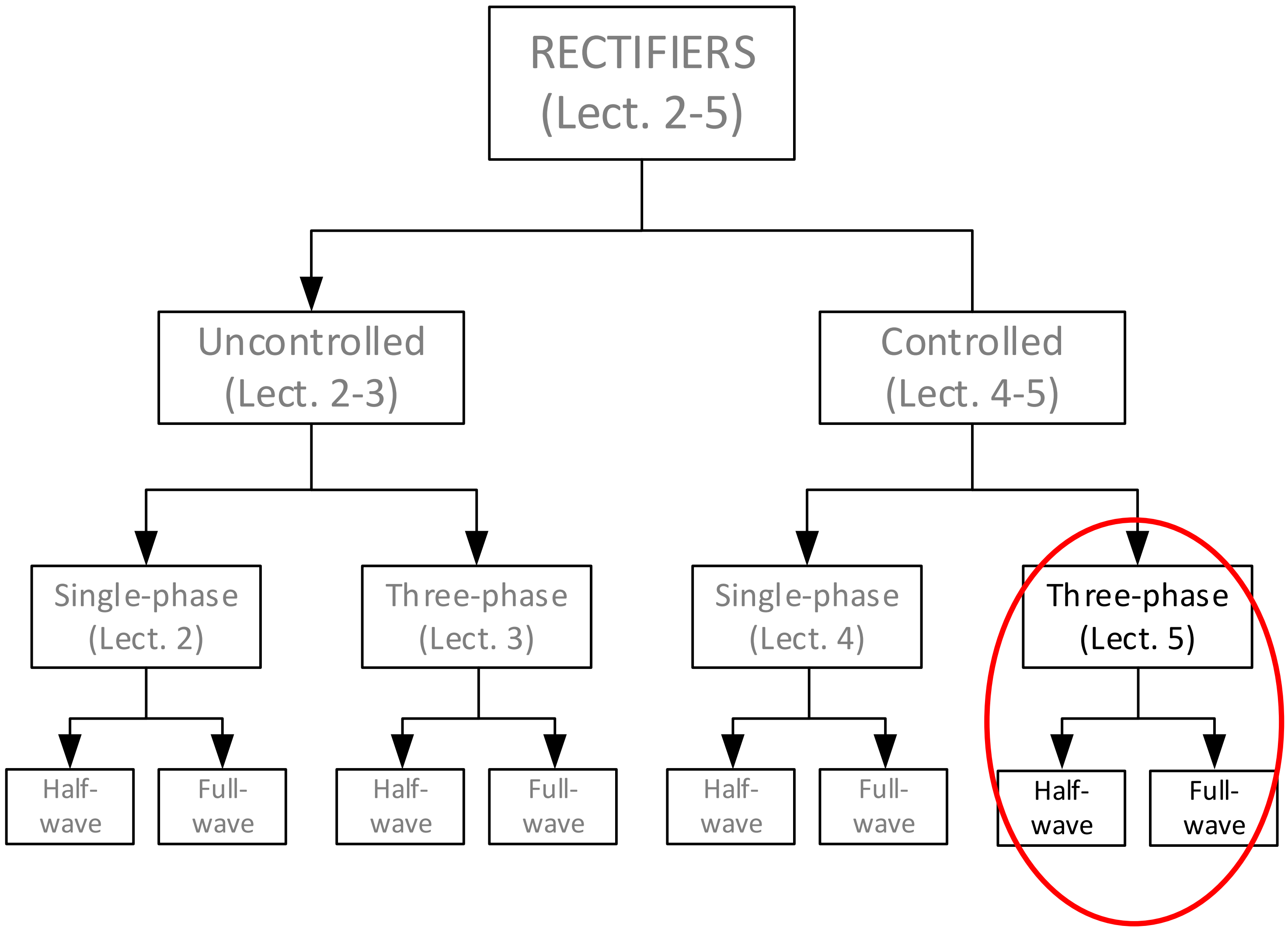
EEE213 Power Electronics and Electromechanism

5. Controlled Rectifier – Three Phase

Classification



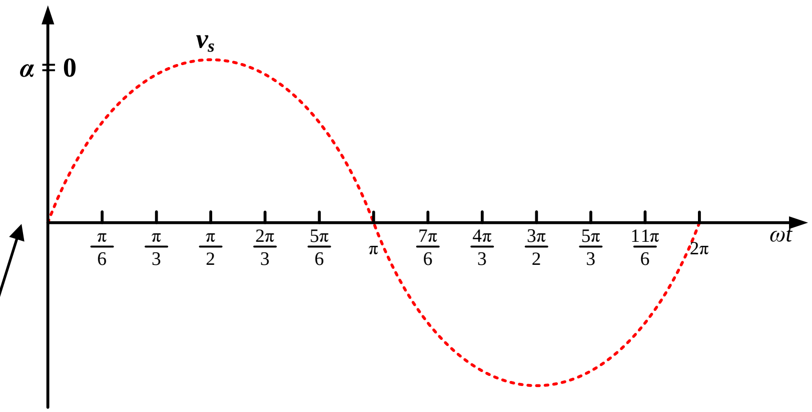
Outline

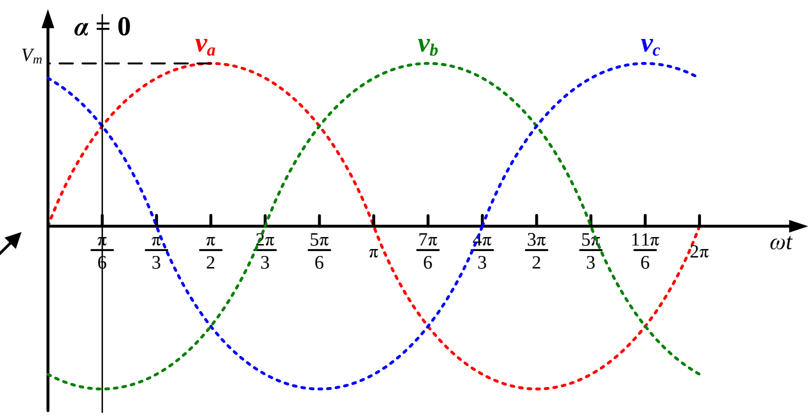
- Three-phase, controlled rectifiers
  - Half-wave
    - Firing angle (triggering angle) α;
    - Resistive loading;
    - Inductive loading;
  - Full-wave (bridge)
    - Resistive loading;
    - Inductive loading.

- Comparison

1.1 Firing angle (triggering angle)

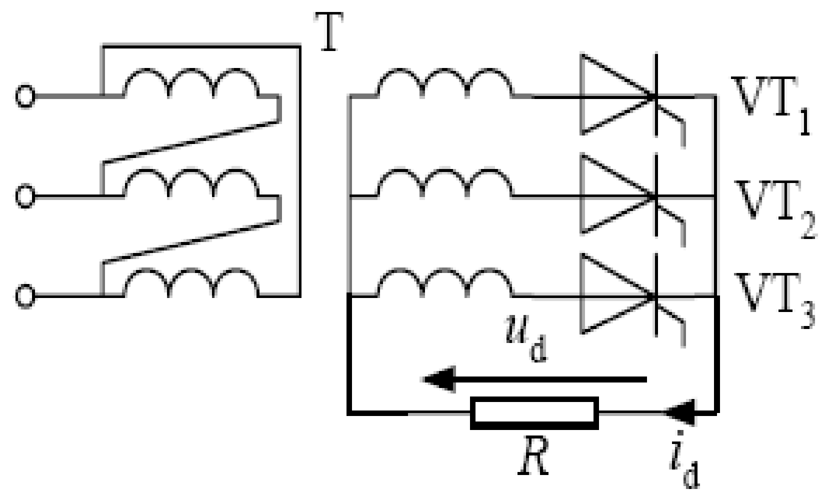
- In the controlled rectifier, the controllability of the circuit is realized by triggering the thyristors at different phase, which is called the ***firing angle***, or ***triggering angle***. It is usually represented by "α";
  - This trigger signal is a current (or voltage) pulse at the "gate" terminal 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***.

