Controlled Rectifiers

(Three-phase)

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Outline

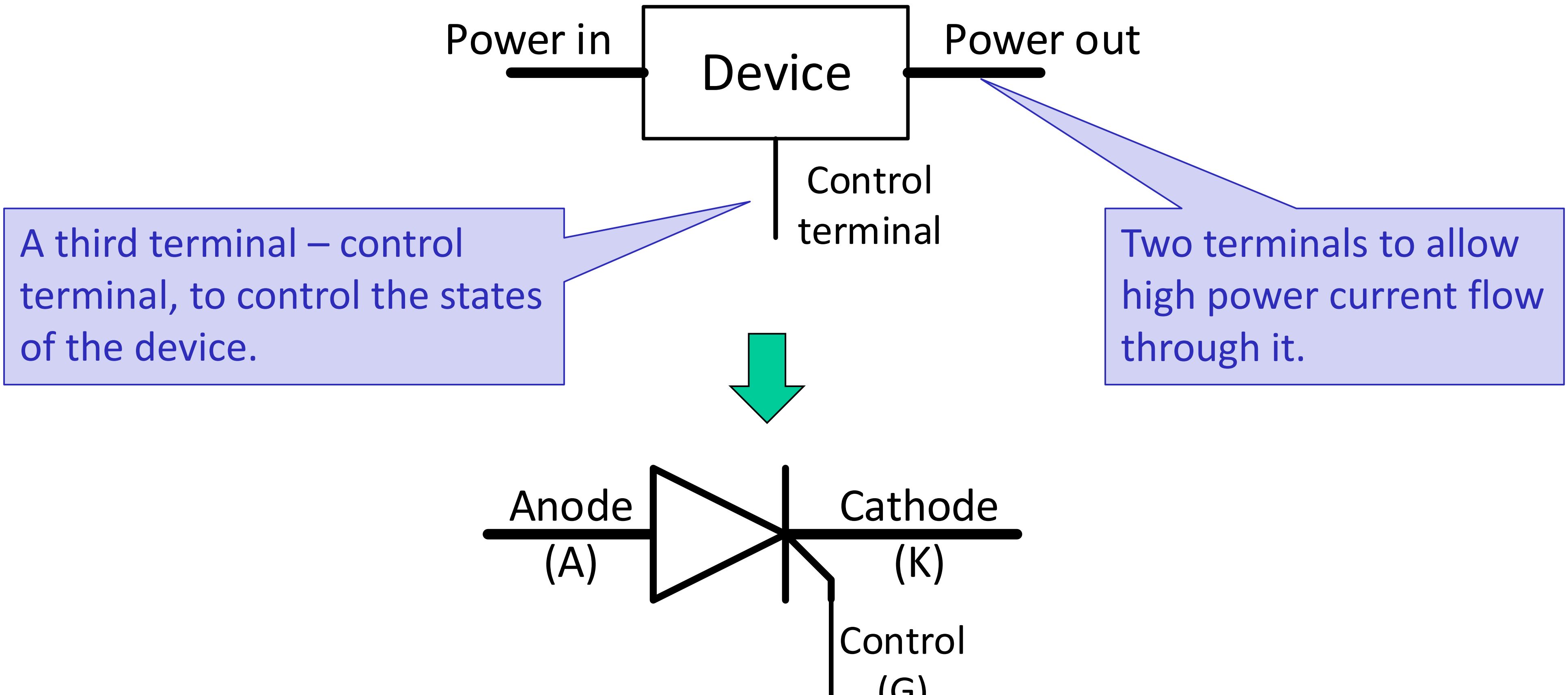
– Review of last week lecture

1. Three-phase Half-wave controlled rectifiers
    1. Firing/triggering angle α;
    2. Resistive loading;
    3. Inductive loading;

2. Full-wave (bridge)
    1. Resistive loading;
    2. Inductive loading.

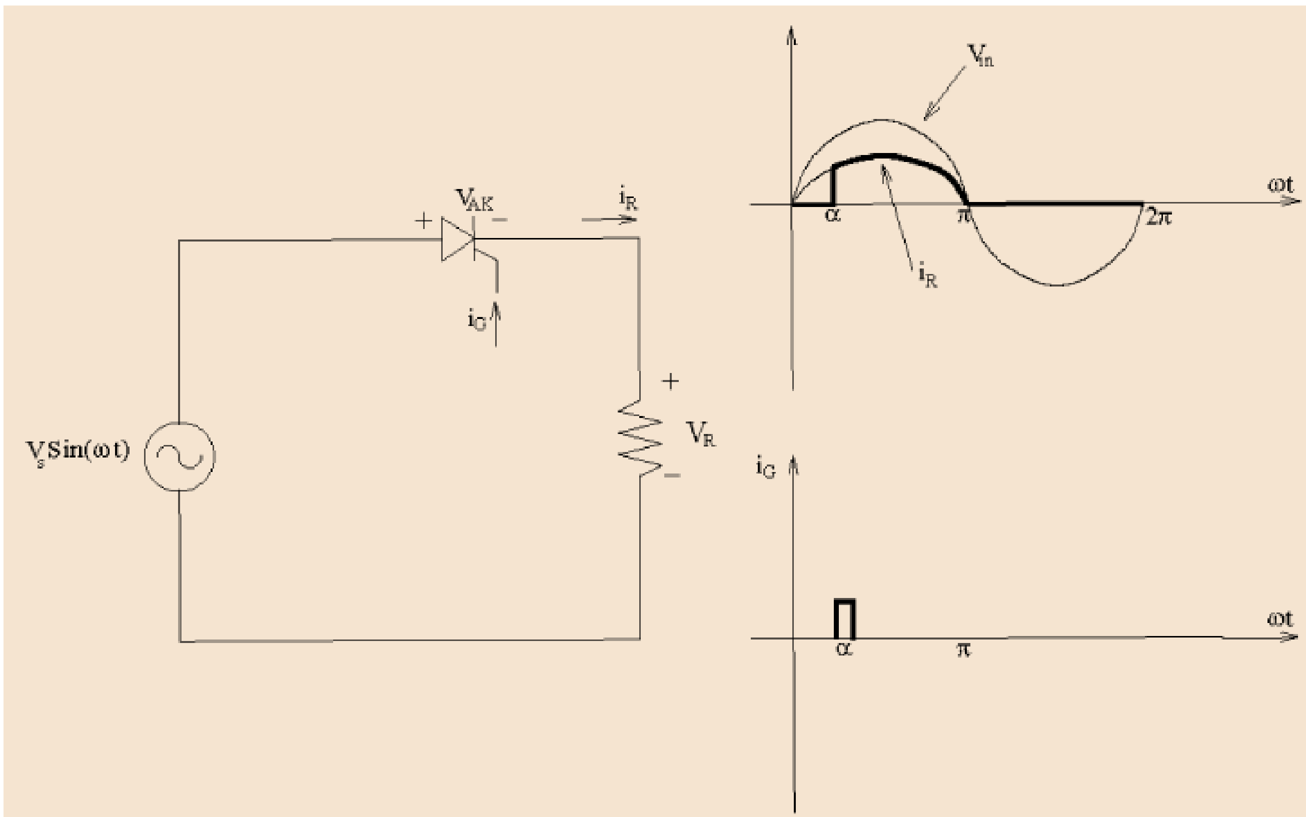
Power semiconductor devices – Review

- Terminals of a controllable power electronic device



SCR in a rectification circuit – Review

- SCR/Thyristor: Acts like a diode where you can select when conduction will start, but not when it stops.
  - Semi-controlled: we control the turn on point, but only turns off when circuit conditions force it to.



SCR Turn-On Analysis – Review

- Two conditions must be met before the SCR can conduct:

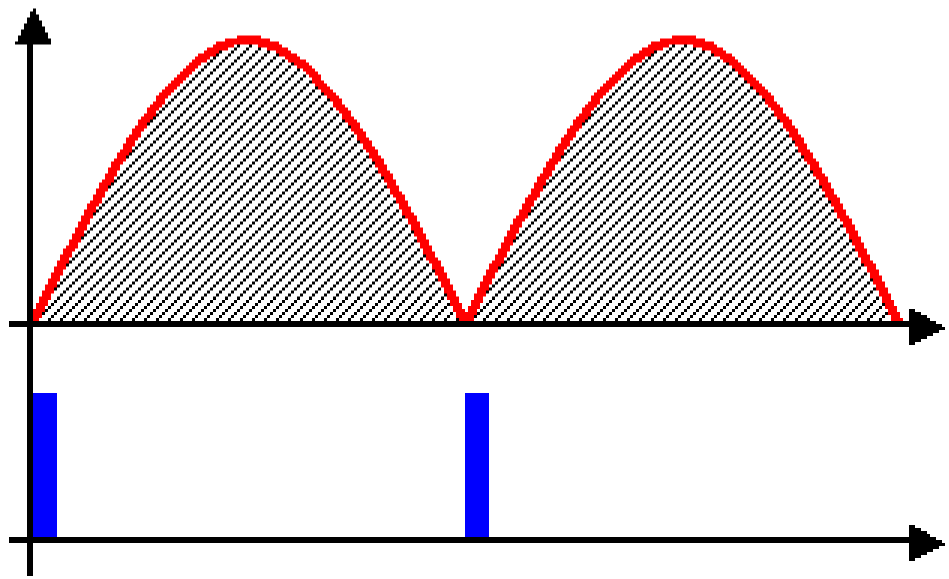
1. The SCR must be forward biased ($v_{AK} > 0$).
2. A current must be applied to the gate of SCR.

