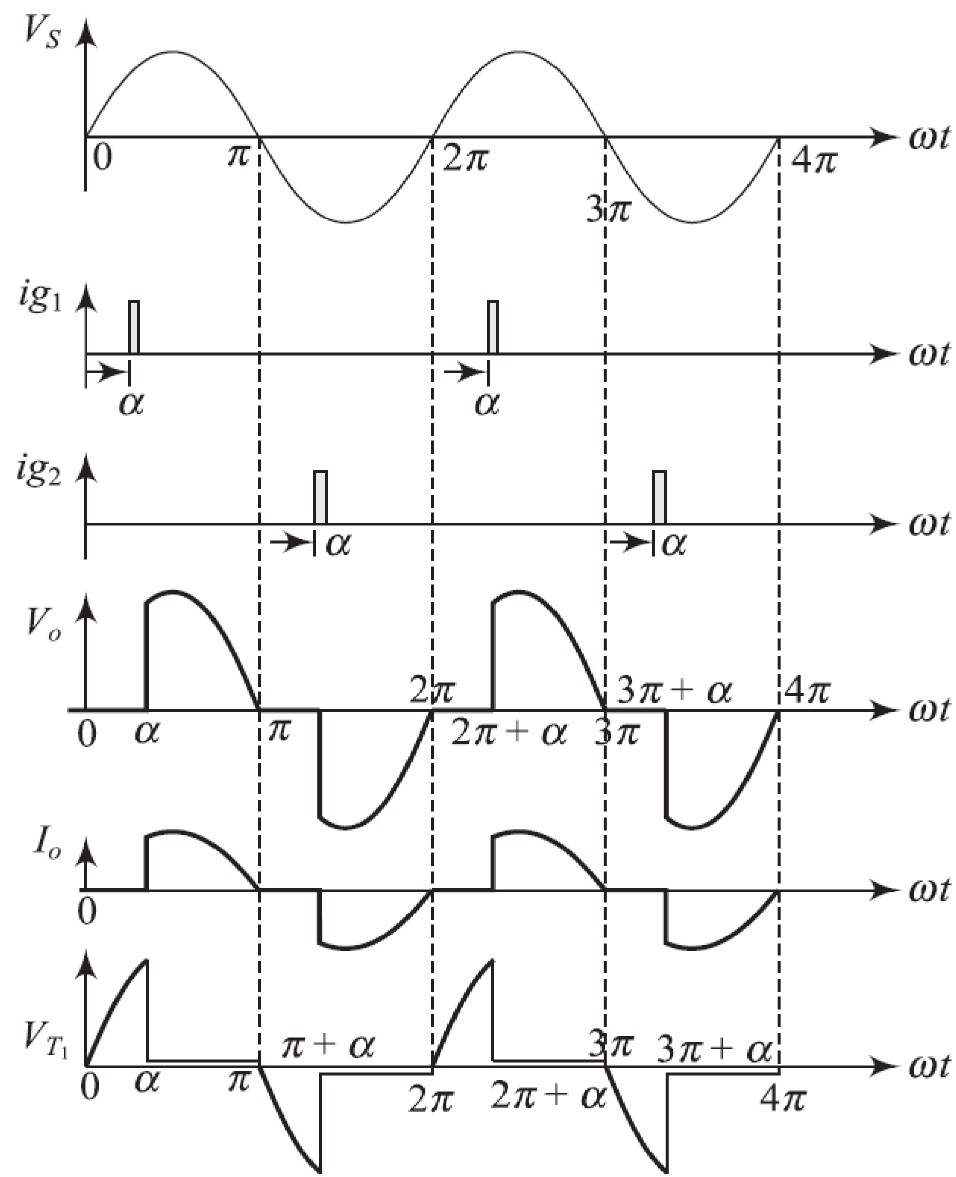
- The rms value of output voltage, $V_{RMS} = \left[\frac{1}{2\pi}\int_{\alpha}^{2\pi} {V_m}^2 \sin^2 \omega t \, dt\right]^{1/2}$

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

- RMS load current, $I_{RMS} = \frac{V_{RMS}}{R}$

1.1 Phase control (1-phase, full-wave—R Load)





– Positive half-cycle: T1 triggers at α and conducts from $\alpha \rightarrow \pi$.

– Negative half-cycle: T1 turns OFF & T2 triggers at $\pi + \alpha$ conducts until 2π.

- Also called, single-phase bidirectional voltage controller.

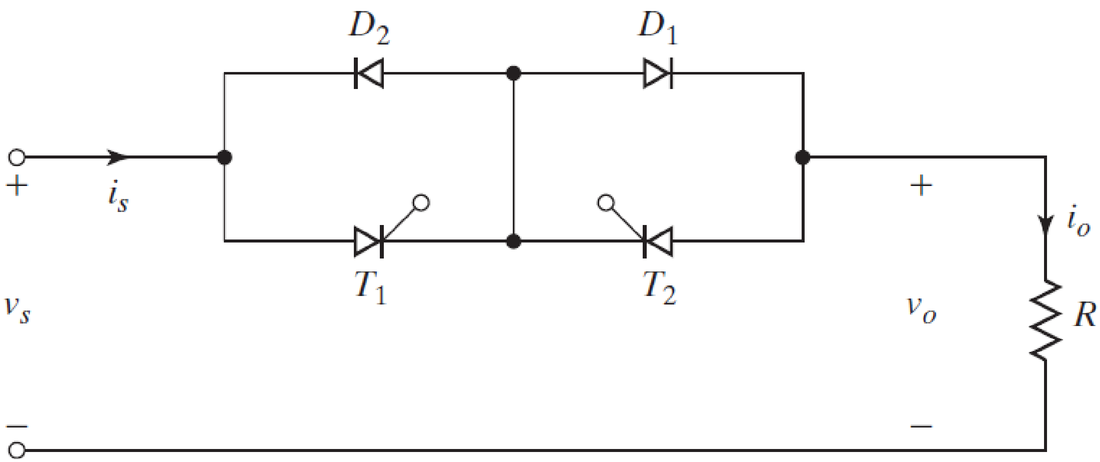
1.1 Phase control (1-phase, full-wave—R Load)