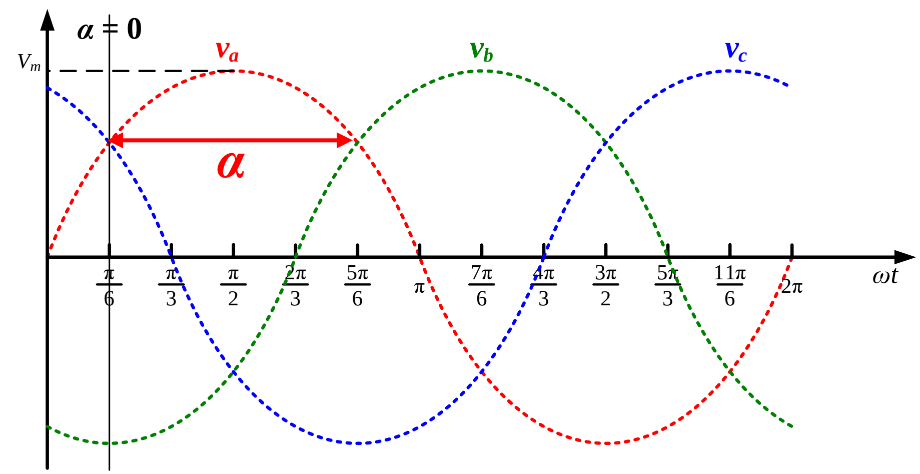




1.1 Three-phase, half-wave, R-load

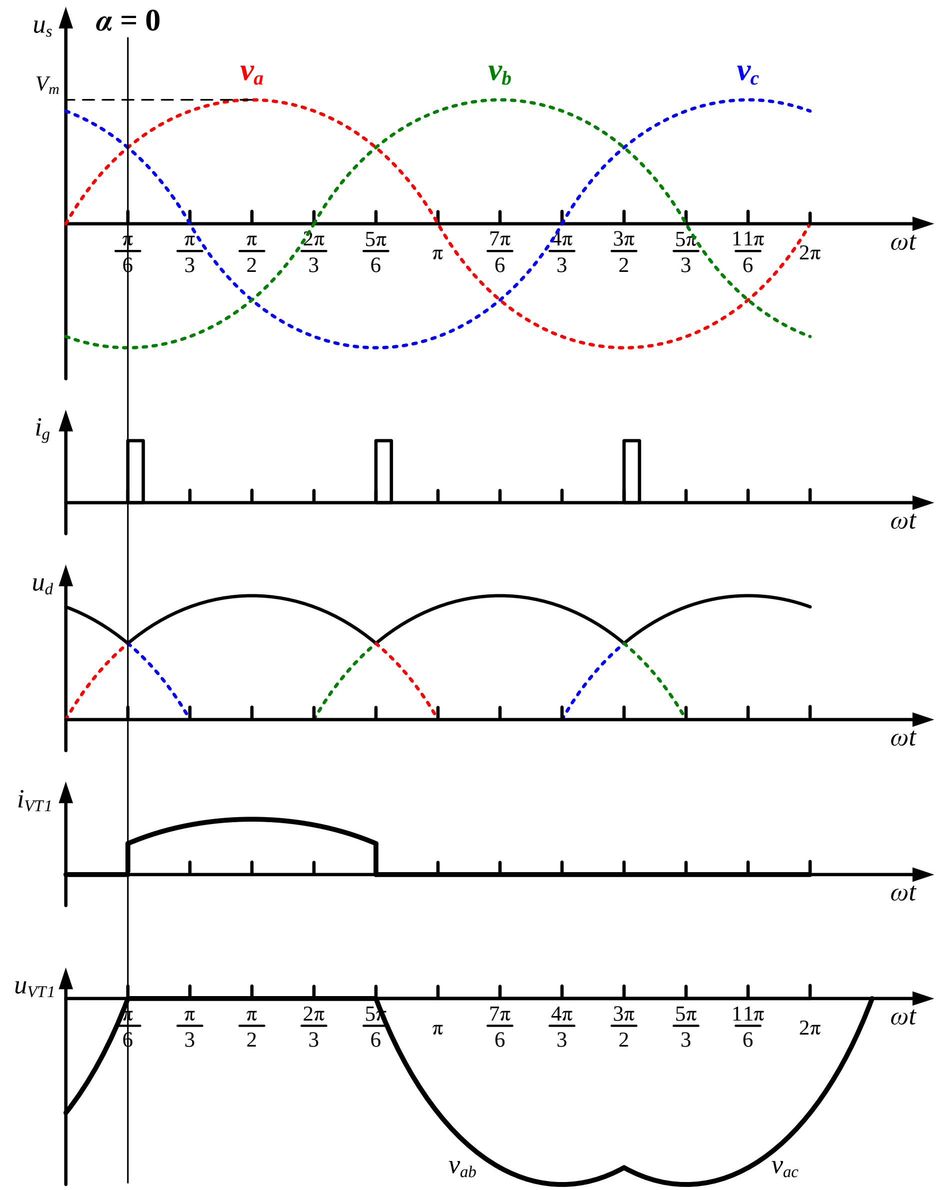
- Resistive load
  - Three phase supply - star connection
  - Common-cathode connection
- Natural commutation (phase-changing) point
  - The earliest trigger angle for each phase
  - It is considered as the starting point for thyristor triggering angle α, i.e. $\alpha = 0^o$
  - Phase-shift range: $\alpha <= 120^o$





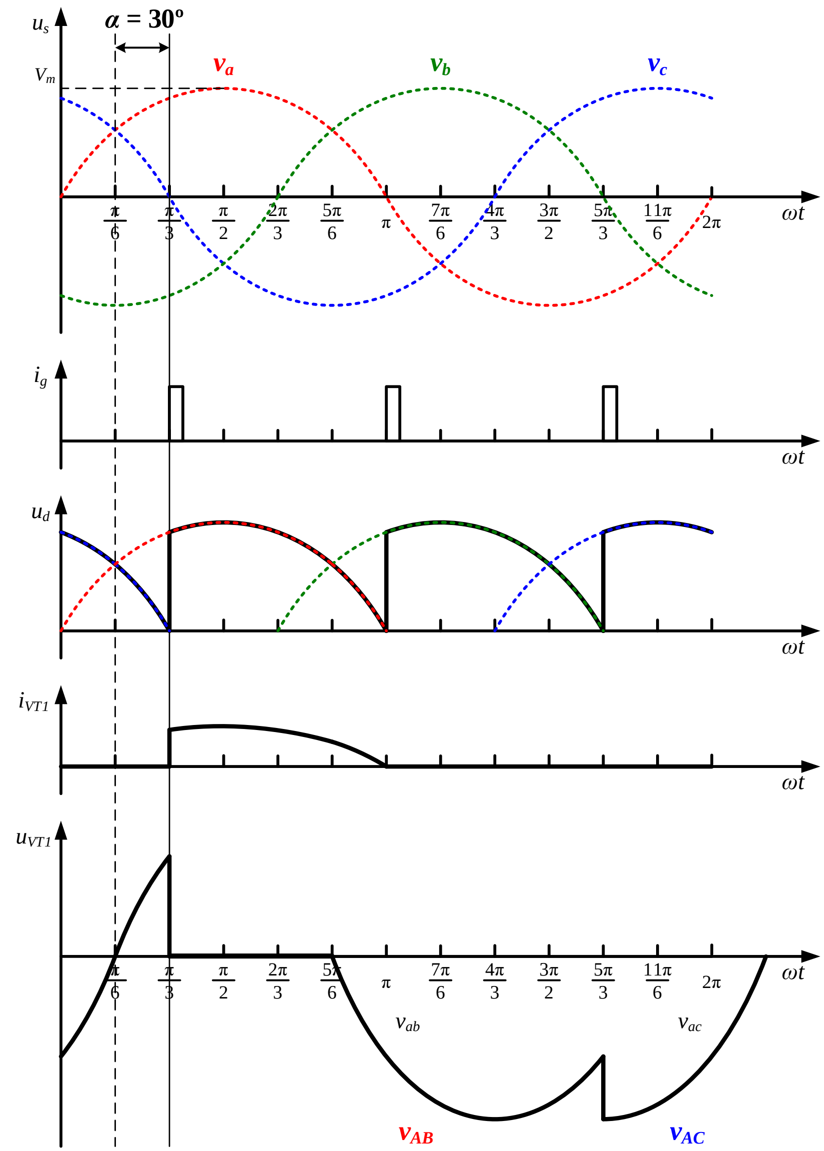
1.1 Three-phase, half-wave, R-load

- When $\alpha = 0^o$ (Same as the uncontrolled circuit);
  - For example: at $\alpha = 0$ ($\omega t = \pi/6$), as soon as VT1 is forward biased (red line v_a becomes the largest one), a trigger signal is provided to VT1, so VT1 starts to conduct;
  - $2\pi/3$ after, when v_b becomes the largest one, another trigger signal is provided to VT2, so VT2 starts to conduct;
  - At $\omega t = 3\pi/2$, when v_c becomes the largest one, the trigger signal to VT3 is provided, so VT3 starts to conduct.