- A *SCR is turned ON* by increasing the anode current. This can be accomplished in one of the following ways:

1. Forward voltage triggering
2. Gate triggering
3. The dv/dt triggering
4. Temperature triggering
5. Light triggering

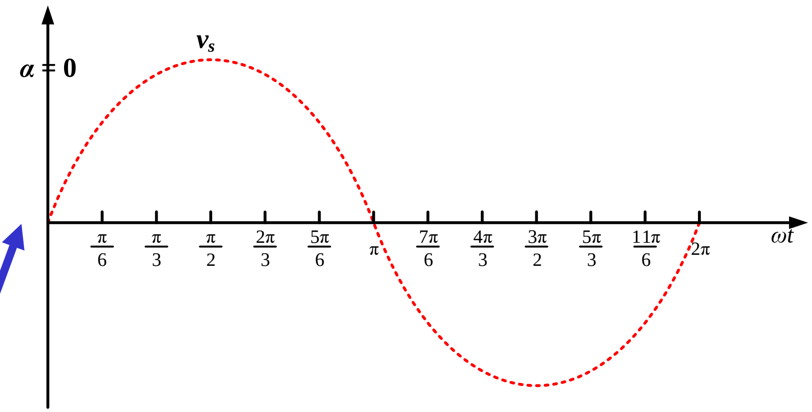
Phase Control – Review

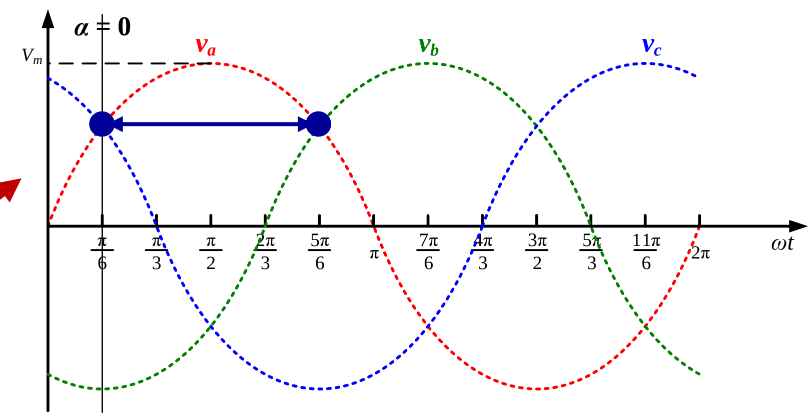
- In this circuit, the control of the output DC voltage is realized by modifying the triggering pulse phase or firing angle, this is called ***Phase Control***.
- Change the firing angle α from 0 to π:



1.1 Firing angle (triggering angle) – Recall

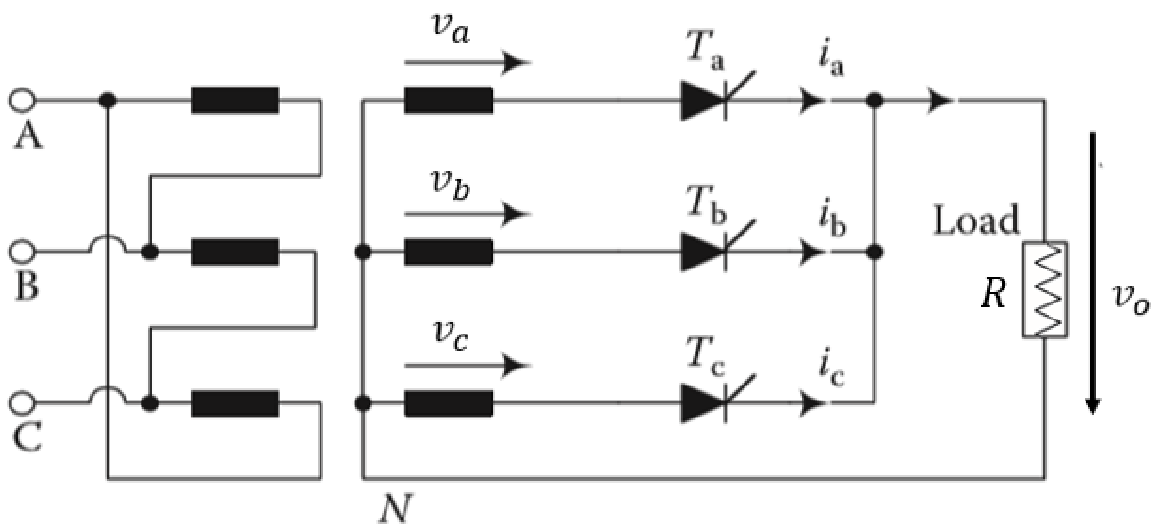
- In controlled rectifier, controllability of the circuit is realized by triggering the thyristors at different phases, which is called the ***firing/triggering angle***. It is usually represented by "$\boldsymbol{\alpha}$";
  - This trigger signal is a current pulse at the "gate" terminal of thyristors;
  - For single phase circuit, $\alpha = 0$ means trigger signal is sent at $\omega t = 0$;
  - For three-phase circuit, $\alpha = 0$ means trigger signal is sent at $\omega t = \pi/6$, which is the first ***natural commutation (phase changing) point***.



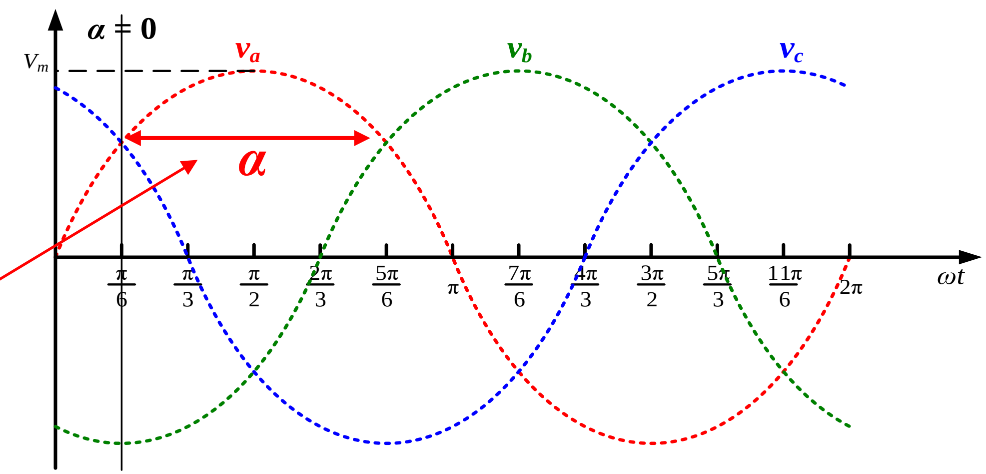


1.1 Three-phase, half-wave, R-load

- Resistive load
  - ❖ Three phase supply – primary in delta and secondary in star connection.
  - ❖ Common-cathode connection.

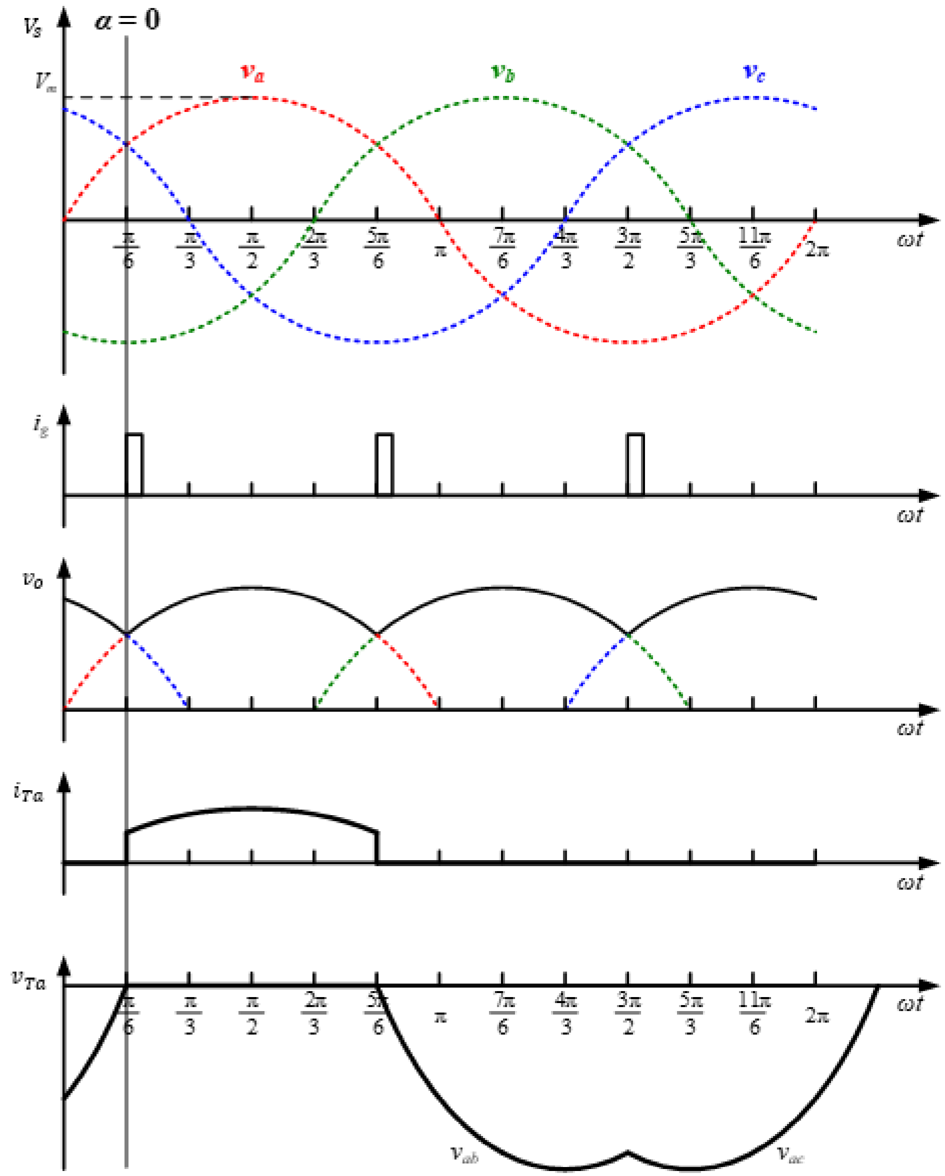


- Natural commutation (phase-changing) point
  - – It is considered as the starting point for thyristor triggering angle α, i.e. $\alpha = 0^0$.
  - – Phase-shift range: $\alpha <= 120^0$.