- RMS output voltage, $V_{RMS} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} {V_m}^2 \sin^2 \omega t \, dt\right]^{1/2} = \frac{V_m}{\sqrt{2}}\left[\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right]^{1/2}$

Can be controlled from $\frac{V_m}{\sqrt{2}}$ to 0 by changing α from 0^0 to 180^0

- RMS load current, $I_{RMS} = \frac{V_{RMS}}{R}$

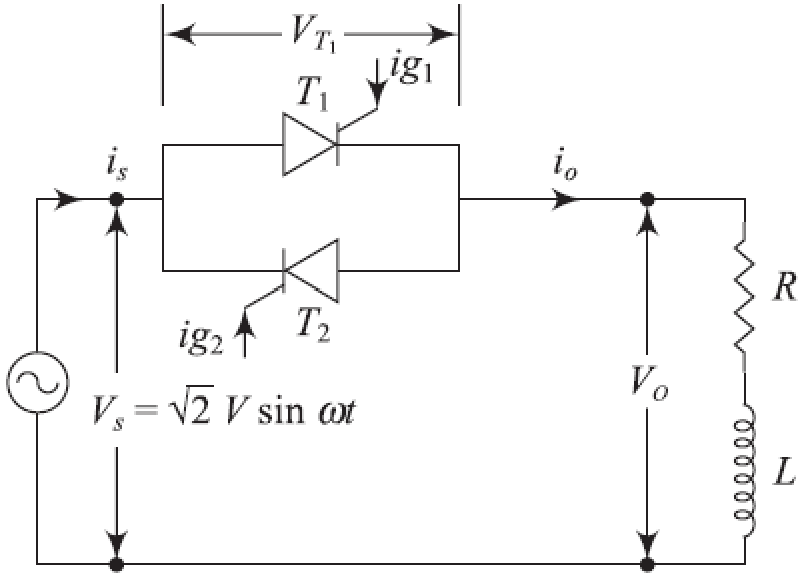
- Average value of output voltage – complete cycle and/or half cycle – Check?

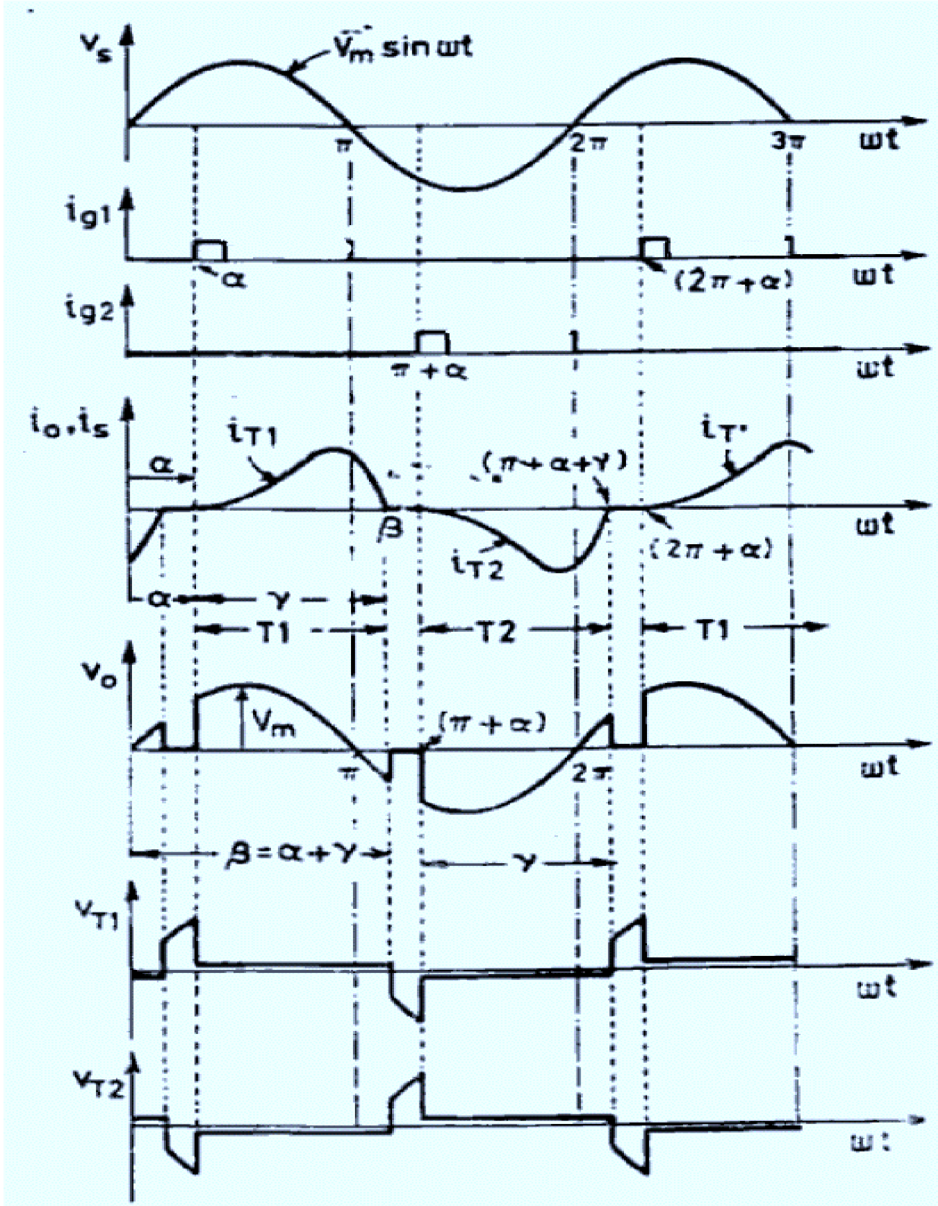


The gating circuits for T1 and T2 must be isolated – possible to have a common cathode for T1 and T2 by adding two diodes. T1, D1 conduct together during positive cycle; T2, D2 conduct during negative cycle.

- Conduction losses will increase and efficiency will drop, due to two devices conduct at the same time.