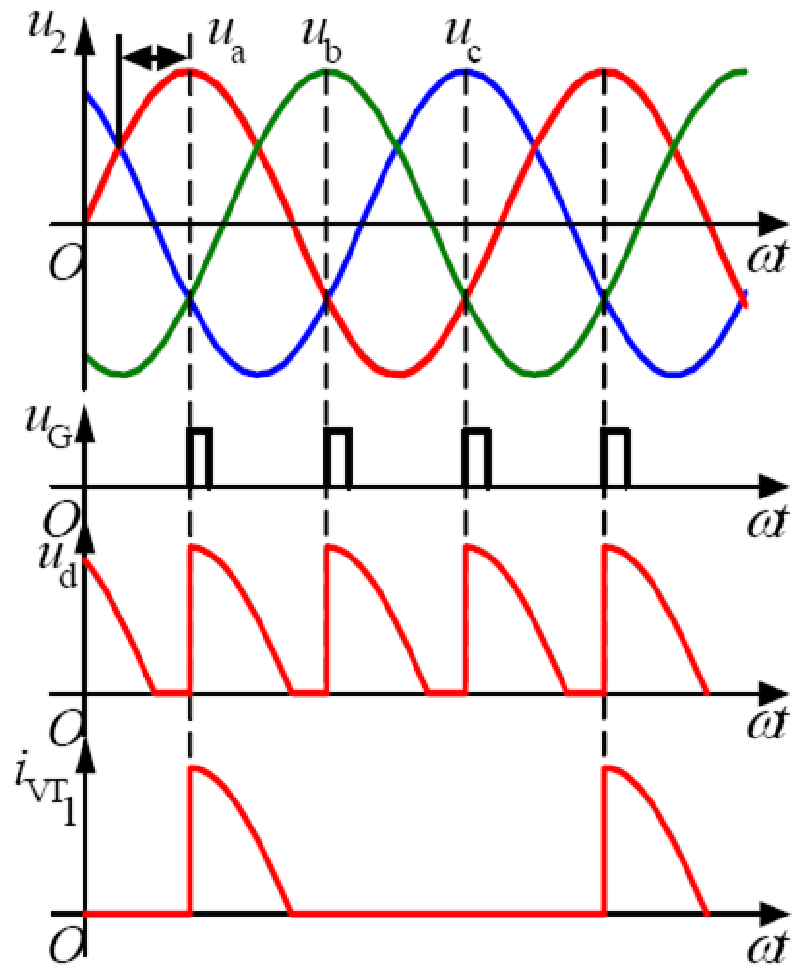
1.1 Three-phase, half-wave, R-load

- When $\alpha = 30^o$
  - From $\omega t = \pi/6$ to $\pi/3$, although VT1 is forward biased (red line v_a is the largest one), no trigger signal is provided to VT1, so VT1 cannot conduct;
  - At $\alpha = 30^o$ ($\omega t = \pi/3$), a trigger signal is provided to VT1, so VT1 starts to conduct;
  - At $\omega t = 5\pi/6$, when v_b becomes the largest one, since no trigger signal is provided to VT2, VT2 will not conduct until $\omega t = \pi$, when the trigger signal provided.



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

- When $\alpha = 60^o$
  - From $\omega t = \pi/6$ to $\pi/2$, although VT1 is forward biased (red line v_a is the largest one), no trigger signal is provided to VT1, so VT1 cannot conduct;
  - At $\alpha = 60^o$ ($\omega t = \pi/2$), a trigger signal is provided to VT1, so VT1 starts to conduct;
  - From $\omega t = \pi$ to $7\pi/6$, v_a is no longer the largest one, VT1 stops; since no trigger signal is provided to VT2, VT2 will not conduct either;
  - At $\omega t = 7\pi/6$, VT2 is forward biased and triggered, so it conducts.



Resistive load, quantitative analysis

- When α ≤ 30º, load current i_d is continuous.

$$U_{\mathbf{d}} = \frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} \sqrt{2}U_2 \sin\omega t d(\omega t) = \frac{3\sqrt{6}}{2\pi}U_2 \cos\alpha = 1.17U_2 \cos\alpha$$

- When α > 30º, load current i_d is discontinuous.

$$U_{\mathbf{d}} = \frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\pi} \sqrt{2}U_2 \sin\omega t d(\omega t) = \frac{3\sqrt{2}}{2\pi}U_2\left[1+\cos(\frac{\pi}{6}+\alpha)\right] = 0.675\left[1+\cos(\frac{\pi}{6}+\alpha)\right]$$

- Average load current

$$I_{\mathrm{d}} = \frac{U_{\mathrm{d}}}{R}$$

- Thyristor voltages: reverse voltage = peak line voltage

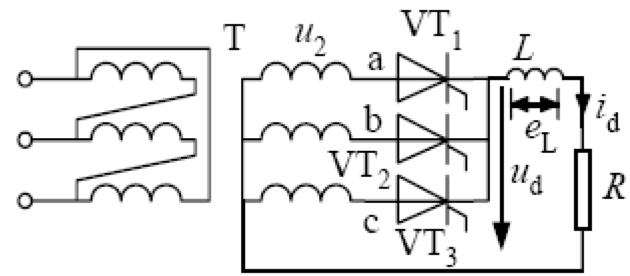
$$U_{RM} = \sqrt{2}\times\sqrt{3}U_2 = \sqrt{6}U_2 = 2.45U_2$$

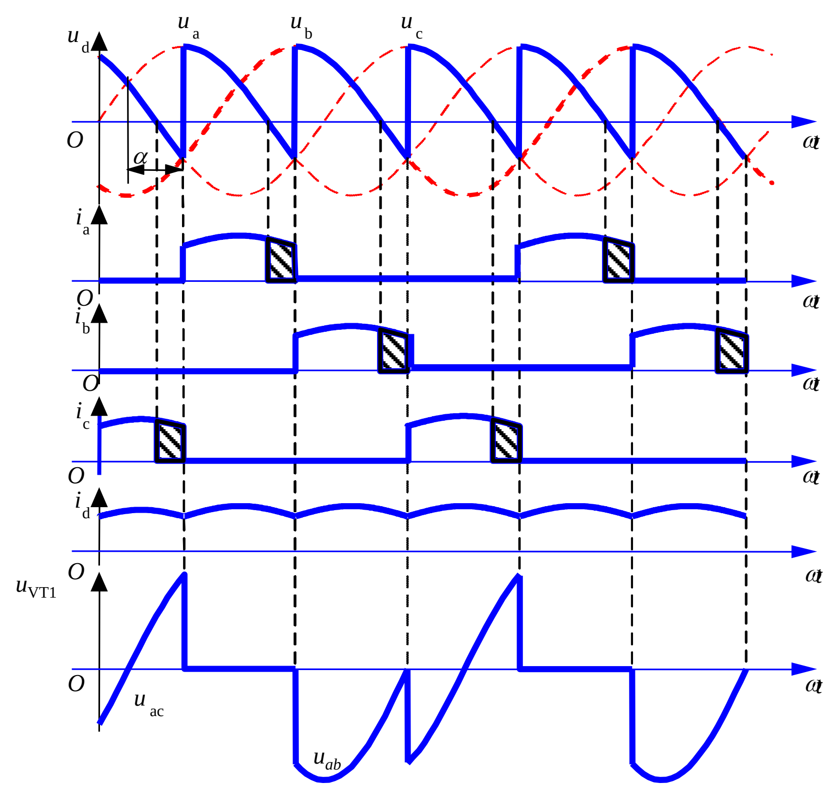
forward voltage = peak phase voltage

$$U_{FM} = \sqrt{2}U_2$$

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

- Inductive load (R-L)
  - When L is large enough, the output current i_d is almost flat;
  - When $\alpha \leq 30^o$, the rectified voltage waveform is similar to resistive load;
  - When $\alpha > 30^o$ (eg. $\alpha = 60^o$ as shown on right):
    - u_2 passes zero to negative, V_{T1} keeps conducting until the pulse for V_{T2} comes.
    - u_d has negative values.
  - Phase-shift range: $\alpha <= 90^o$





Inductive load, quantitative analysis

- Load current i_d is always continuous, so

$$U_{\mathbf{d}} = \frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha}\sqrt{2}U_2 \sin\omega t d(\omega t) = \frac{3\sqrt{6}}{2\pi}U_2\cos\alpha = 1.17U_2\cos\alpha$$

- Thyristor current:

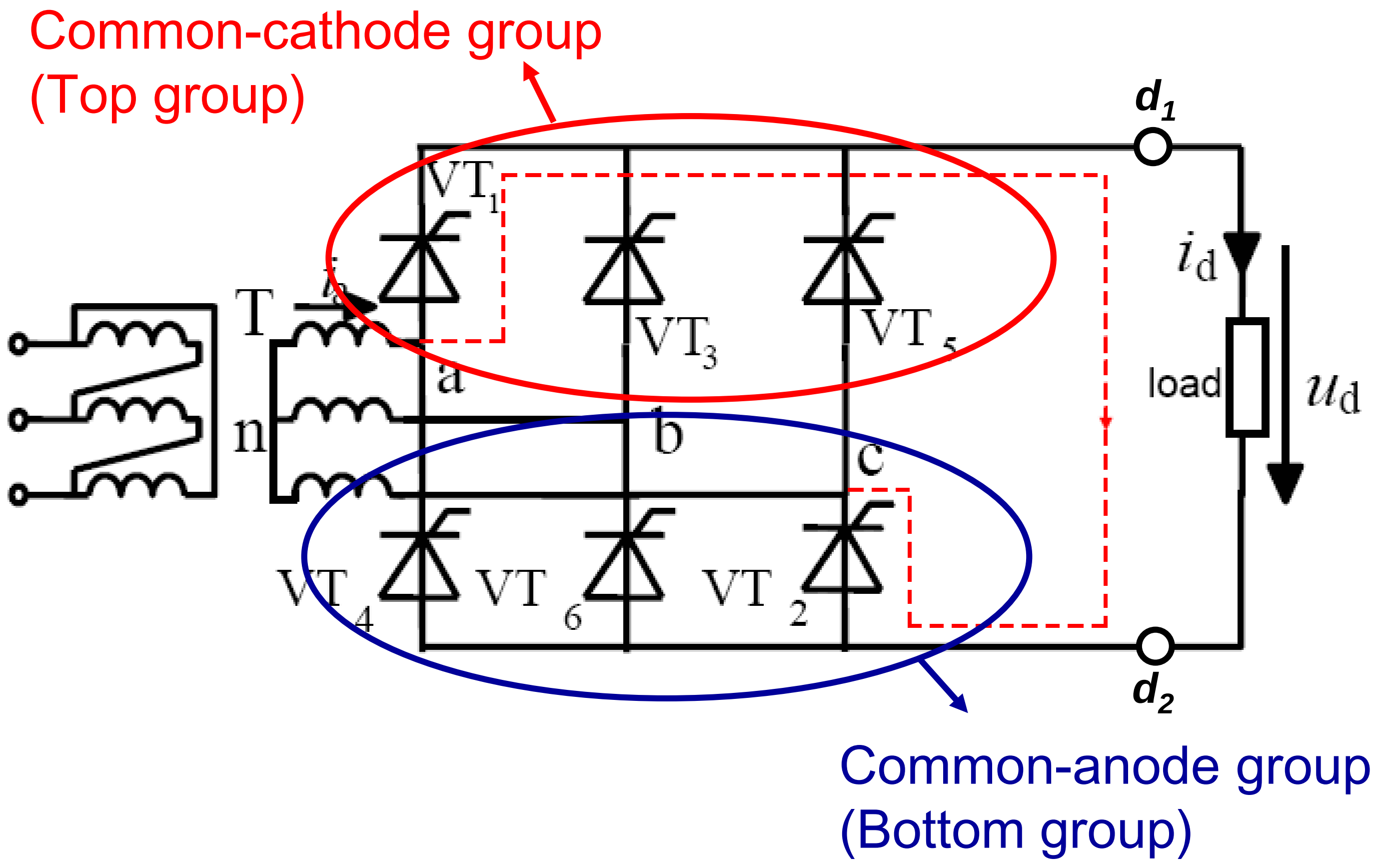
$$I_2 = I_{\mathrm{VT}} = \frac{1}{\sqrt{3}}I_{\mathrm{d}} = 0.577I_{\mathrm{d}}$$

- Thyristor voltages:

forward voltage = reverse voltage = peak line voltage

$$U_{FM} = U_{RM} = \sqrt{2}\times\sqrt{3}U_2 = \sqrt{6}U_2 = 2.45U_2$$

2 Three-phase bridge fully-controlled rectifier

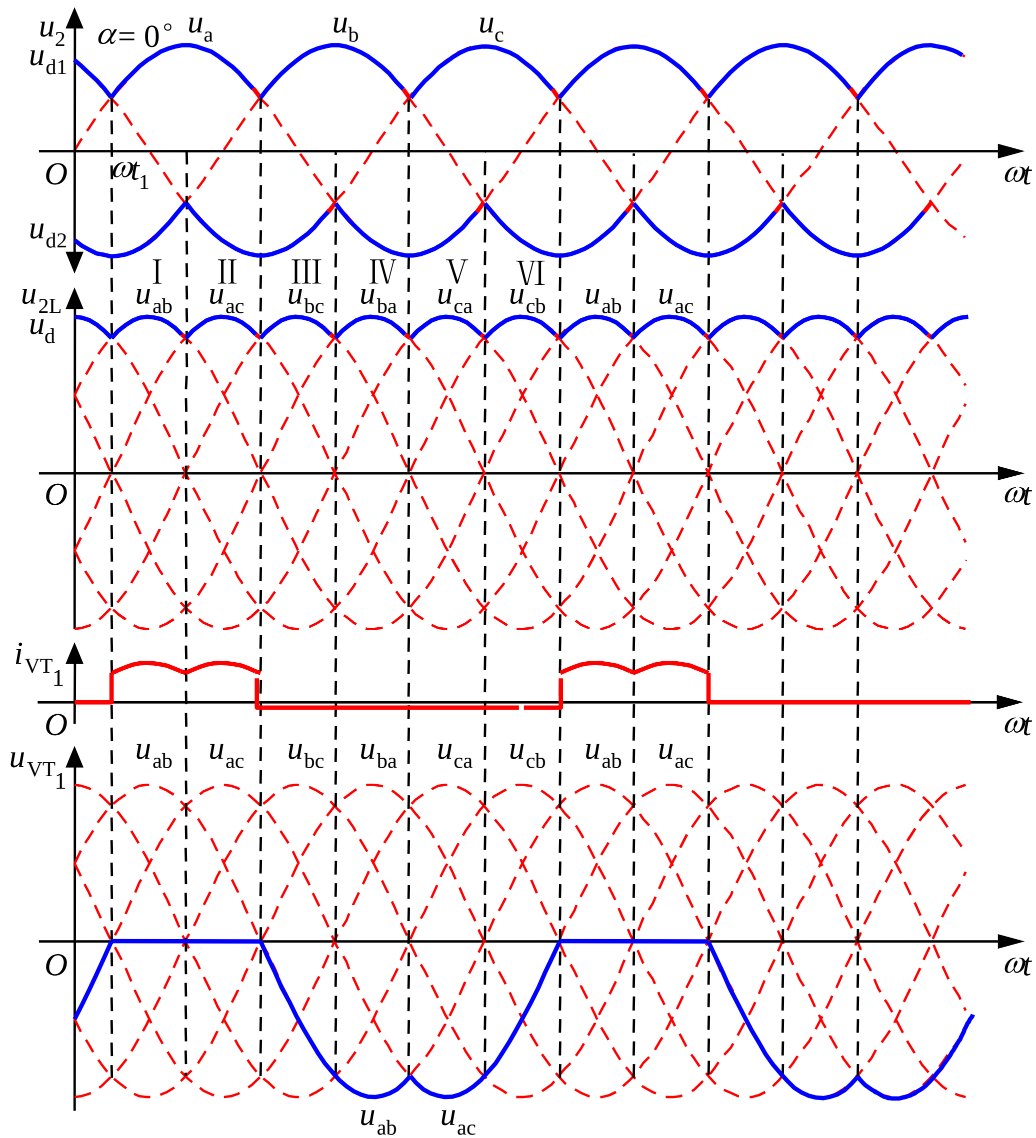


- Numbering of the 6 thyristors indicates the trigger sequence:

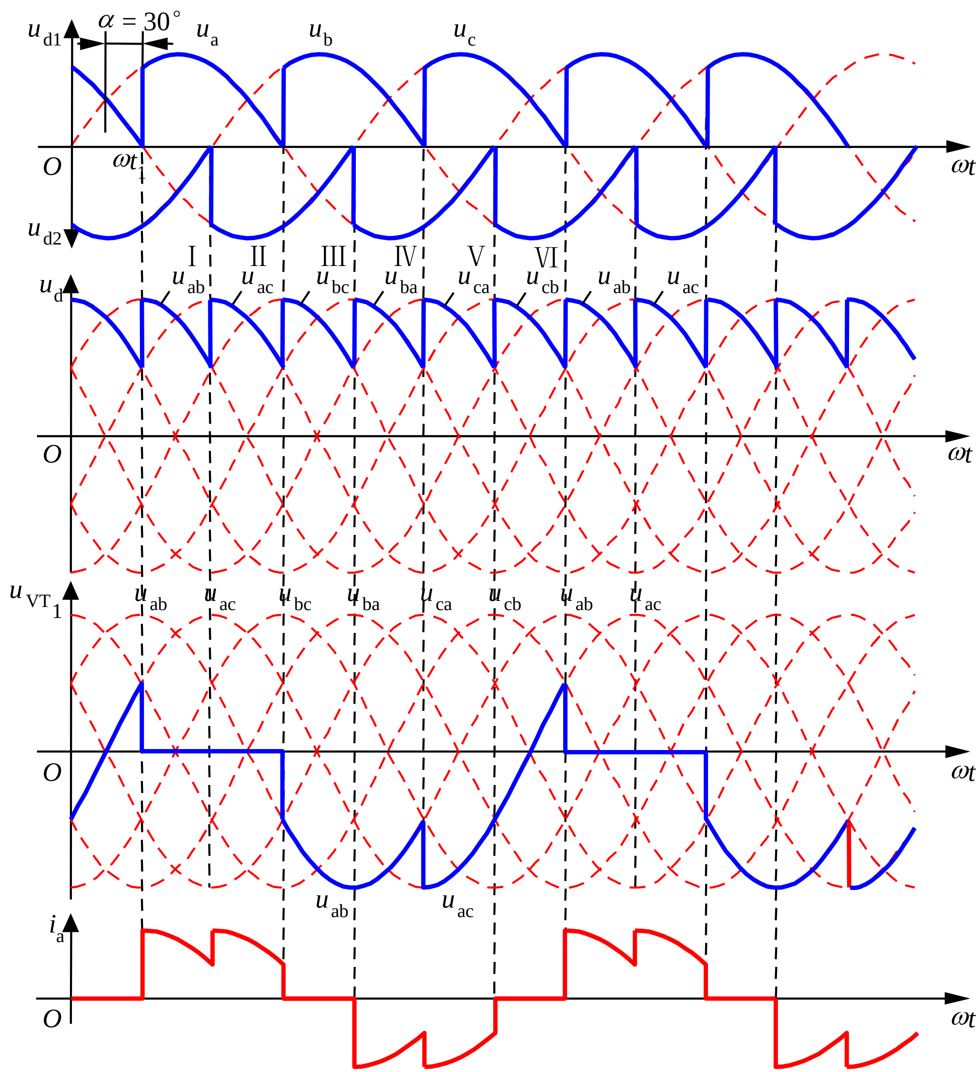
$V_{T1} \rightarrow V_{T2} \rightarrow V_{T3} \rightarrow V_{T}4 \rightarrow V_{T5} \rightarrow V_{T6}$

2.1 Resistive load

- Resistive load
  - $\alpha = 0^o$



- Resistive load
  - $\alpha = 30^{o}$



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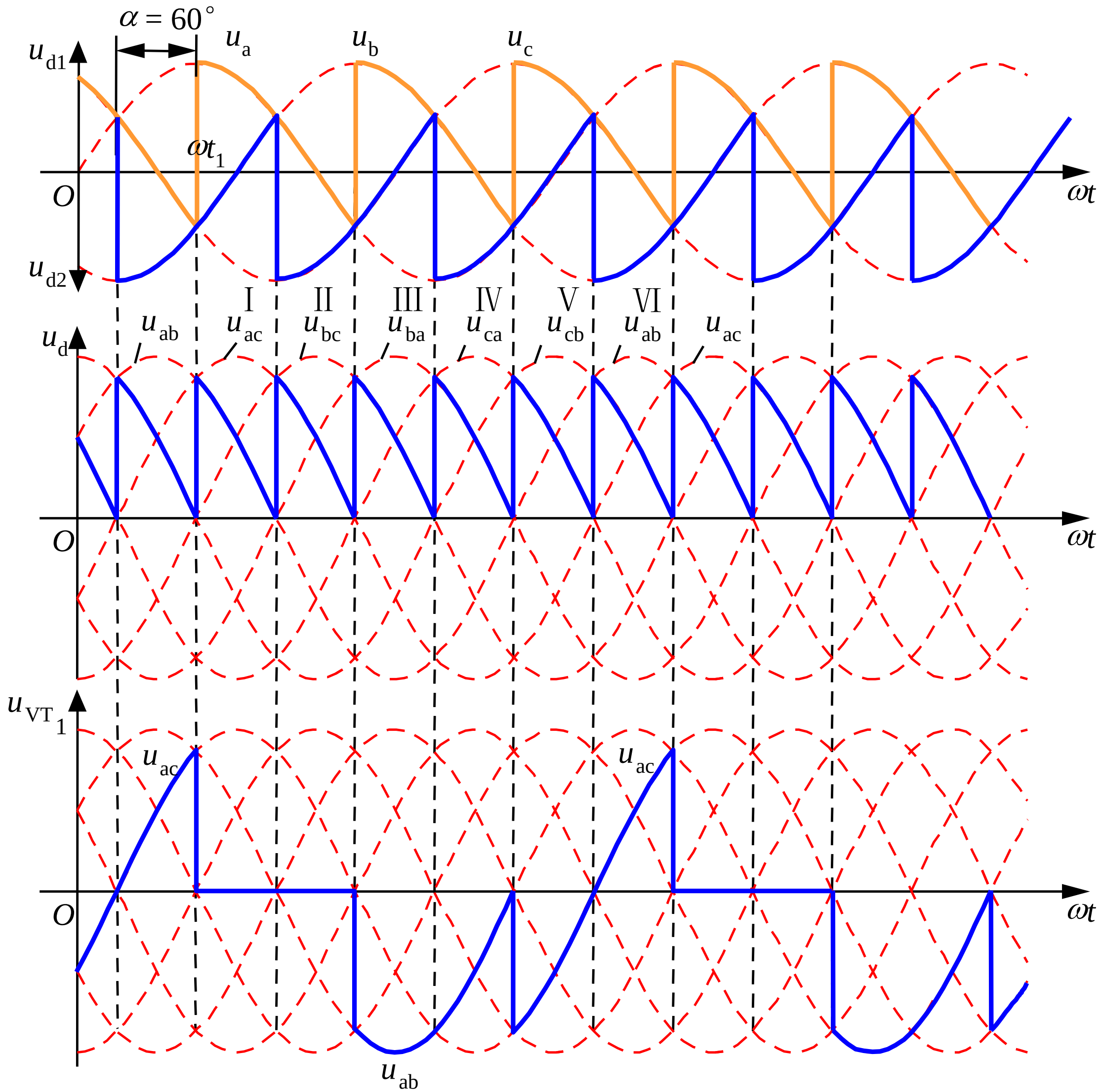
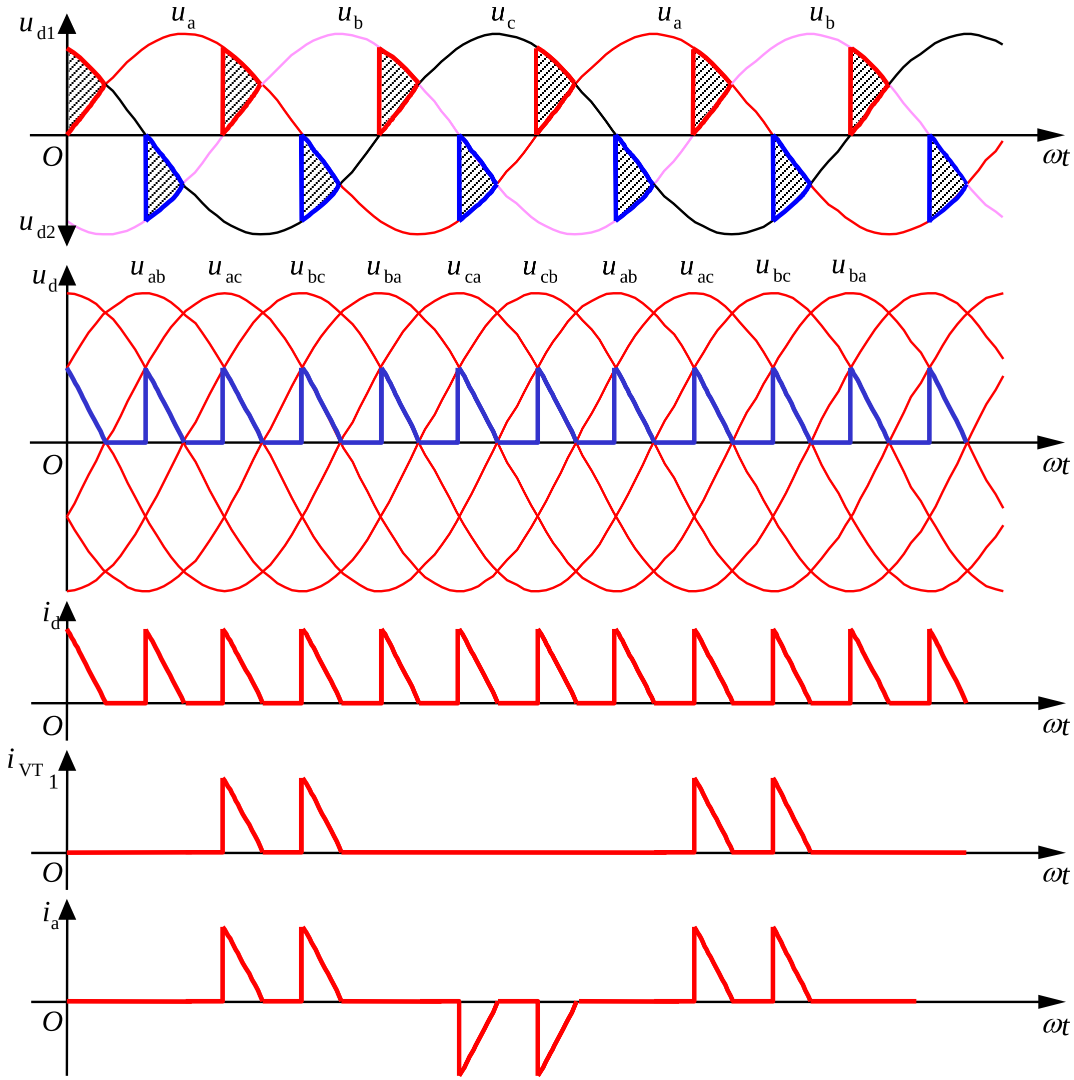
- Resistive load
  - $\alpha = 60^{o}$