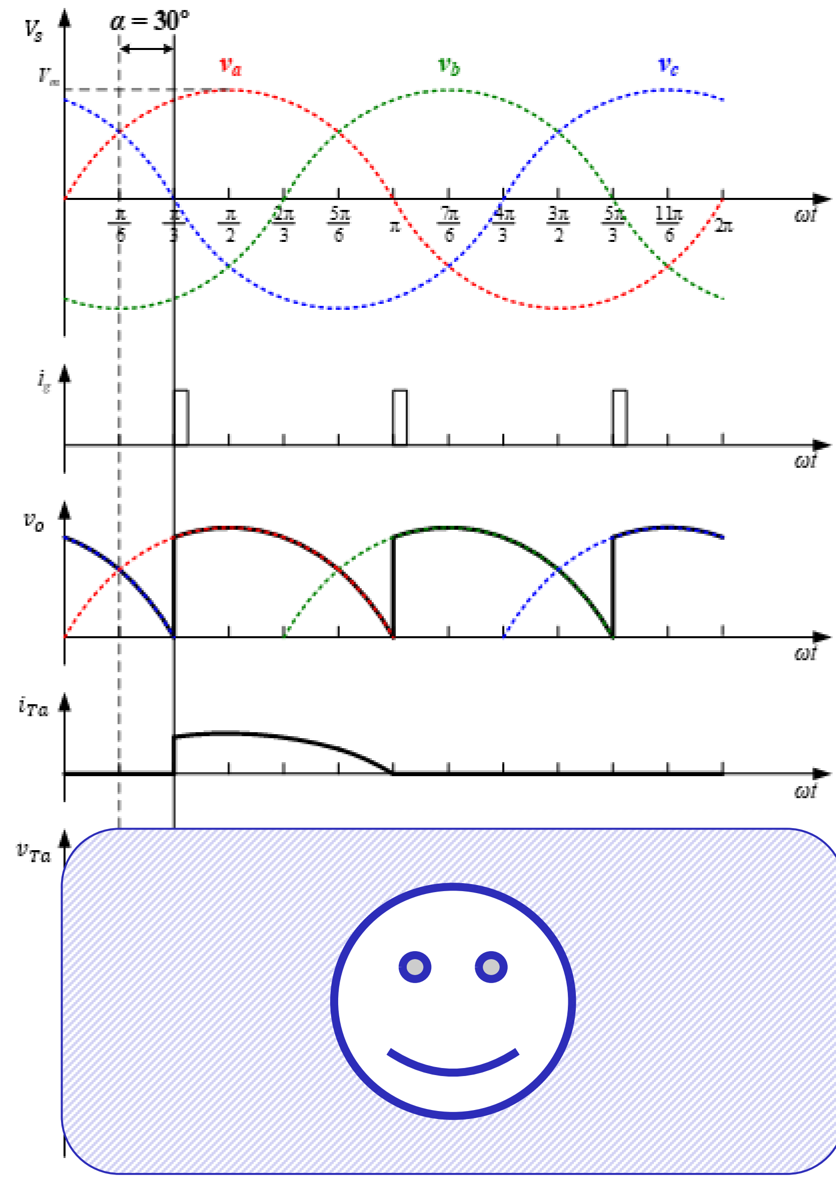
1.1 Three-phase, half-wave, R-load

- When $\alpha = 0^0$(Same as the uncontrolled, 3-phase, half-wave)
  - Example: At $\alpha = 0\ (\omega t = \pi/6)$, as soon as T_a is forward biased (red line v_a becomes the largest one), a trigger signal is provided to T_a, so T_a starts to conduct;
  - At $\omega t = 5\pi/6$, when v_b becomes the largest one, another trigger signal is provided to T_b , so T_b starts to conduct;
  - At $\omega t = 3\pi/2$, when v_c becomes the largest one, the trigger signal to T_c is provided, so T_c starts to conduct.



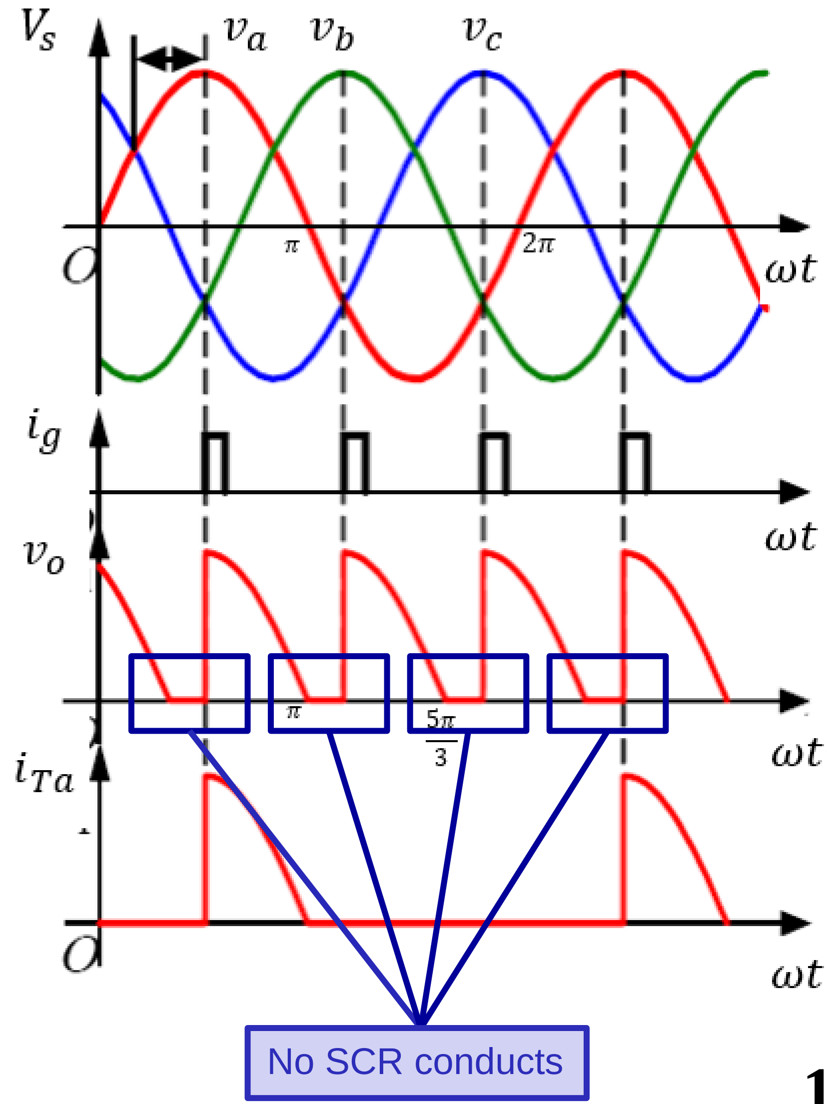
1.1 Three-phase, half-wave, R-load

- When $\alpha = 30^0$
  - From $\omega t = \pi/6$ to $\pi/3$, although T_a is forward biased (red line v_a is the largest one), no trigger signal is provided to T_a, so T_a cannot conduct;
  - At $\alpha = 30^0$ ($\omega t = \pi/3$), a trigger signal is provided to T_a, so T_a starts to conduct;
  - At $\omega t = 5\pi/6$, when v_b becomes the largest one, since no trigger signal is provided to T_b, it will not conduct until $\omega t = \pi$. It will conduct only when the trigger signal provided.



1.1 Three-phase, half-wave, R-load

- When $\alpha = 60^0$
  - From $\omega t = \pi/6$ to $\pi/2$, although T_a is forward biased (red line v_a is the largest one), no trigger signal is provided to T_a, so it cannot conduct;
  - At $\alpha = 60^0$ ($\omega t = \pi/2$), a trigger signal is provided to T_a, therefore it starts to conduct;
  - From $\omega t = \pi\ to\ 7\pi/6$, v_a is no longer the largest one, T_a stops; since no trigger signal is provided to T_b, it will not conduct either. In this region, no SCR will conduct.
  - At $\omega t = 7\pi/6$, T_b is triggered and forward biased, therefore it conducts.