1.1 Phase control (1-phase, full-wave–RL Load)





- $[0 \rightarrow \pi]$: T1 is forward biased and will be triggered at α.

- At $\omega t = \pi$, load current is not zero because of inductance.

- $[\pi + \alpha \rightarrow \pi + \alpha + \gamma]$: Load current starts up in reversed direction through the load.

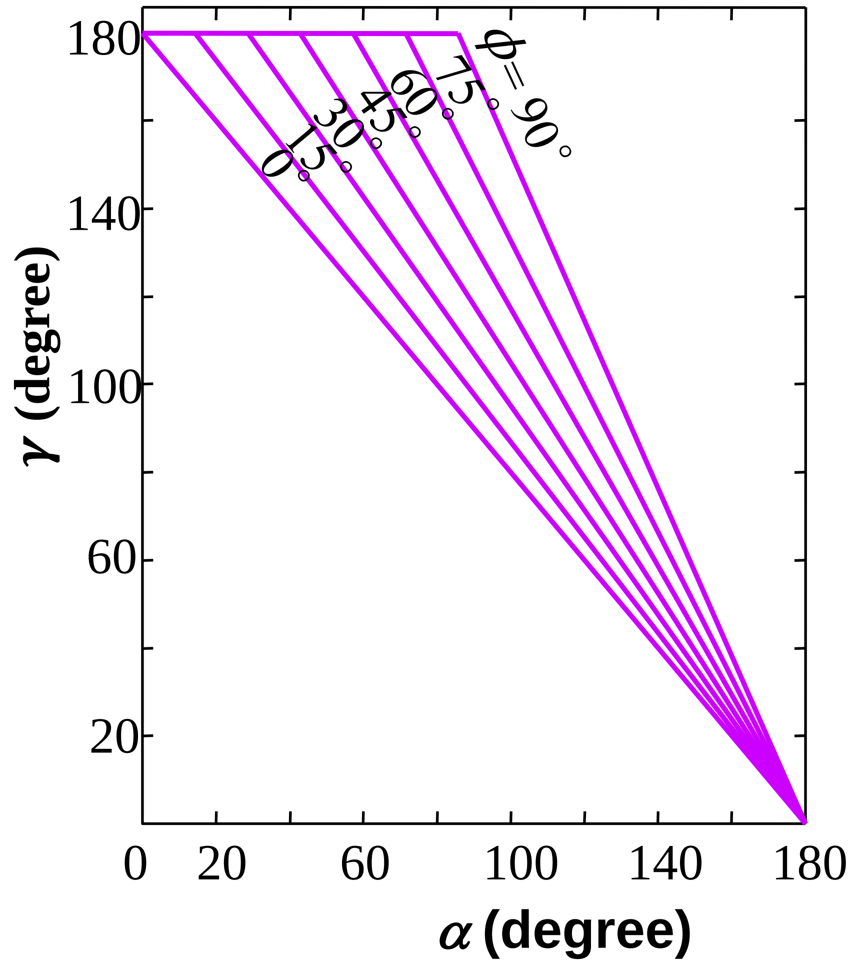
Quantitative analysis

Calculation to find termination/extinction angle β is similar to shown in Week 4, Half-wave controlled rectifier, Slide. 22.

$$\sin(\alpha - \varphi)e^{-\frac{\beta-\alpha}{\tan\varphi}} = \sin(\beta - \varphi)$$

with the knowledge of angles α and φ, the termination angle β can be calculated.

- For various values of γ and α, curves → are obtained for different values of φ. Note that the phase angle φ cannot exceed 90^0.