- Resistive load
  - $\alpha = 90^{o}$

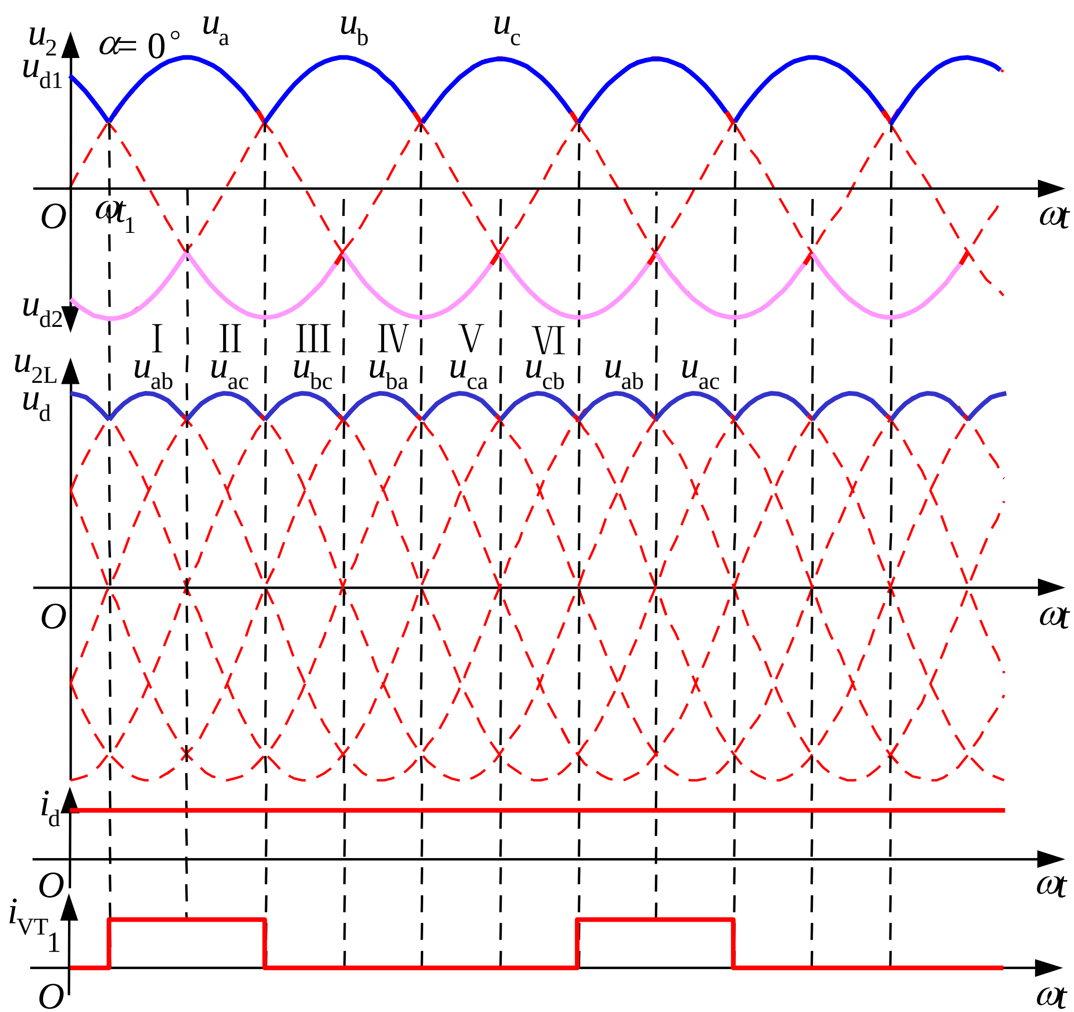


Summary

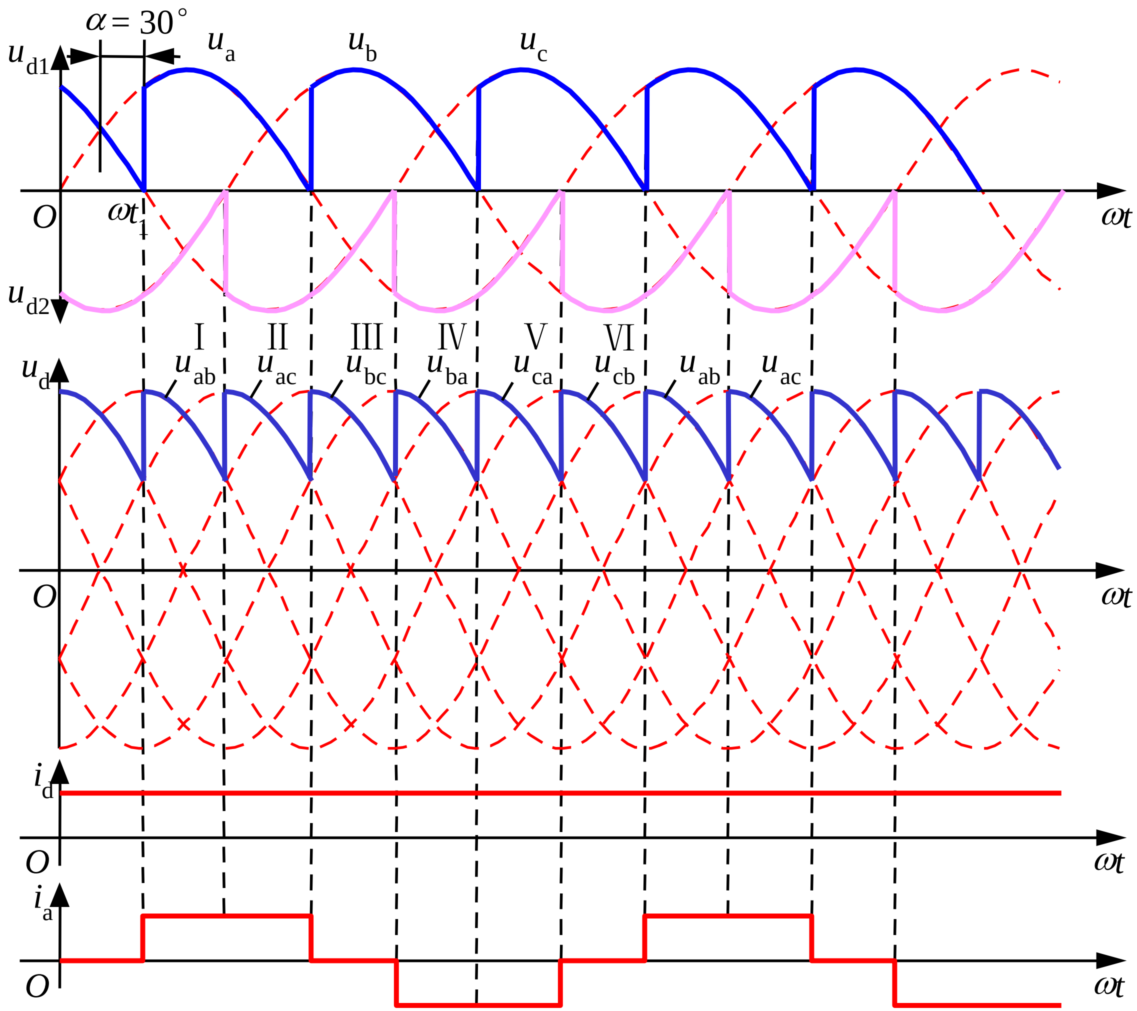
- Two thyristor from each group (top or bottom group) form the current loop;
- Trigger the two thyristor simultaneously;
- Trigger pulses should be:
  - According the sequence of $V_{T1} \rightarrow V_{T2} \rightarrow V_{T3} \rightarrow V_{T4} \rightarrow V_{T5} \rightarrow V_{T6}$
  - With 60^o phase difference
- 6 pulses in one period;
- Voltage waveform across the thyristor is the same as three-phase half-wave circuit, so do the forward and inverse peak voltages.

