Controlled rectifiers

(Single-phase)

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Outline

- Power Electronic Devices
  - Thyristors
    - SCR (Silicon Controlled Rectifier)
    - Triac
    - GTO (Gate Turn-Off)
  - Static and dynamic characteristics
- Single phase-controlled rectifiers
  - Half-wave circuit (R & RL loading)
  - Full-bridge rectifier (R, RL, & RLE)
    - Continuous load current (RLE)
    - Discontinuous load current (RLE)
  - Summary

1.1 Power Electronic Devices

- Power electronic devices
  - are the electronic devices that can be directly used in the power processing circuits to *convert or control* electric power.

- In broad sense

Power electronic devices
- Vacuum devices
- Semiconductor devices (focus in this module)

- Very often:

Power electronic devices = Power semiconductor devices

1.1.2 Power semiconductor devices

Important feature

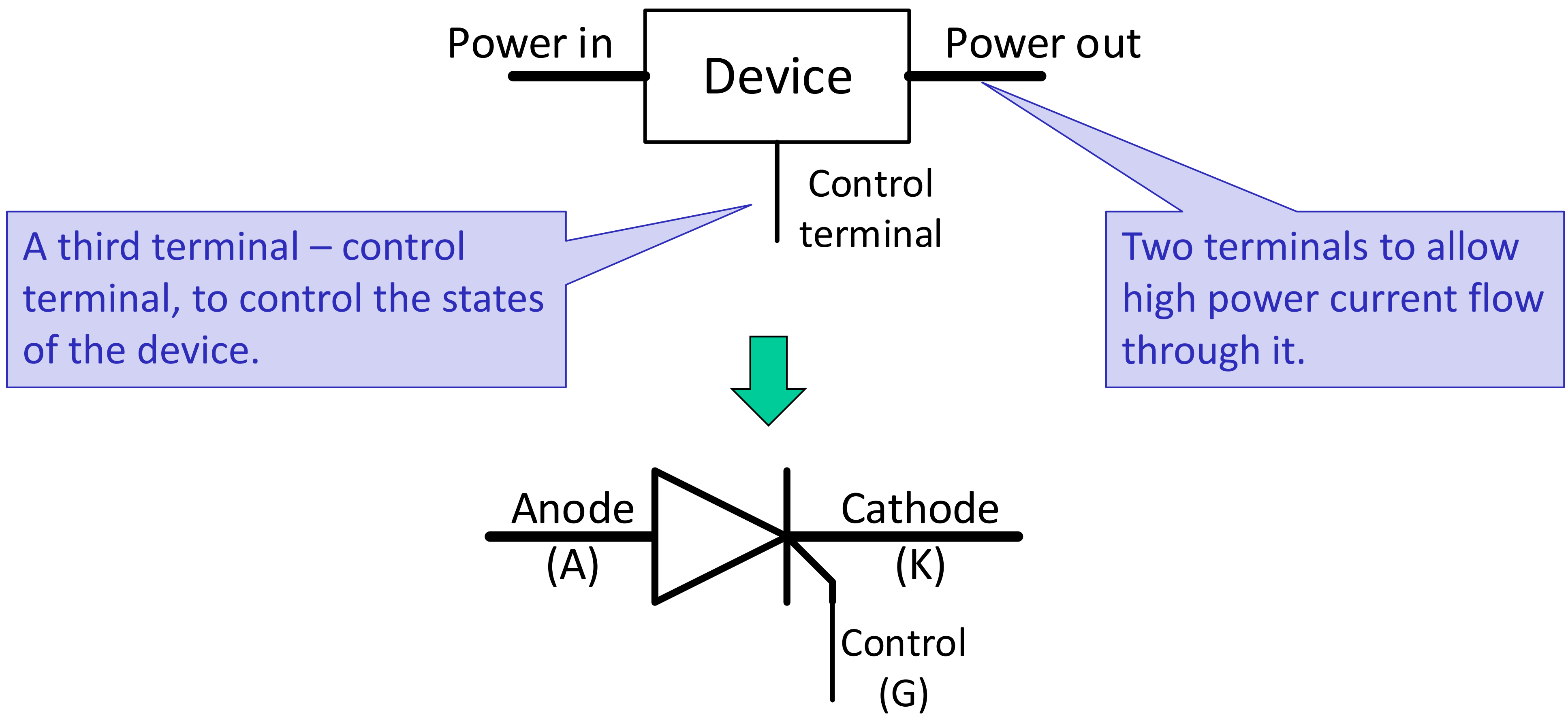
Controllability

- Power Diode – uncontrollable
- Thyristor (THYRatron tube & transISTOR)
  - **SCR (Silicon Controlled Rectifier)** – ON controllable
  - TRIAC (Triode ac switch) – ON controllable
  - GTO (Gate turn-off thyristor) – **ON/OFF controllable**
- Power Transistors – **ON/OFF controllable**
  - Power BJT
  - Power MOSFET
  - IGBT

https://en.wikipedia.org/wiki/Power_semiconductor_device

1.1.2 Power semiconductor devices

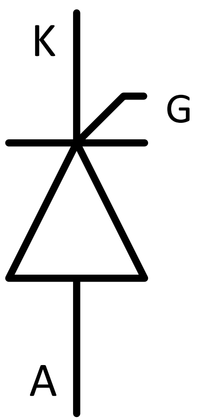
- Terminals of a controllable power electronic device