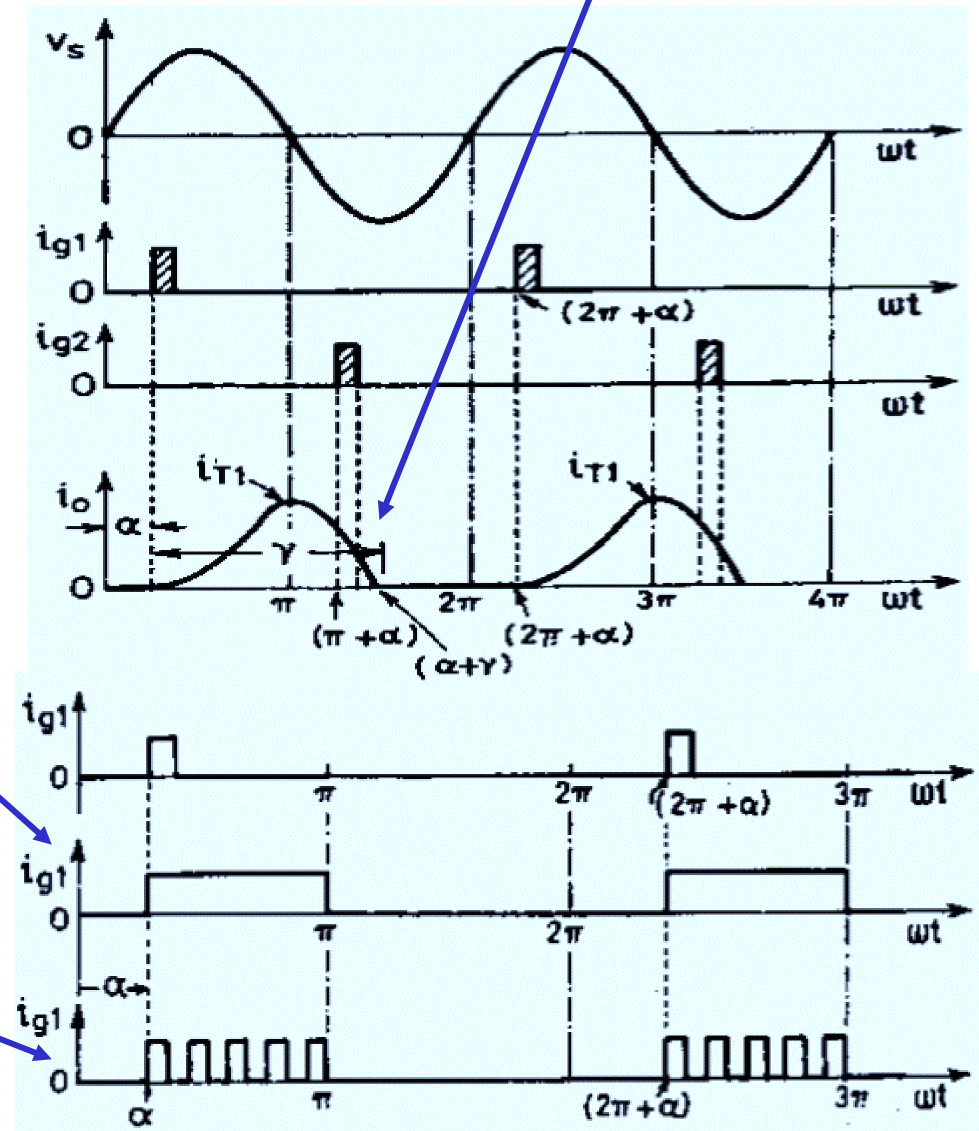


$$\varphi = \arctan(\omega L / R)$$

Short Pulse gating

T1 conducts alone, undesirable!!

- Pulse gating is, however, *not suitable for RL loads*.
- Larger the load inductance, the longer the switch conducts. If the firing pulse for the other switch arrives earlier than this switch turns off, then it may not be fired.
  - **Continuous pulse firing:** leads to more heating of the SCR gate and increases the size of pulse transformer.
  - **High-frequency carrier gating:** A train of pulses with short duration should be used to mitigate the above disadvantages.



1.2. On-off control

The main problem of phase control is the high THD.

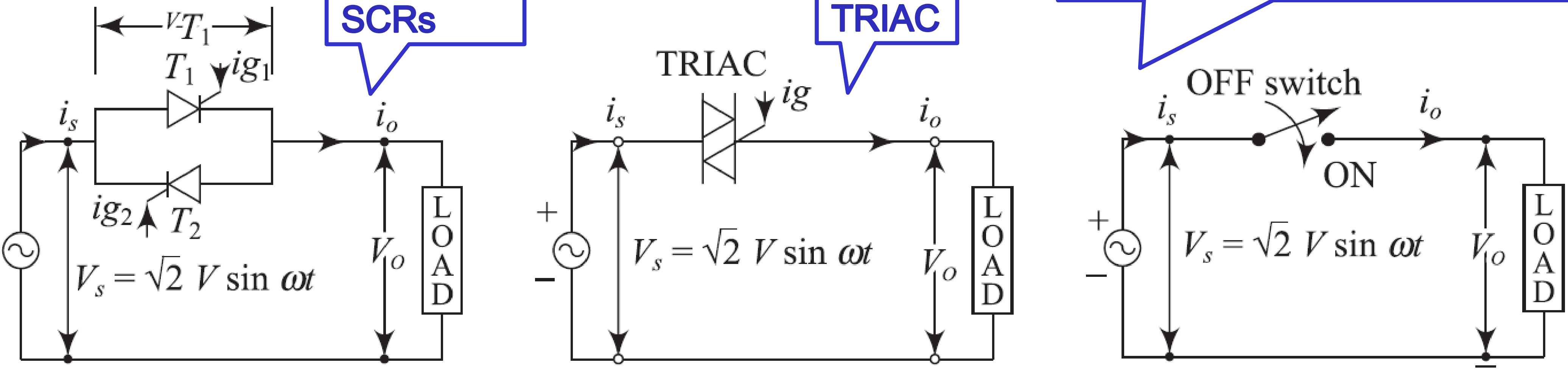
- On-off control
  - The switch conducts for some cycles and then turn off for some cycles: *duty cycle*
  - Zero-voltage/zero-current crossing to reduce the THD.
  - Very good for applications having high mechanical inertia or high thermal time constant.