2.2 Inductive load

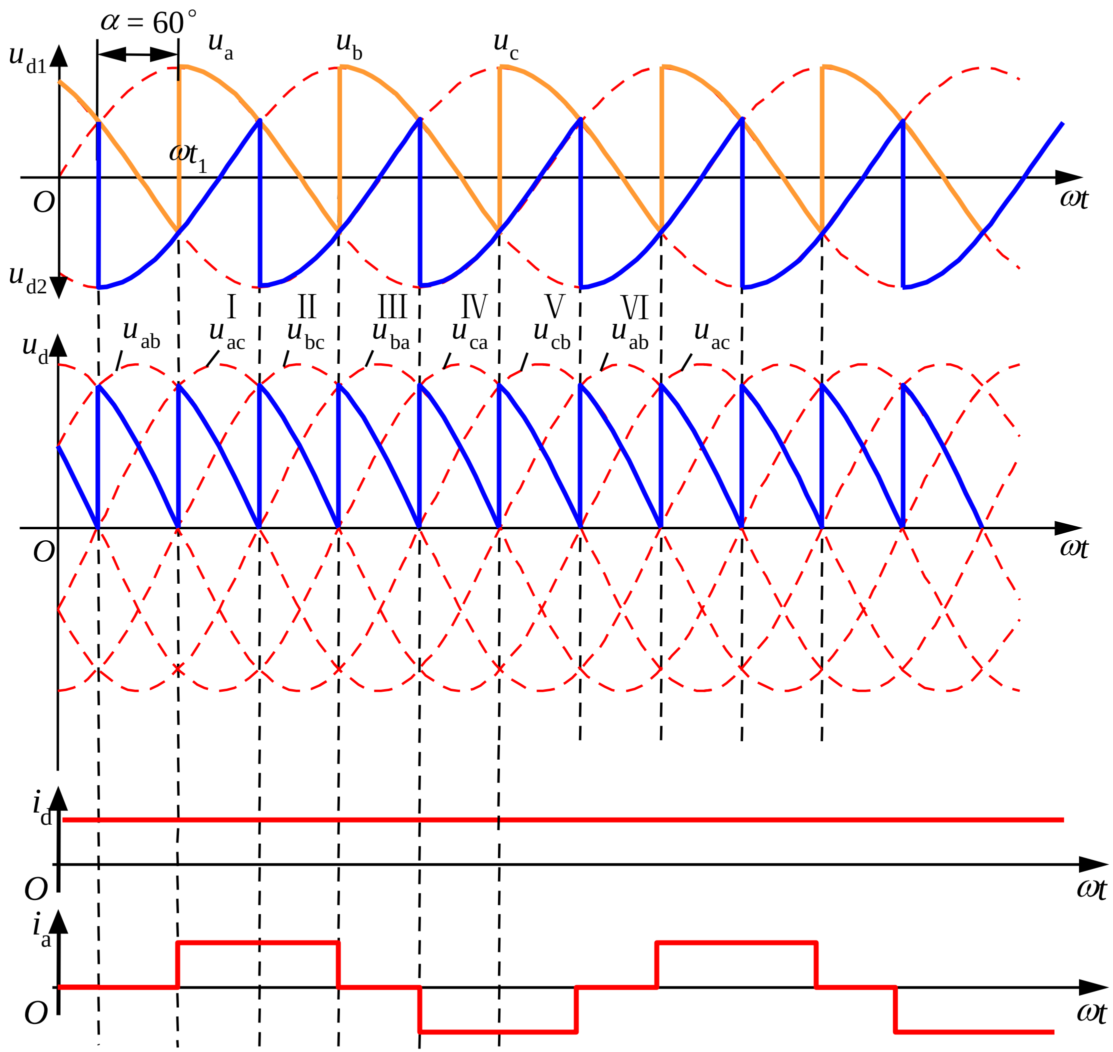
- Inductive load (R-L load)
  - $\alpha = 0^o$



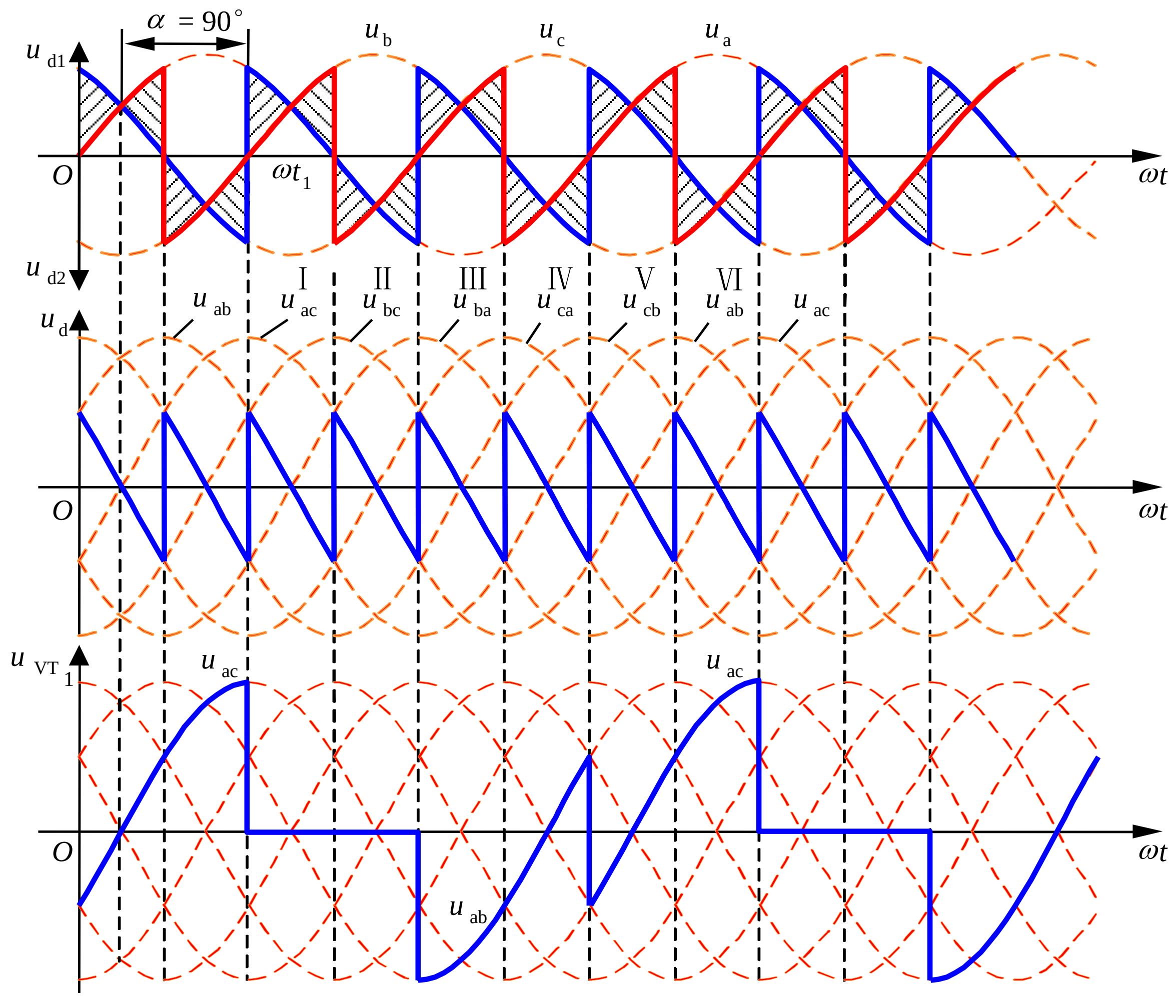
- Inductive load (R-L load)
  - $\alpha = 30^o$