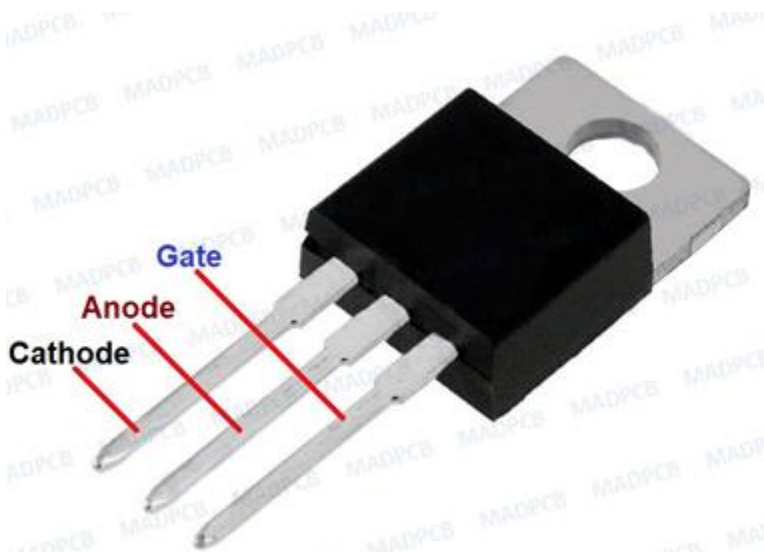


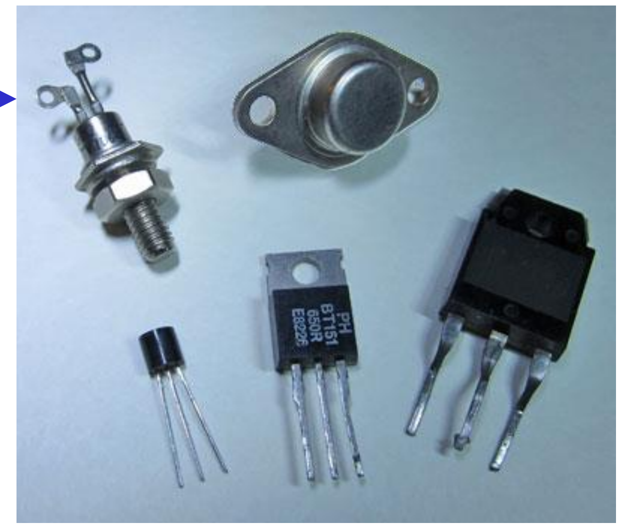
1.1.3 Silicon Controlled Rectifier (可控硅)

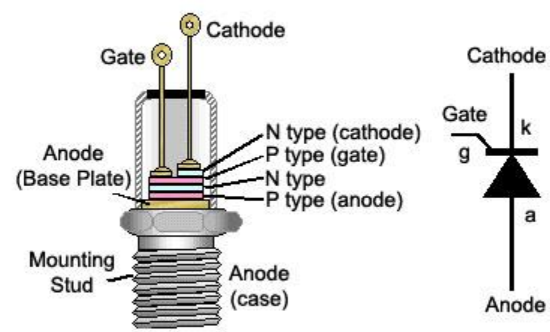
- SCR acts as bi-stable switches, *conducting* when their gate receives a current pulse, and continue to conduct for as long as they are forward biased (that is, as long as the voltage across the device has not reversed).
  - Three-terminals: anode, cathode, gate