Resistive load, quantitative analysis

- When $\alpha \le 30^0$,

- Average value of output voltage, $V_o = \frac{1}{2\pi/3}\int_{\alpha+\pi/6}^{\alpha+5\pi/6} V_m \sin\omega t \, d(\omega t) = \frac{3\sqrt{3}}{2\pi} V_m \cos\alpha$

- RMS voltage, $V_{RMS} = \left[\frac{1}{2\pi/3}\int_{\alpha+\pi/6}^{\alpha+5\pi/6} V_m^2 \sin^2\omega t \, d(\omega t)\right]^{1/2} = \sqrt{3} V_m \left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi}\cos 2\alpha\right]^{1/2}$

- Average load current, $I_o = \frac{V_o}{R} = \frac{3\sqrt{3}V_m}{2\pi R}\cos\alpha$

- RMS load current, $I_{RMS} = \frac{V_{RMS}}{R} = \frac{\sqrt{3}V_m}{R}\left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi}\cos 2\alpha\right]^{1/2}$

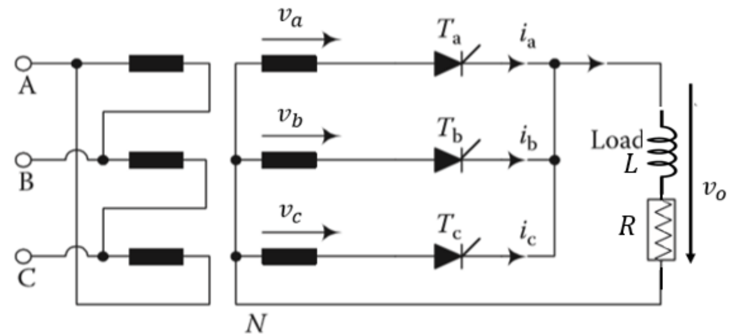
- When $\alpha > 30^0$,

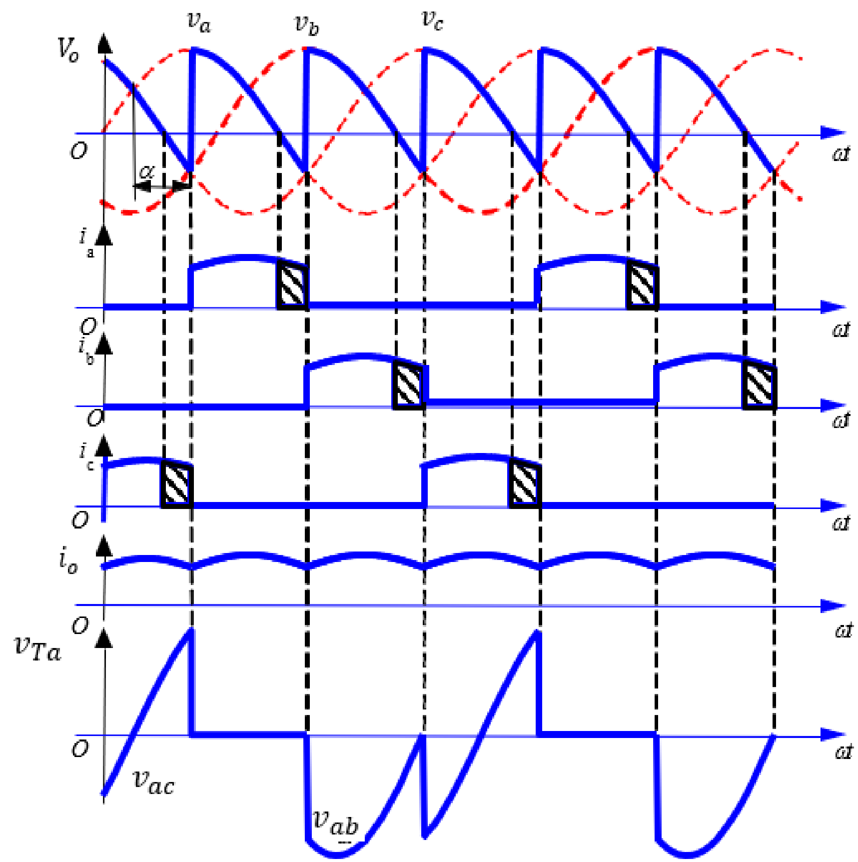
- Average output voltage, $V_o = \frac{1}{2\pi/3}\int_{\alpha+\pi/6}^{\pi} V_m \sin\omega t \, d(\omega t) = \frac{3V_m}{2\pi}[1 + \cos(\alpha + 30^0)]$

- RMS voltage, $V_{RMS} = \left[\frac{1}{2\pi/3}\int_{\alpha+\pi/6}^{\pi} V_m^2 \sin^2\omega t \, d(\omega t)\right]^{1/2} = \frac{\sqrt{3}V_m}{2\sqrt{\pi}}\left[\left(\frac{5\pi}{6} - \alpha\right) + \frac{1}{2}\sin(2\alpha + \pi/3)\right]^{1/2}$

1.2 Three-phase, half-wave, RL-load

- Inductive load (R-L)
  - The load inductance L is large enough, the output current i_o is continuous and almost flat;
  - When $\alpha \le 30^0$, the rectified voltage waveform is similar to resistive load;
  - When $\alpha > 30^0$ (eg. $\alpha = 60^0$ ⟶):
    - At $\omega t = \pi$, v_a is zero but i_a is not zero due to RL load. So, T_a keeps conducting beyond π.
    - v_o goes negative beyond $\omega t = \pi$.
  - When T_b is turned on, load current shifts from T_a to T_b.





Inductive load, quantitative analysis

- Load current i_o is always continuous, and

Average value of output voltage, $V_o = \frac{1}{2\pi/3}\int_{\alpha+\pi/6}^{\alpha+5\pi/6} V_m \sin\omega t\, d(\omega t) = \frac{3\sqrt{3}}{2\pi} V_m \cos\alpha$

RMS voltage, $V_{RMS} = \left[\frac{1}{2\pi/3}\int_{\alpha+\pi/6}^{\alpha+5\pi/6} V_m^2 \sin^2\omega t\, d(\omega t)\right]^{1/2} = \sqrt{3}V_m\left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi}\cos 2\alpha\right]^{1/2}$

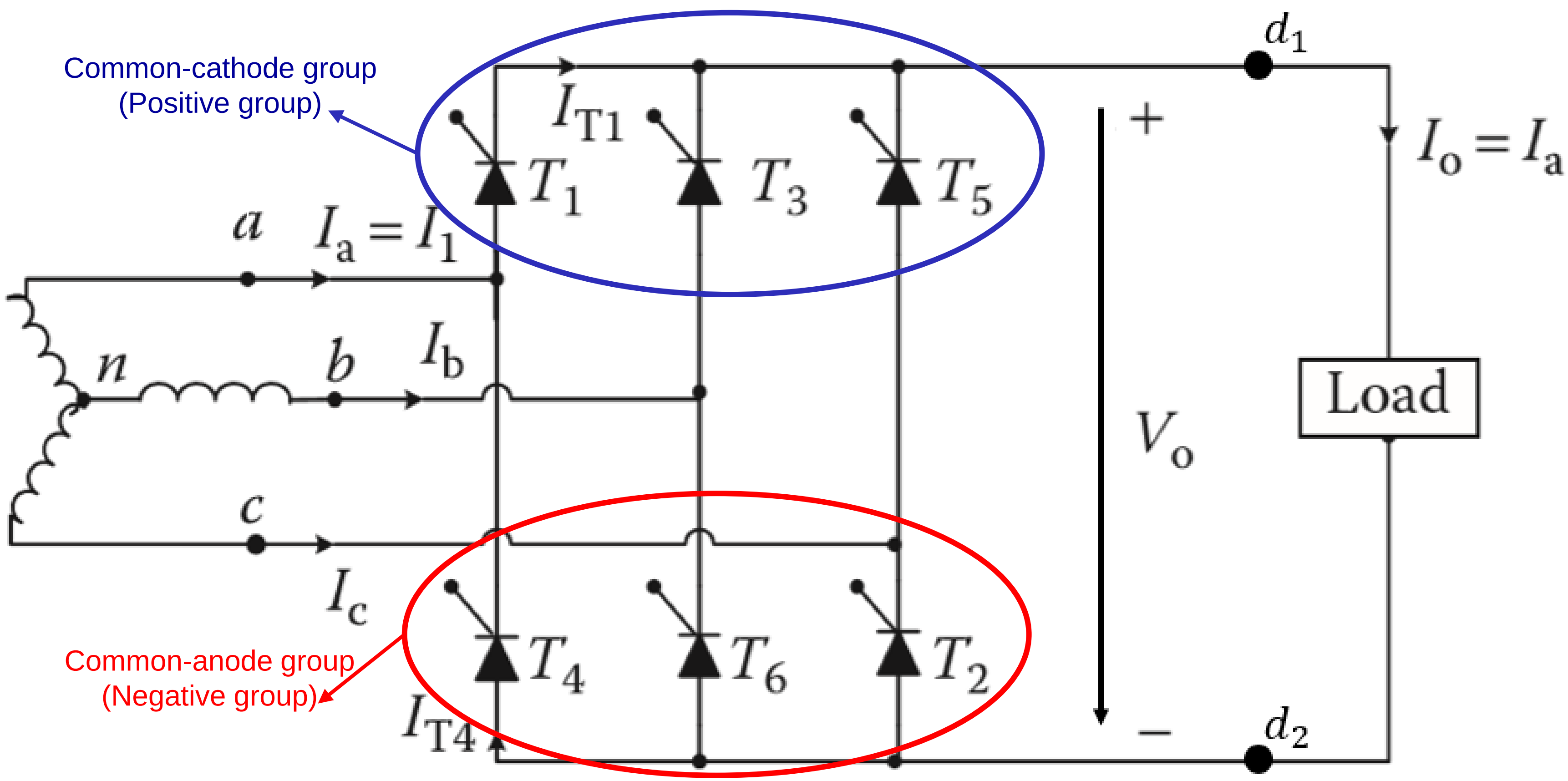
- The average value of thyristor current = Average value of source current, $I_{SA} = \frac{(I_o \times 120)}{360}$

- RMS value of thyristor current:

$$I_{T,RMS} = \left[\frac{I_o^2 \times 120}{360}\right]^{1/2} = \frac{I_o}{\sqrt{3}}$$

How?

2 Three-phase bridge fully-controlled rectifier



- Numbering of the 6 thyristors indicates the trigger sequence:

$$T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \rightarrow T_5 \rightarrow T_6$$

Commutation occurs every 60º interval, alternatively in upper and lower group of SCRs.