1.2.1 Basic On-off control

Using two SCRs

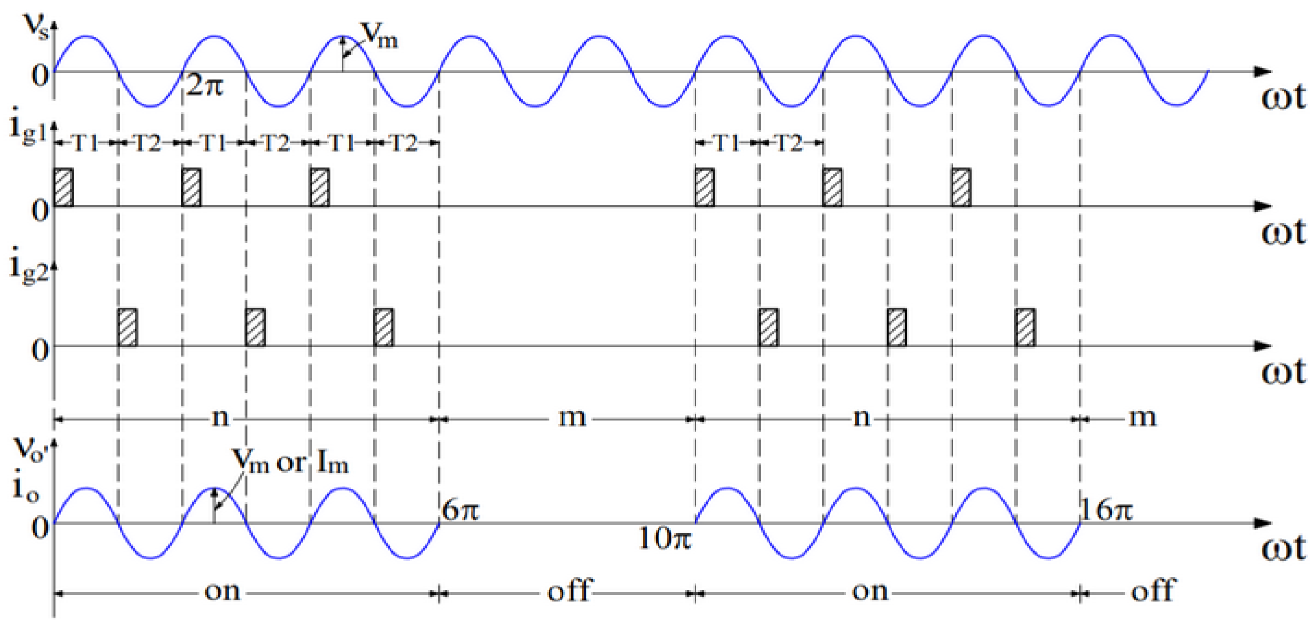
Using TRIAC

Equivalent circuit using switch



Duty cycle

$$k = \frac{n}{n+m}$$



1.2.1 Basic On-off control

- The rms output voltage is

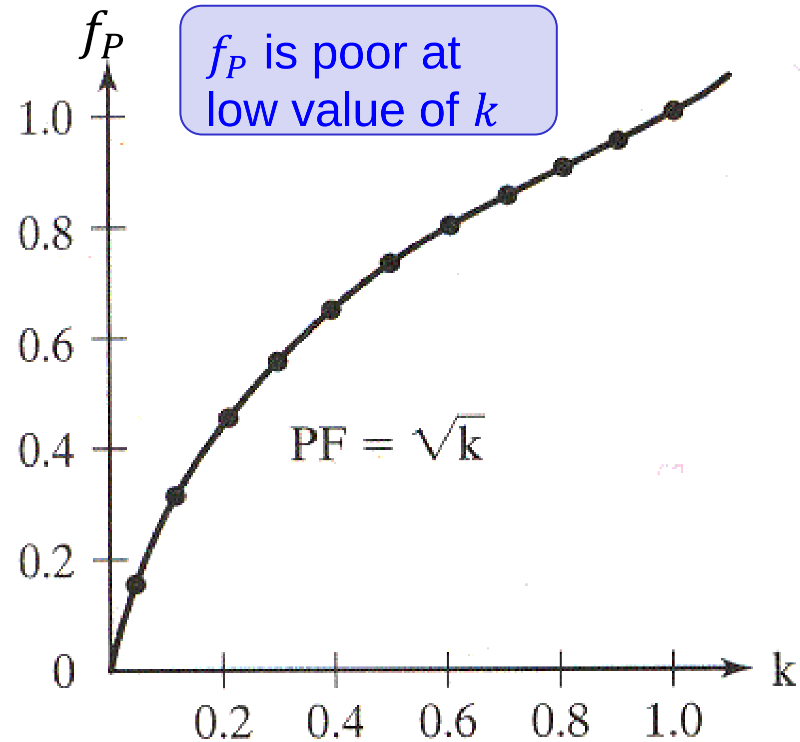
$$V_{RMS} = \sqrt{\frac{1}{2\pi}\frac{n}{n+m}\int_0^{2\pi} V_m^2 \sin^2 \omega t \, d(\omega t)} = \frac{V_m}{\sqrt{2}}\sqrt{\frac{n}{n+m}} = V_s\sqrt{k}$$

- RMS load current, $I_{RMS} = \frac{V_{RMS}}{R}$
- Power deliver to load

$$\frac{V_{RMS}^2}{R} = \frac{k.V_S^2}{R}$$

- The input power factor is

$$f_P = \frac{V_{RMS} I_{RMS}}{V_s I_s} = \frac{V_{RMS}}{V_s} = \sqrt{k}$$



f_P is poor at low value of k

1.2.2 Static Switches

- Power semiconductor devices (like SCRs) which can be turned ON & OFF within few microseconds – *fast acting static switch*.
- The on-off control strategy can be easily extended to build static switches, which
  - Have very high switching speeds
  - Have no moving parts
  - Have no bouncing at the time of turning on
- Classified as: 1) ac switches, 2) dc switches – ***based on input.***
- AC switches may be single-phase or three-phase – *note that the switches are turned ON at zero-crossing of load current*.

Review of SCR Commutation

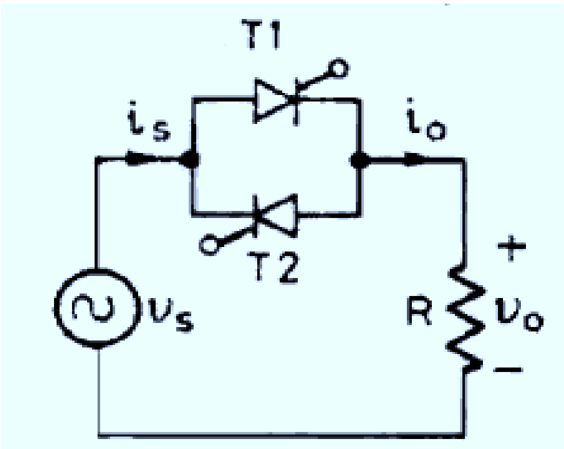
- Natural or Line Commutation: In AC circuits, the *turning-OFF*, or commutation, of a *SCR by supply voltage itself*.

  ✓ No requirement of external circuits for turning OFF the SCR.

- Forced Commutation: In some thyristor circuits, the input voltage is DC and the forward current of the thyristor is forced to zero by *an additional circuit* called commutation circuit to *turn-OFF the thyristor*.

  ✓ The commutation circuit normally consists of a capacitor, an inductor, and one or more thyristor(s) and/or diode(s).