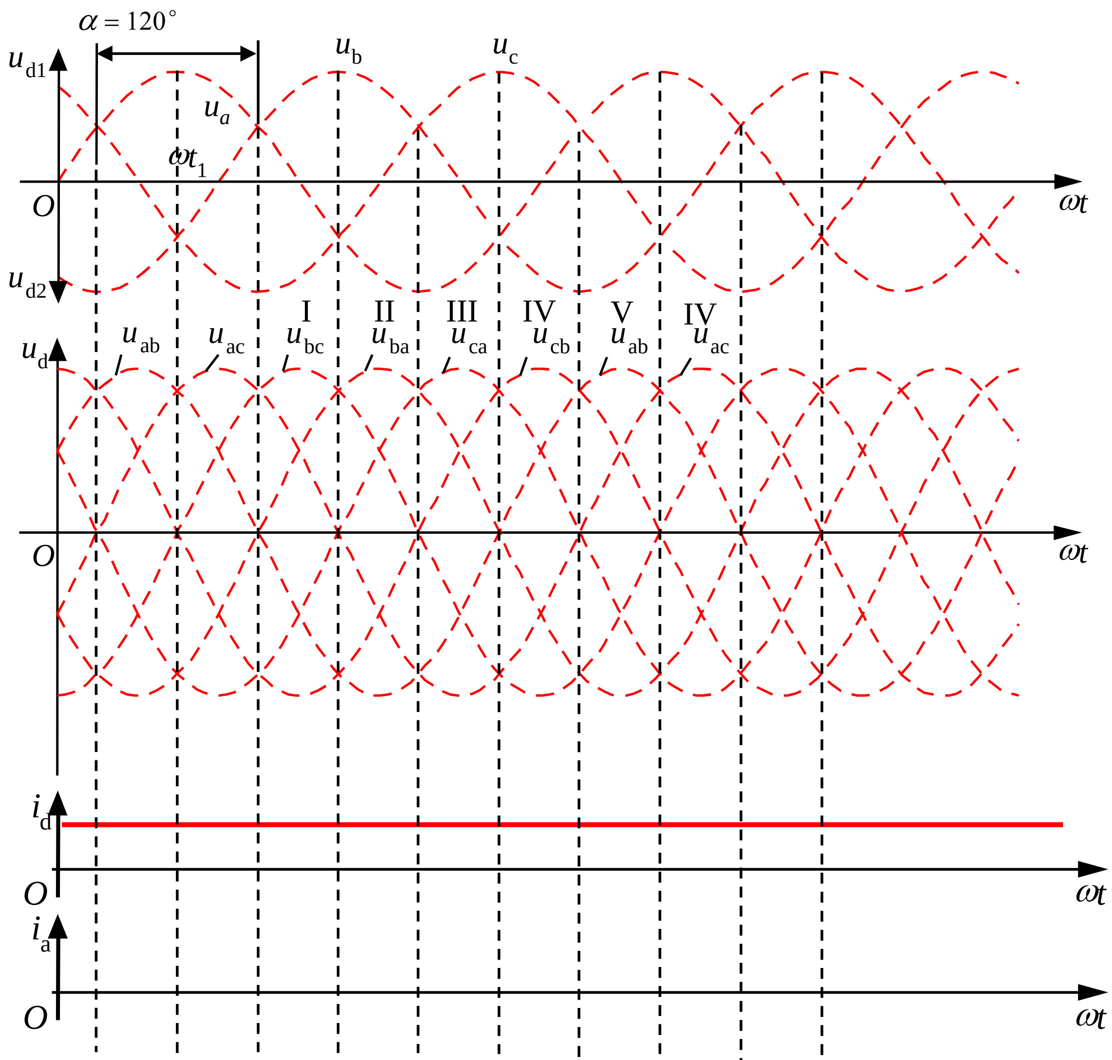
- Inductive load (R-L load)
  - α = 60º



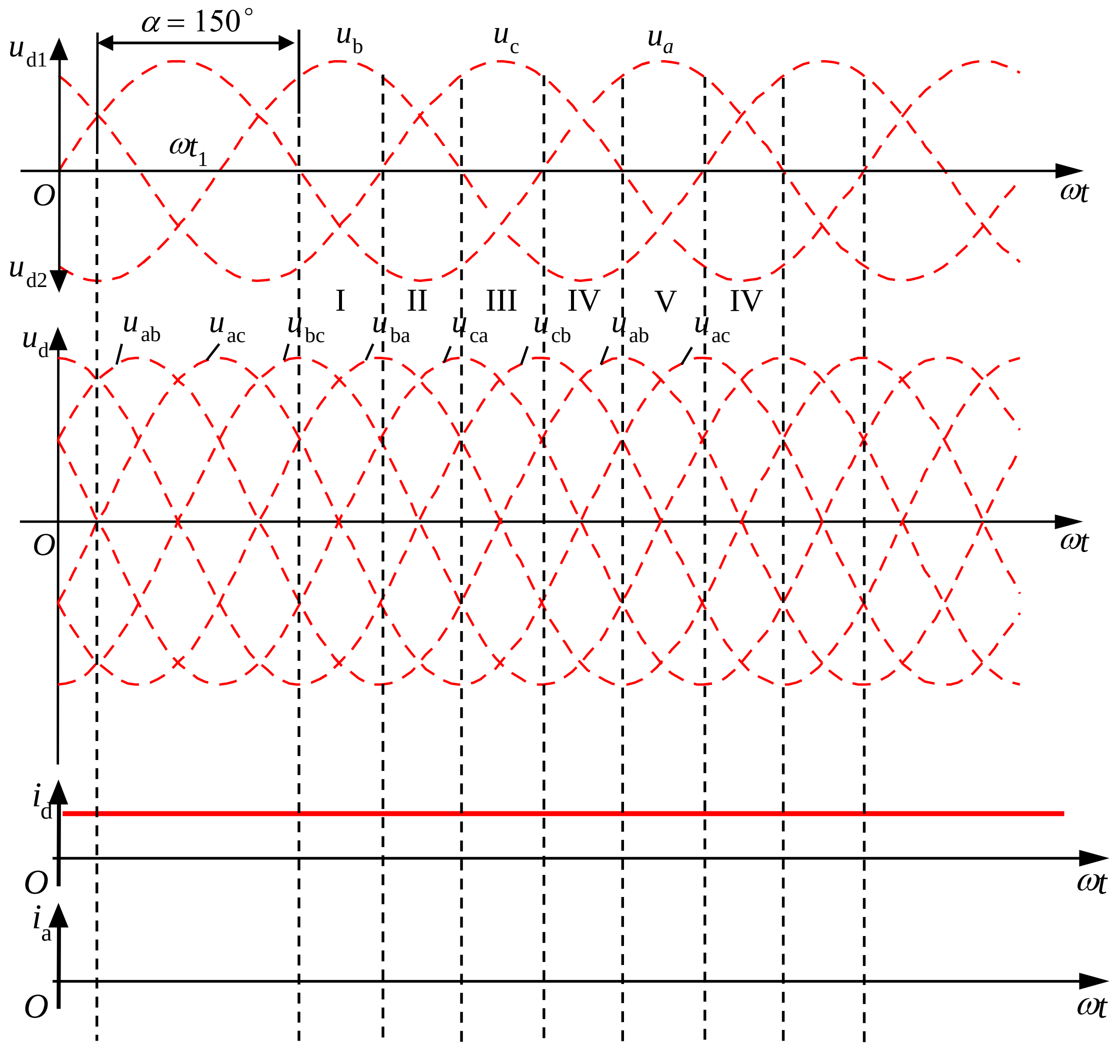
- Inductive load (R-L load)
  - α = 90º



- Inductive load (R-L load)
  - α = 120º



- Inductive load (R-L load)
  - $\alpha = 150^o$



Quantitative analysis

- Average output voltage

$$U_{d0} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_{ab} d(\omega t) = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{6}U_2 \sin\left(\omega t + \frac{\pi}{6}\right) d(\omega t) = \frac{3\sqrt{6}U_2}{\pi}\cos\alpha = 2.34U_2\cos\alpha$$

  – For resistive load, When a > 60º, load current id is discontinuous.

$$U_{d0} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}} \sqrt{6}U_2 \sin\left(\omega t + \frac{\pi}{6}\right) d(\omega t) = 2.34U_2\left[1 + \cos(\frac{\pi}{3} + \alpha)\right]$$

- RMS output voltage

$$U_{dRMS} = \sqrt{\frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \left(\sqrt{6}U_2 \sin\left(\omega t + \frac{\pi}{6}\right)\right)^2 d(\omega t)} = \sqrt{3}U_2\sqrt{1 + \frac{3\sqrt{3}}{2\pi}\cos 2\alpha}$$

- Average output current (load current) for resistive load

$$I_d = \frac{U_d}{R}$$

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

$$I_2 = \sqrt{\frac{1}{2\pi}\left(I_d^2 \times \frac{2\pi}{3} + \left(-I_d^2\right) \times \frac{2\pi}{3}\right)} = \sqrt{\frac{2\pi}{3}} I_d = 0.816 I_d$$

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

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