2.1 Resistive load

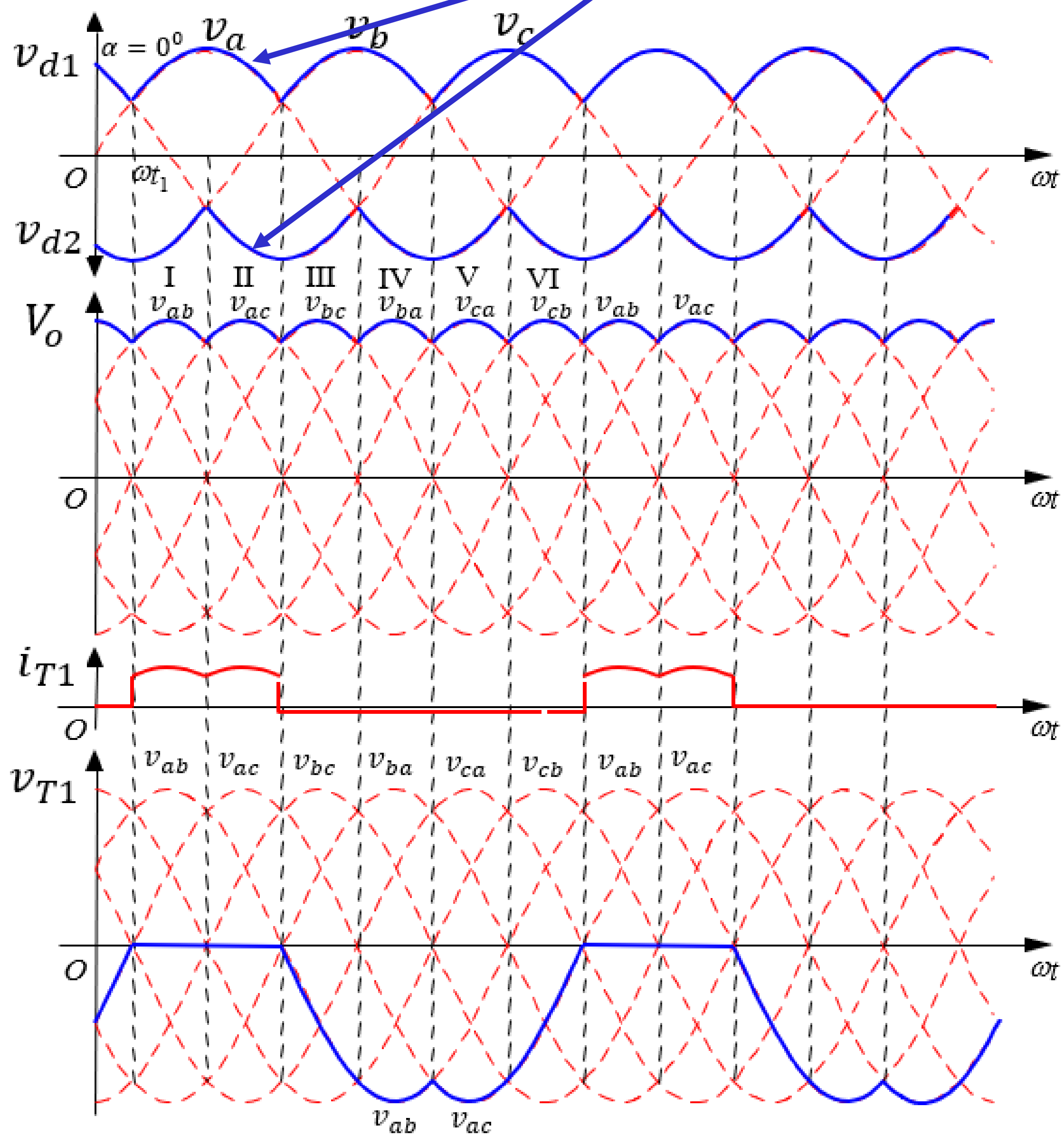
Positive and negative groups of SCRs are fired at an interval of 120°

- Resistive load
  - $\alpha = 0°$
  - Thyristors behave like diodes
  - T_1 is triggered at $\omega t = \pi/6$, T_2 starts at $\pi/2\ldots$
  - Load (output) voltage is similar to uncontrolled case