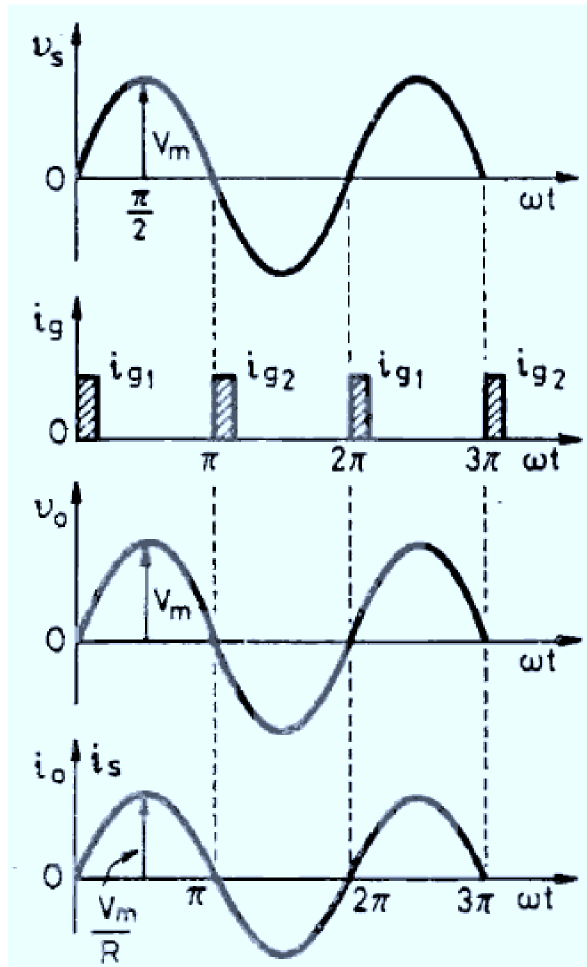
1.2.2 Single-phase AC switches



SCRs act like switches and are line/natural commutated

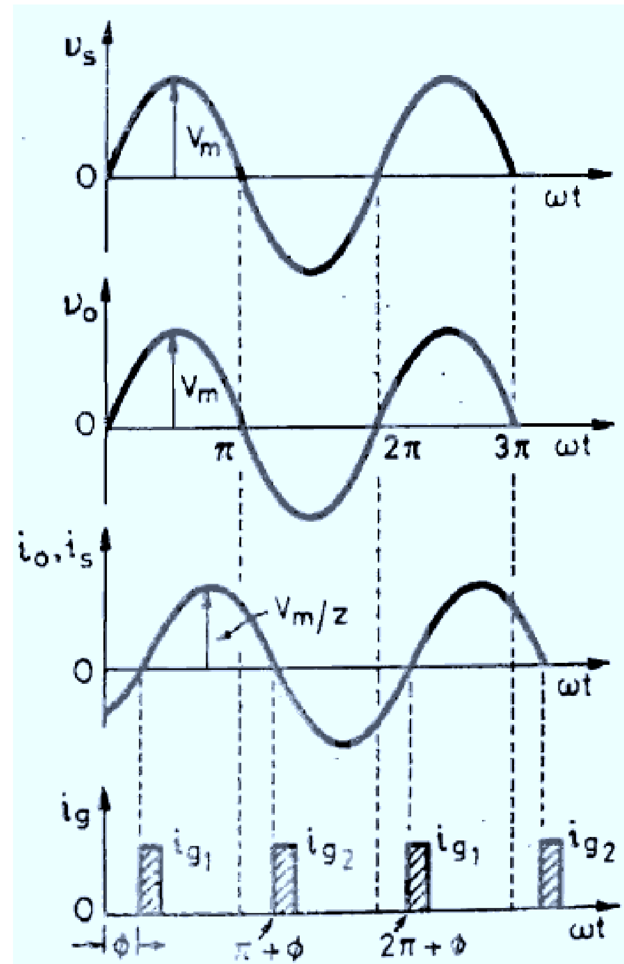
Resistive load:

zero-current crossing



Inductive load:

zero-current crossing

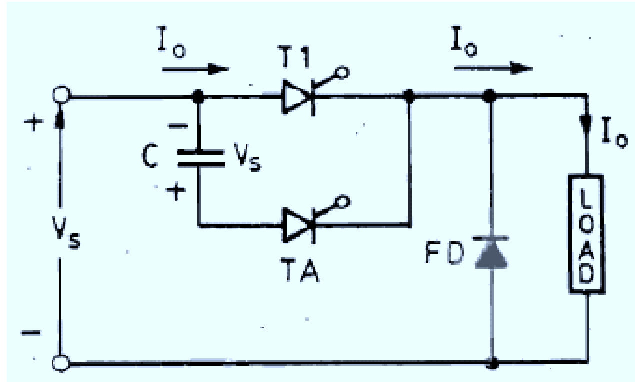


<u>**Resistive load:**</u> T1 is triggered at $\omega t = 0, 2\pi, \ldots$ and T2 is triggered at $\omega t = \pi, 3\pi$,.. when the load current waveform is passing through zero.

<u>**RL – load:**</u> Load current i_o lags v_o by PF, $\varphi = \tan^{-1}\left(\frac{\omega L}{R}\right)$. T1 is triggered at $\omega t = \varphi, 2\pi + \varphi, \ldots$ and T2 is triggered at $\omega t = \pi + \varphi, 3\pi + \varphi, \ldots$

1.2.2 DC Switches

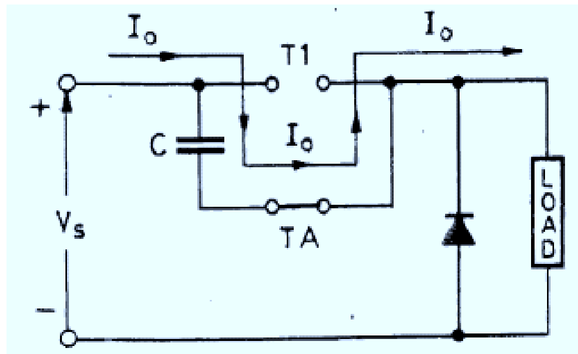
- The input voltage for DC switches is DC. Power semiconductor devices used may be transistors, thyristors or GTOs.

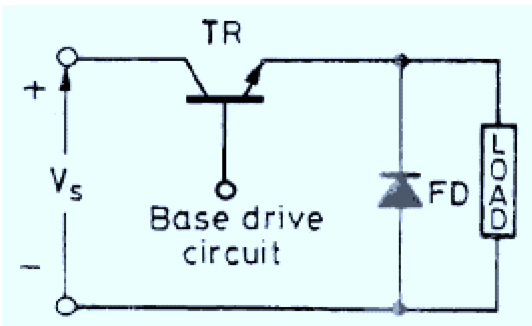


✓ If thyristors are used, they must be turned OFF by *forced commutation* as an integral part of dc switch.