$$V_{an} = V_m \sin \omega t$$

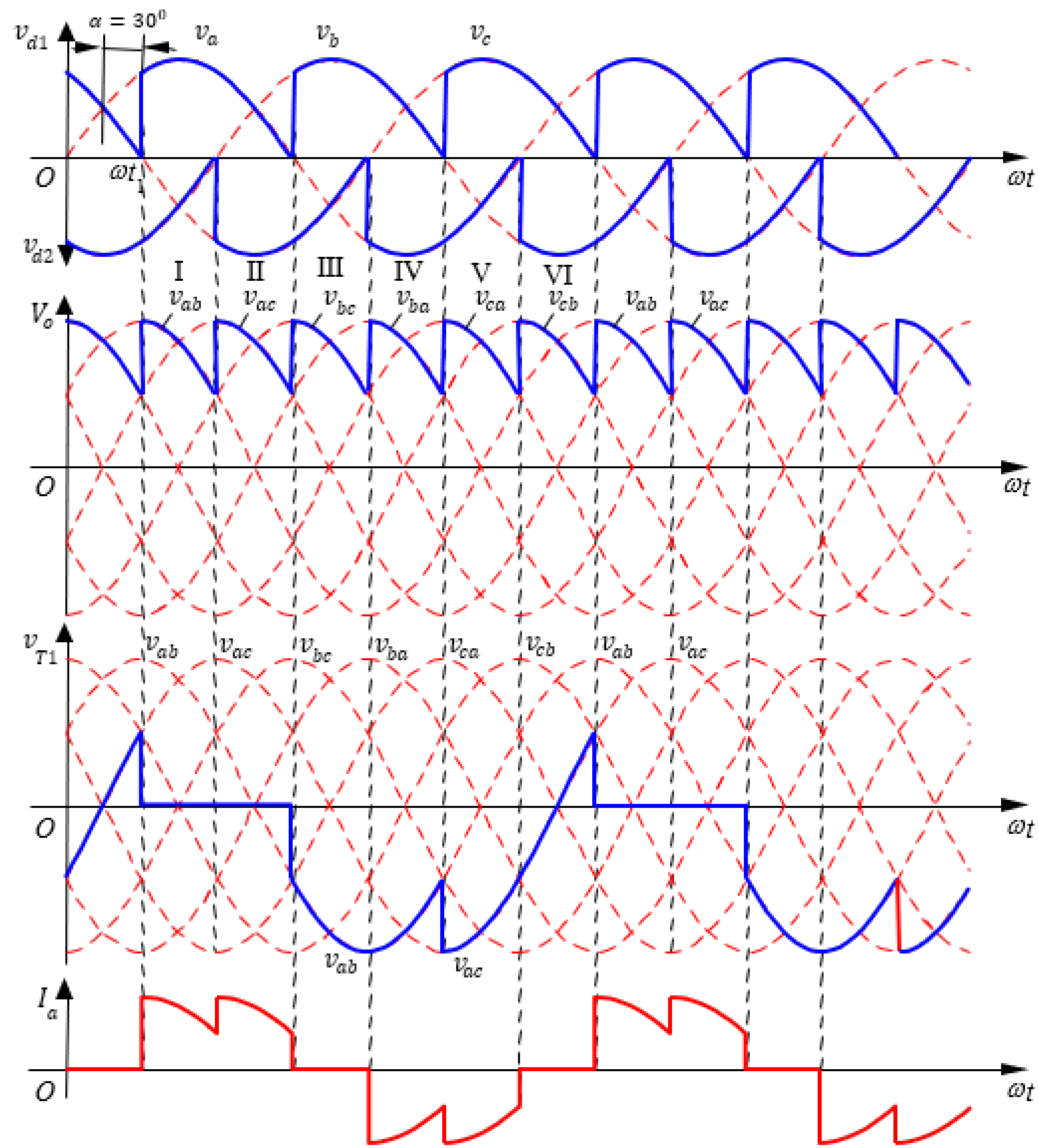
$$V_{bn} = V_m \sin(\omega t - 120^0)$$

$$V_{cn} = V_m \sin(\omega t - 240^0)$$



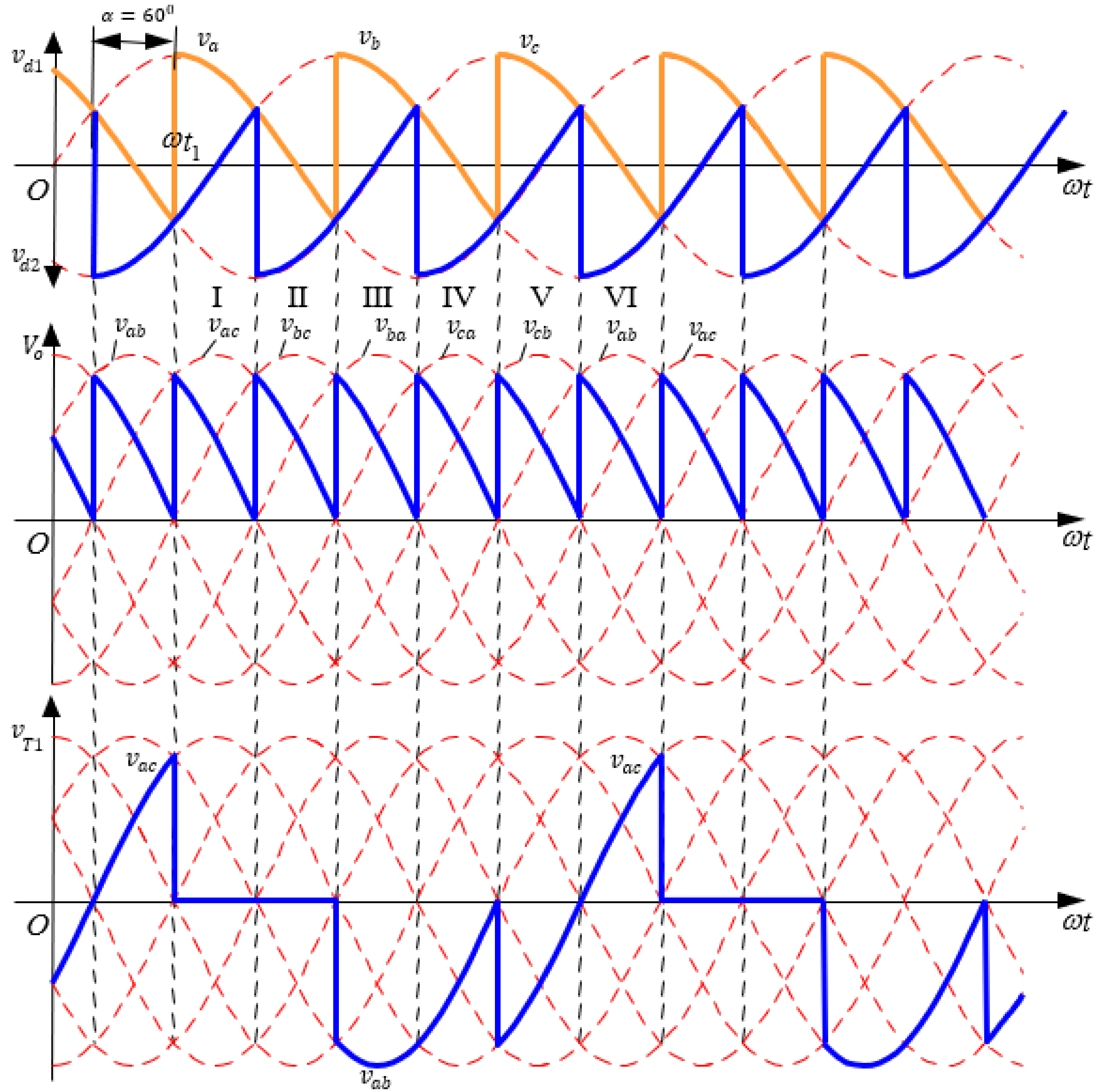
2.1 Resistive load

- Resistive load
  - $\alpha = 30^{o}$
  - T_1 starts conducting at $\omega t = 60^{o}$, T_2 conducts at 120^{o}, T_3 conducts 180^{o} and so on....
  - At $\omega t = 60^{o}$, T_1 connected to line "a" from positive group and T_6 connected to line "b" would conduct, therefore output voltage follows the line voltage v_{ab}.
  - Output voltage is continuous



2.1 Resistive load

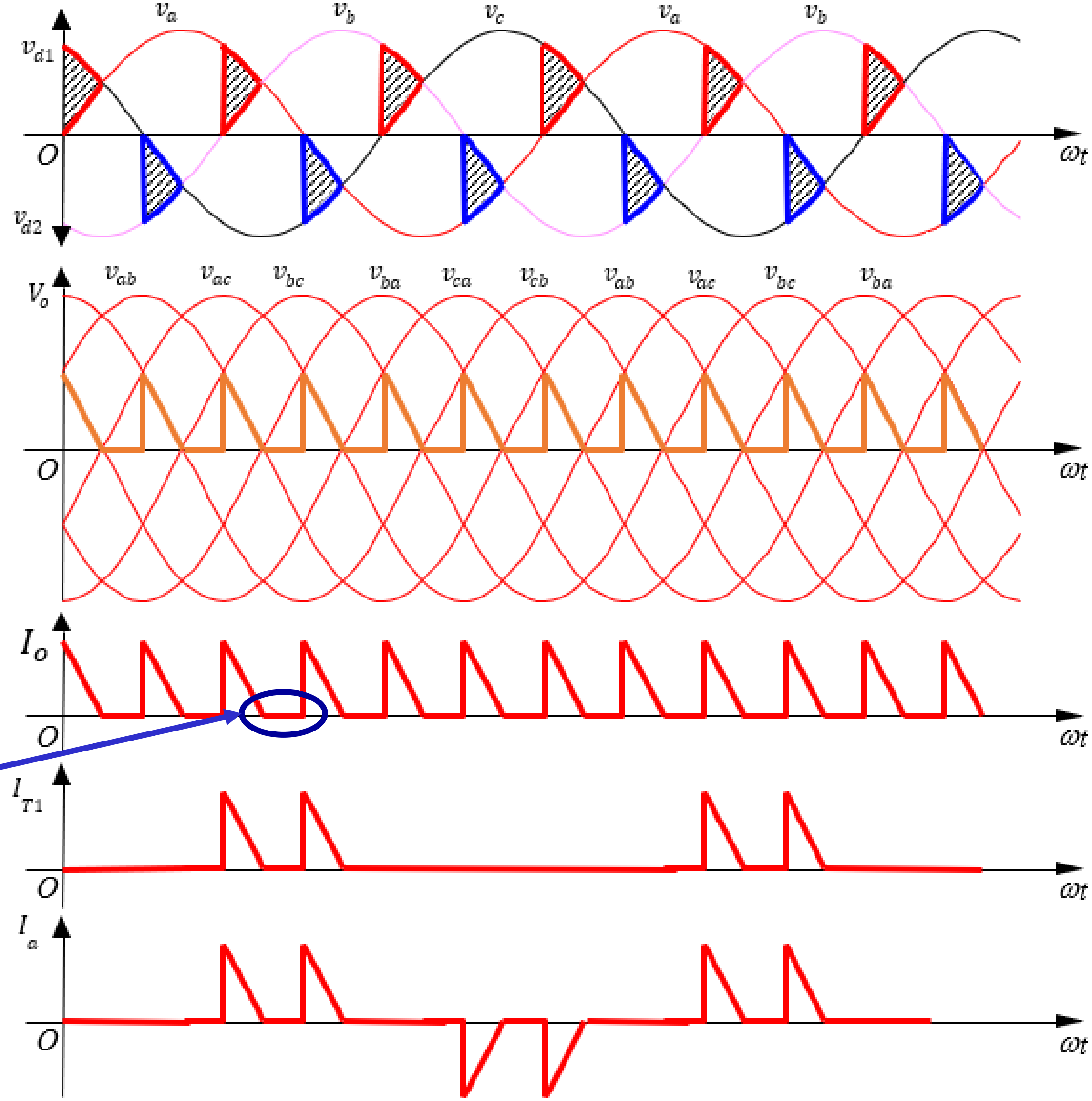
- Resistive load
  - $\alpha = 60^{\circ}$
  - T_1 starts conducting at $\omega t = 90^{\circ}$, T_2 conducts at 150°, T_3 conducts 210° and so on....
  - Output voltage is continuous



2.1 Resistive load

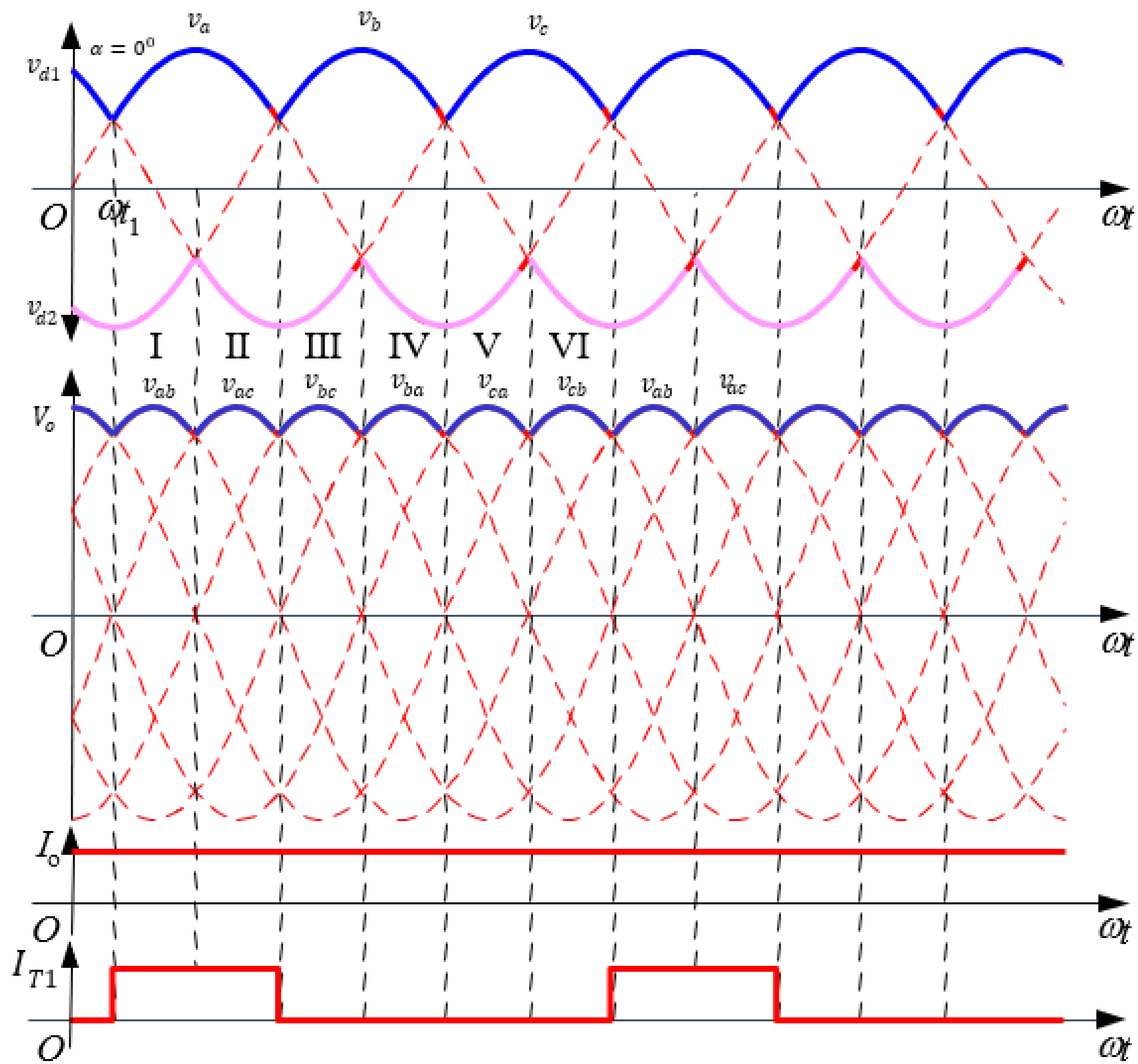
- Resistive load
  - $\alpha = 90^o$
  - T1 starts conducting at $\omega t = 120^o$
  - Output is discontinuous due to resistive load
  - At $\omega t = 150^o$, output voltage,

$$V_{ab} = V_{an} - V_{bn}$$
$$= V_m \sin 150^0$$
$$- V_m \sin(150^0 - 120^0) = 0$$



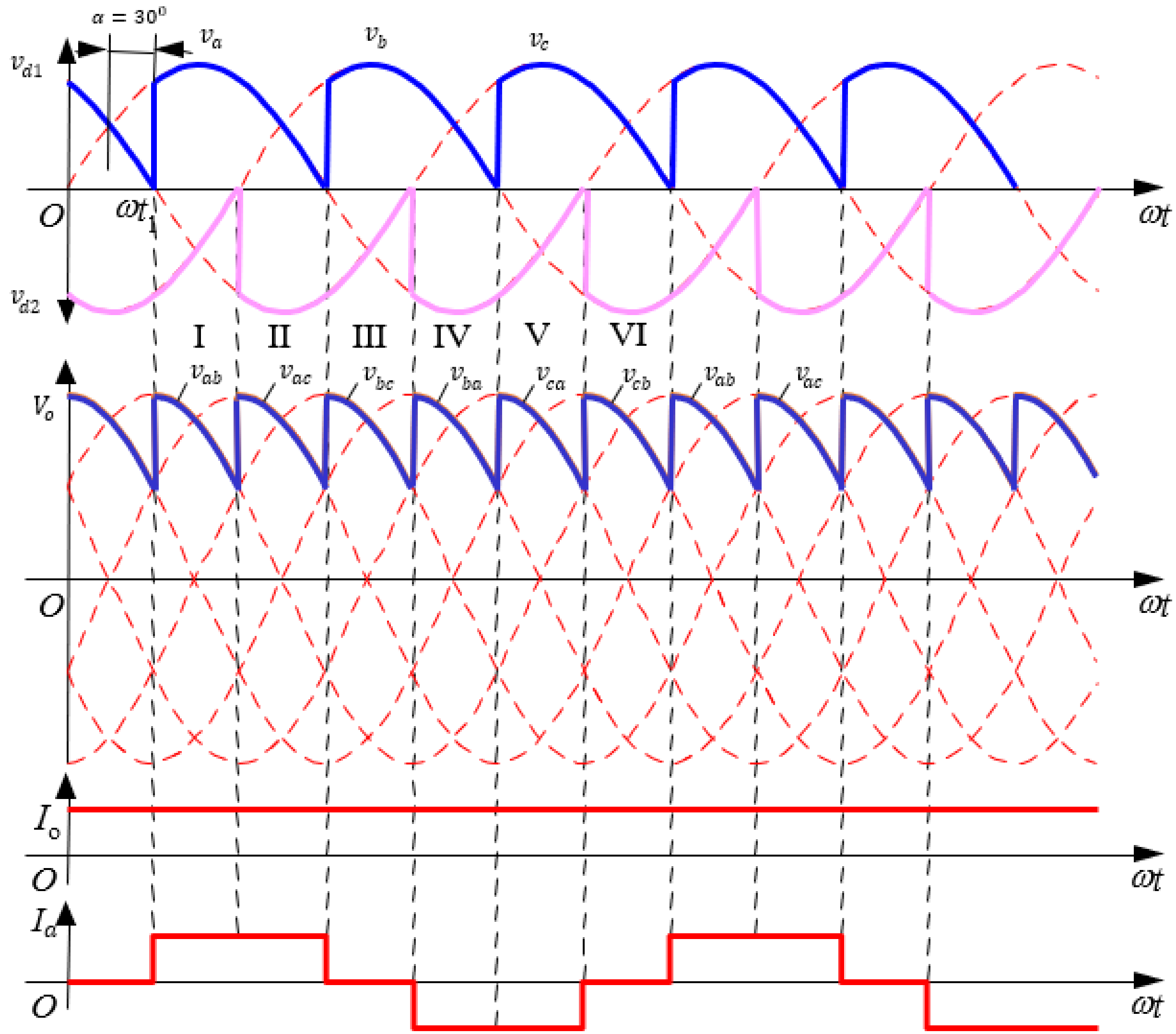
2.2 Inductive load

- Inductive load (R-L load)
  - $\alpha = 0^o$
  - Note that load inductance L is large so that the load current is continuous and constant at magnitude.
  - T_1 is triggered at $\omega t = \pi/6$
  - Output voltage is continuous



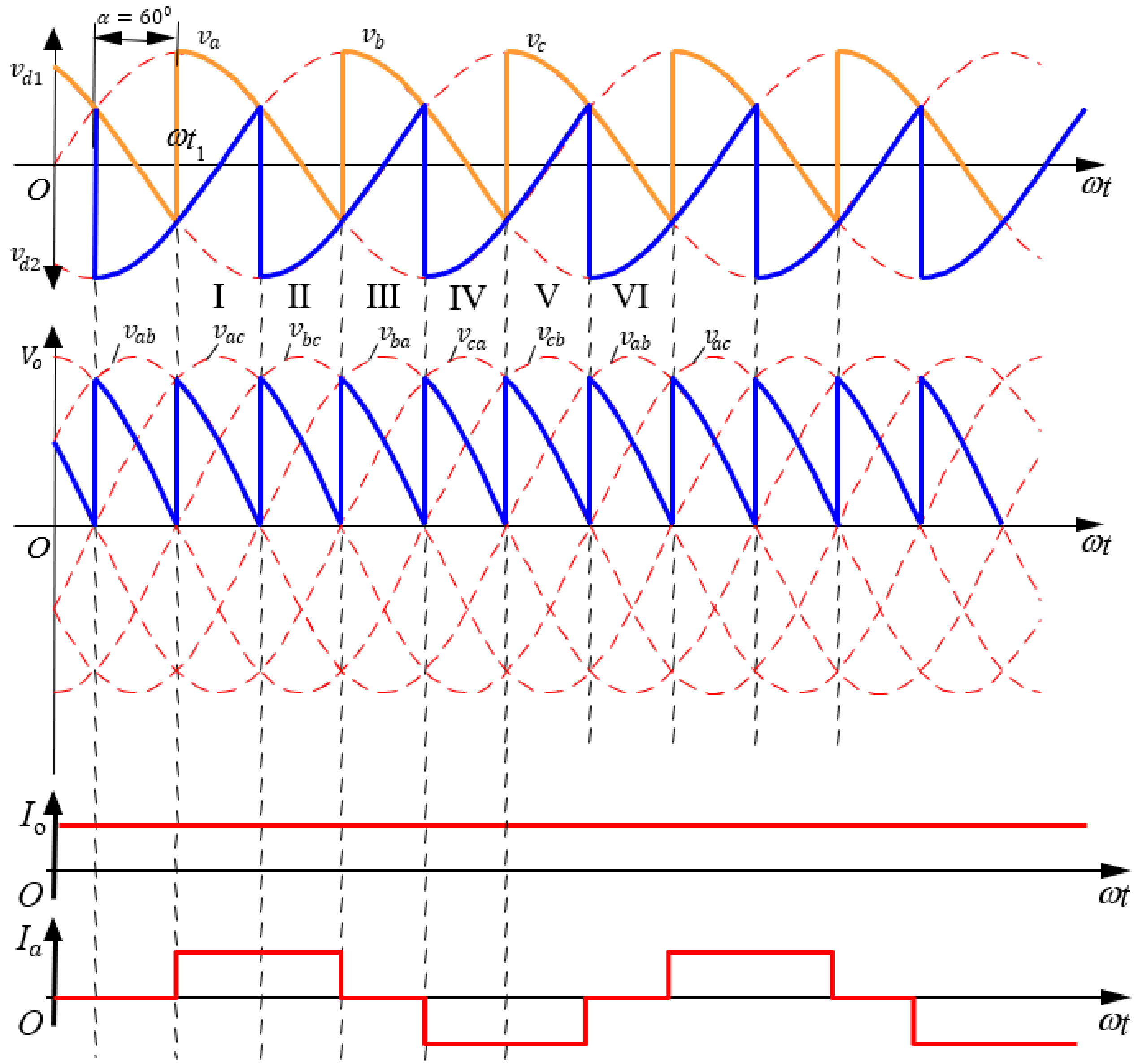
2.2 Inductive load

- Inductive load (R-L load)
  - α = 30°
  - T_1 is triggered at $\omega t = \pi/3$
  - Output voltage is continuous