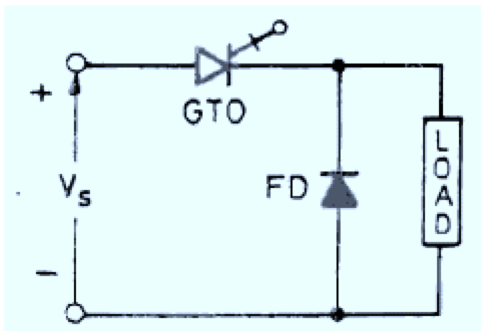
✓ Here, T1 is main thyristor and TA is the auxiliary thyristor. Capacitor C is charged to source voltage V_s with lower plate positive. When T1 is ON, current I_o flows from source to load through T1.

✓ For breaking dc circuit, TA is turned ON, capacitor C applies a reverse voltage across T1 turning it OFF.





Transistor dc switch



GTO dc switch

2.1 Cycloconverters

- Converts input power at one frequency to output power at a different frequency with one-stage conversion.

- It can be used to eliminate the requirement of one or more intermediate converters.
  - ✓ Another name—*direct frequency converter* (as compared to AC-DC-AC frequency converter)
    - If the output frequency is greater than input frequency → *step-up (forced)*
    - If the output frequency is less than input frequency → *step-down (natural)*

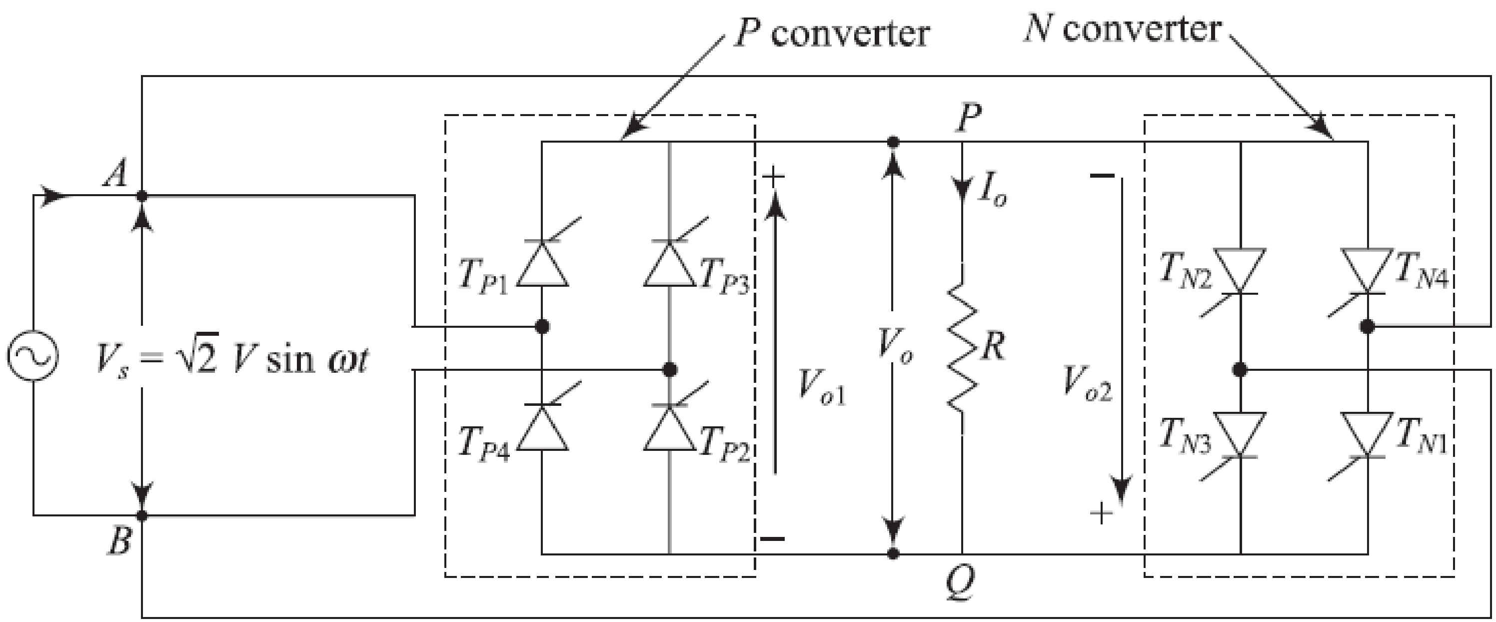
- Applications of cycloconverters are:
  - ✓ Speed control of very high power ac drives
  - ✓ Industrial heating etc.,

2.2 Single-phase Cycloconverters (step-up)

- Two single-phase controlled converters – *bridge rectifiers*

- Positive group – $T_{P1}, T_{P2}, T_{P3}, T_{P4}$; Negative group – $T_{N1}, T_{N2}, T_{N3}, T_{N4}$.

- The output voltage and current are reversed in the negative direction.



2.2 Single-phase Cycloconverters (step-up)

- During positive half-cycle:

$\boldsymbol{\omega t = 0} \rightarrow T_{P1}, T_{P2}, T_{N1}, T_{N2}$ – forward

$A - T_{P1} - P - Load - Q - T_{P2} - B$

At $\boldsymbol{\omega t_1} \rightarrow T_{P1}, T_{P2}$ are turned OFF by forced commutation and gate signals are applied to T_{N1}, T_{N2}.

$A - T_{N1} - Q - Load - P - T_{N2} - B$

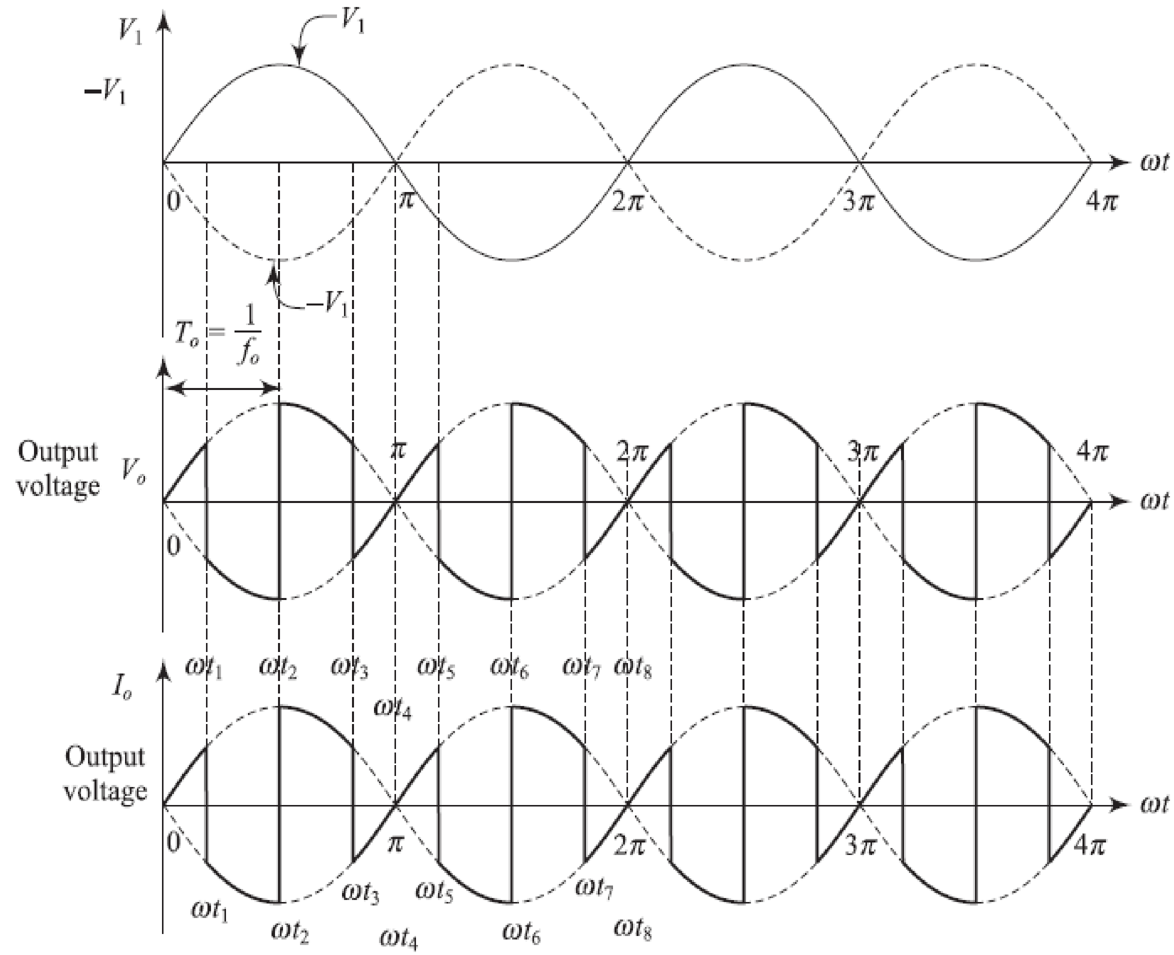
At $\boldsymbol{\omega t_2} \rightarrow T_{N1}, T_{N2}$ are turned OFF by forced commutation and gate signals are applied to T_{P1}, T_{P2}.

$A - T_{P1} - P - Load - Q - T_{P2} - B$

This process will continue for positive half-cycle.

- During negative half-cycle:

$\boldsymbol{\omega t = 0} \rightarrow T_{P3}, T_{P3}, T_{N3}, T_{N4}$ – forward



Conduction of thyristor																
	T_{P1}	T_{N1}	T_{P1}	T_{N1}	T_{P3}	T_{N3}	T_{P3}	T_{N3}	T_{P1}	T_{N1}	T_{P1}	T_{N1}	T_{P3}	T_{N3}	T_{P3}	T_{N3}
	T_{P2}	T_{N2}	T_{P2}	T_{N2}	T_{P4}	T_{N4}	T_{P4}	T_{N4}	T_{P2}	T_{N2}	T_{P2}	T_{N2}	T_{P4}	T_{N4}	T_{P4}	T_{N4}

Example

A single-phase half-wave ac voltage controller feeds a load of $R = 20\ \Omega$ with an input voltage of 230 V, 50 Hz. Firing angle of thyristor is 45^0. Determine (a) rms value of output voltage (b) power delivered to load and input pf and (c) average output voltage.

<u>**Solution:**</u> Here $V_s = 230\ V$, $V_m = \sqrt{2} \times 230\ V$, $\alpha = 45^0 = \frac{\pi}{4}$, $R = 20\ \Omega$

a) The rms value of load voltage is (from Slide 7)

$$V_{RMS} = \frac{V_m}{2}\left[\frac{1}{\pi}\left\{(2\pi - \alpha) + \frac{sin2\alpha}{2}\right\}\right]^{1/2}$$

$$= \frac{\sqrt{2} \times 230}{2}\left[\frac{1}{\pi}\left\{\left(2\pi - \frac{\pi}{4}\right) + \frac{sin90}{2}\right\}\right]^{1/2} = 224.682V$$

Example

b) Rms value of load current, $I_{RMS} = \frac{V_{RMS}}{R} = \frac{224.682}{20} = 11.2341\ A$

Load power, $P_{RMS} = I_{RMS}^2 \times R = 11.2341^2 \times 20 = 2524.1\ W$

RMS source current, $I_{s,RMS}$ = RMS load current, I_{RMS} =11.2341 A

Input pf $= \frac{V_{RMS}}{V_s} = \frac{2524.1}{230} = 0.9769$

c) Average output voltage, $V_o = \frac{V_m}{2\pi}(\cos\alpha - 1) = -15.17\ V$

Summary

- The control strategies of AC voltage controllers are: 1) ON-OFF control or Integral cycle control, 2) Phase control.
- Single-phase half-wave AC voltage controller: Only positive half-cycle can be controlled, negative half-cycle cannot be controlled.
- Single-phase half-wave AC voltage controller: both positive and negative half-cycles can be controlled.
- Integral cycle/On-Off control: The switch conducts for some cycles and then turn off for some cycles: *duty cycle*
- Cycloconverter: Converts input power at one frequency to output power at a different frequency with one-stage conversion.
- Natural commutation (*SCR turn-OFF by supply voltage itself*) and forced commutation (*SCR turn-OFF by an additional circuit*).

See you in the next class (April 14th)

The End