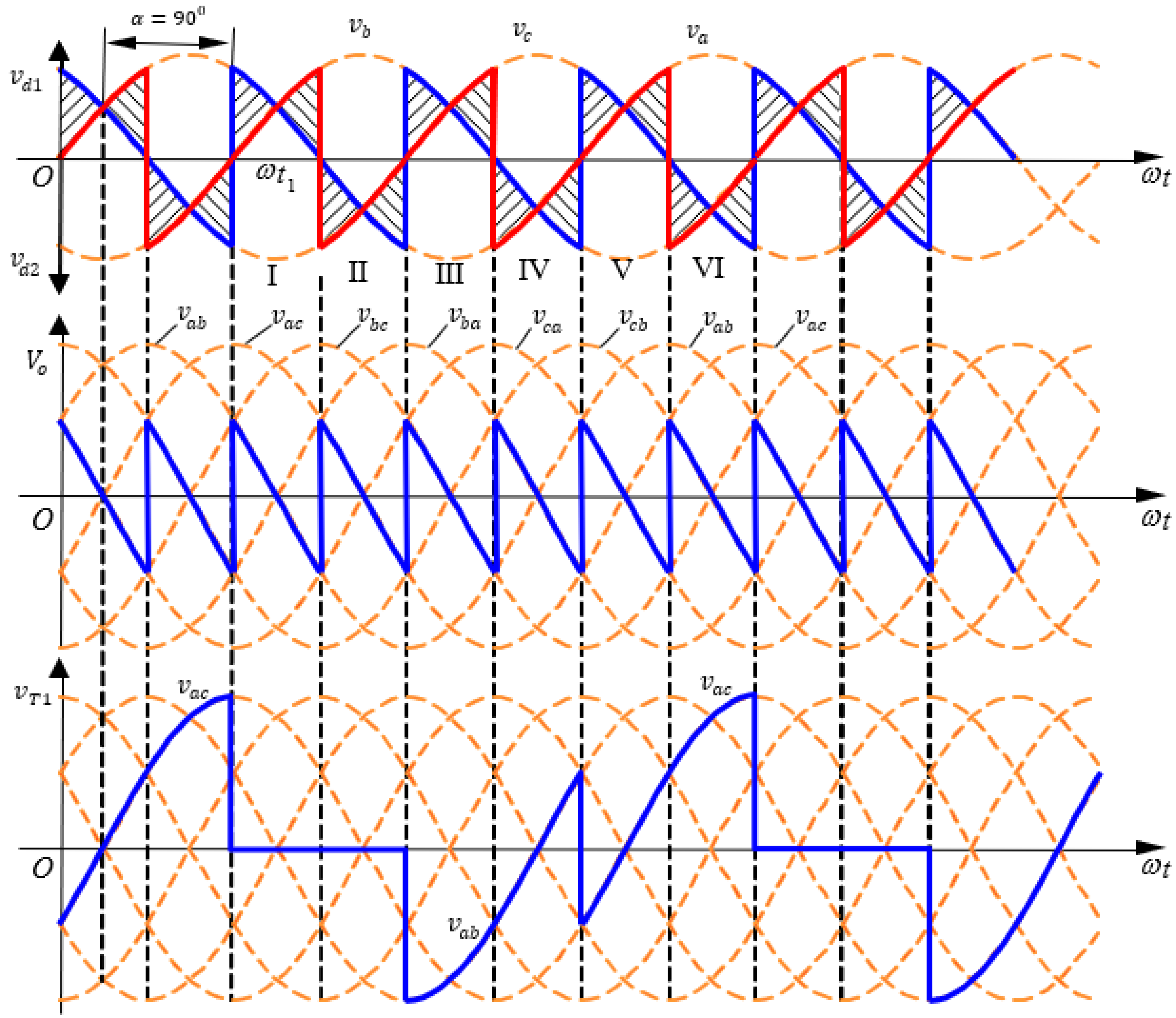
2.2 Inductive load

- Inductive load (R-L load)
  - $\alpha = 60^o$
  - T_1 is triggered at $\omega t = \pi/2$
  - Output voltage is continuous



2.2 Inductive load

- Inductive load (R-L load)
  - α = 90º
  - T_1 is triggered at $\omega t = 120$
  - Output voltage is continuous and goes negative due to RL load



Quantitative analysis

- Average output voltage (R-load, for $\alpha \leq 60^0$ and any α for RL load)

$$V_{dc} = \frac{3}{\pi}\int_{\pi/6+\alpha}^{\pi/2+\alpha} v_{ab}\, d(\omega t) = \frac{3}{\pi}\int_{\pi/6+\alpha}^{\pi/2+\alpha} \sqrt{3}\, V_m \sin\left(\omega t + \frac{\pi}{6}\right) d(\omega t)$$
$$= \frac{3\sqrt{3}\, V_m}{\pi} \cos\alpha$$

  – For resistive load, when $\alpha > 60^0$, load current I_o is discontinuous.

$$V_{dc} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}} \sqrt{3}\sin\left(\omega t + \frac{\pi}{6}\right) d(\omega t) = \frac{3\sqrt{3}V_m}{\pi}\left[1 + \cos\left(\frac{\pi}{3} + \alpha\right)\right]$$

- RMS output voltage

$$V_{rms} = \left[\frac{3}{\pi}\int_{\pi/6+\alpha}^{\pi/2+\alpha} 3V_m^2 \sin^2\left(\omega t + \frac{\pi}{6}\right) d(\omega t)\right]^{1/2}$$
$$= \sqrt{6}\, V_m \left(\frac{1}{4} + \frac{3\sqrt{3}}{8\pi}\cos 2\alpha\right)^{1/2}$$

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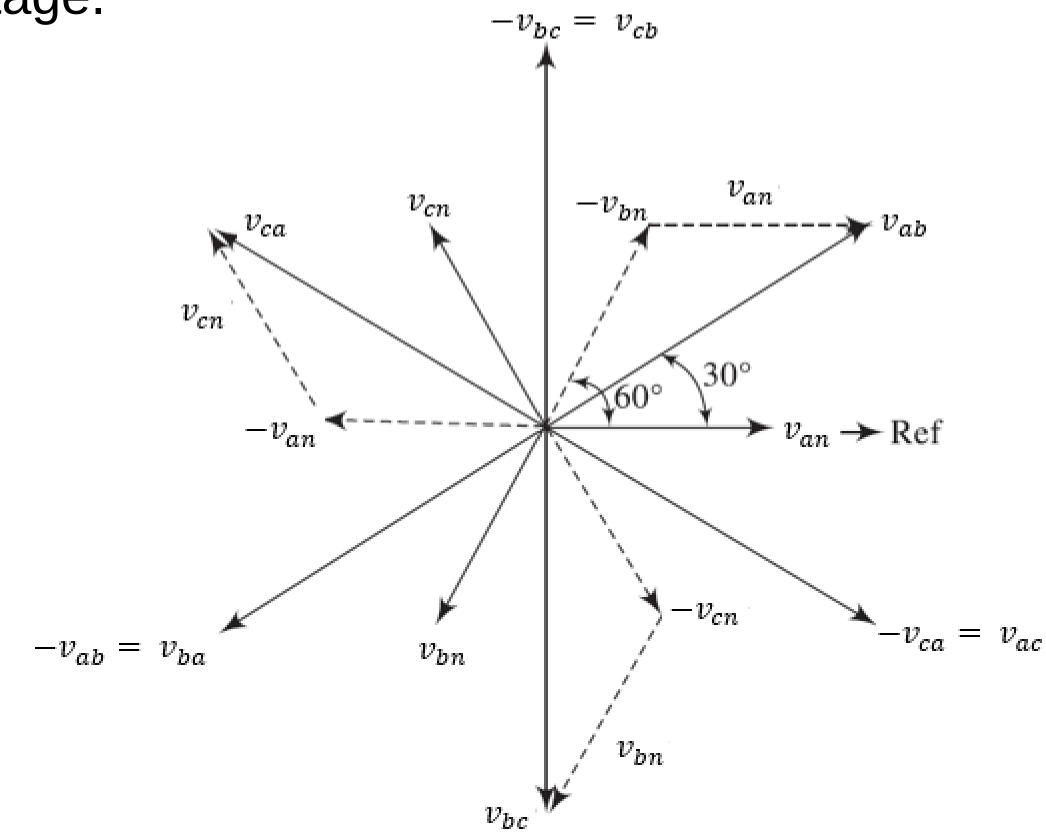
Quantitative analysis – Notes

- V_m is the peak value of the phase voltage.

$$v_{an} = V_m \sin\omega t$$
$$v_{bn} = V_m \sin(\omega t - 120^0)$$
$$v_{cn} = V_m \sin(\omega t - 240^0)$$

- Line to line voltages lead the phase voltage by 30^0.

$$v_{ab} = \sqrt{3} V_m \sin(\omega t + 30^0)$$
$$v_{bc} = \sqrt{3} V_m \sin(\omega t - 90^0)$$
$$v_{ca} = \sqrt{3} V_m \sin(\omega t - 210^0)$$
$$\cong V_{ml} \sin(\omega t - 210^0)$$



Quantitative analysis

- Average output current (load current) for resistive load

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

- Thyristor voltage and current
  - Same as three-phase half-wave rectifier

- For EMF load, L is large enough
  - All the same as inductive load except the calculation of average output current $I_o = \frac{V_o - E}{R}$

Exercise – Try to solve!

- A three-phase half-wave controlled converter is operated from 3-phase, 230 V, 50 Hz supply with load resistance $R = 10\Omega$. An average output voltage of 50% of the maximum possible output voltage is required. Determine

    a) the firing angle,
    b) average and rms values of load current,
    c) rectification efficiency

Summary

- 3-phase half-wave rectifier with R–load: 1) Continuous conduction mode when $\alpha < 30^0$, 2) Discontinuous mode when $\alpha > 30^0$.

- 3-phase full-wave rectifier: Triggering pulses should be
  - According the sequence of $V_{T1} \rightarrow V_{T2} \rightarrow V_{T3} \rightarrow V_{T4} \rightarrow V_{T5} \rightarrow V_{T6}$
  - With 60^o phase difference
  - 6 pulses in one period;
  - Continuous conduction mode for $\alpha \leq 60^0$ in R-load and for any α in RL load, otherwise, *discontinuous mode*.

- The output voltage waveforms for $\alpha = 0^0, 30^0, 60^0$ of 3-phase fully controlled bridge rectifier with RL load will be same as the waveforms for $\alpha = 0^0, 30^0, 60^0$ of 3-phase fully controlled bridge rectifier with R load.

See you in the next class (March 24th)

- Tutorial in the next lecture

The End