Symbol



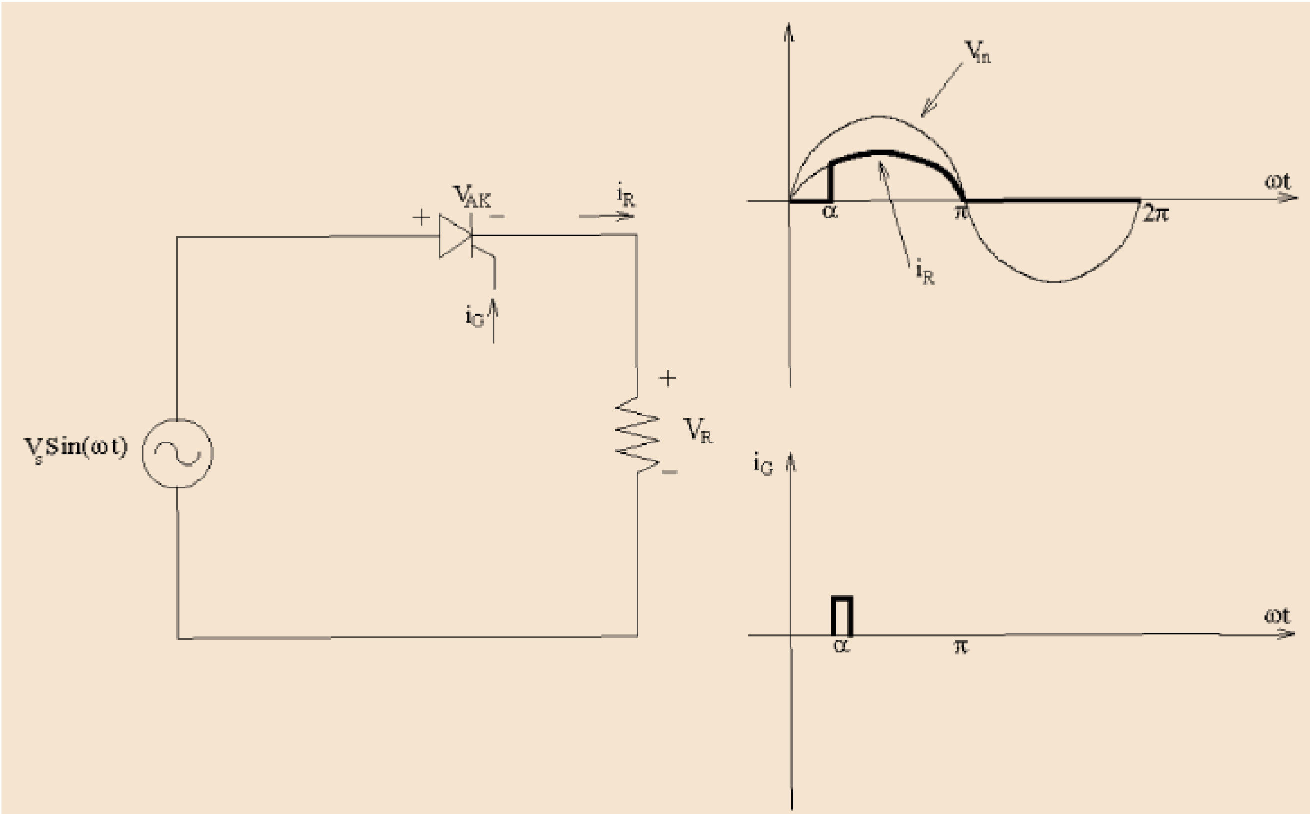






SCR in a rectification circuit

- 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

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

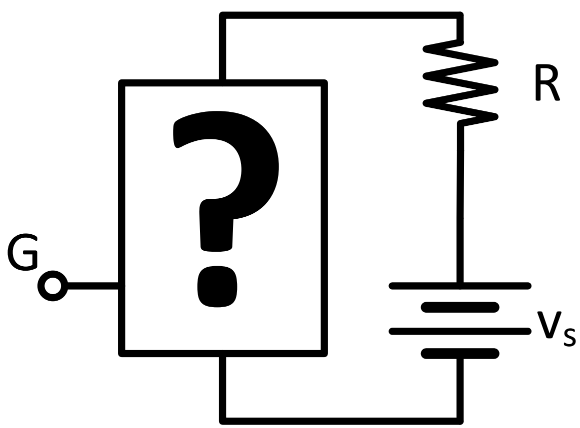
1. The SCR must be forward biased ($v_{AK} > 0$).
2. A current must be applied to the gate of SCR.

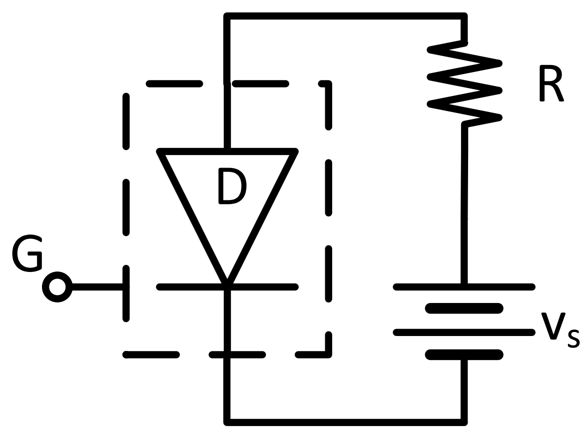
- A *SCR is turned ON* by increasing the anode current. This can be accomplished in one of the following ways:

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

Induction problem – how this device evolved?

- Find a 3 terminal device (or design a circuit) to put in the box to realize the following functions:
  - Give a control signal to gate G to make the circuit conduct;
  - Remove the control signal, the circuit keeps conduction.

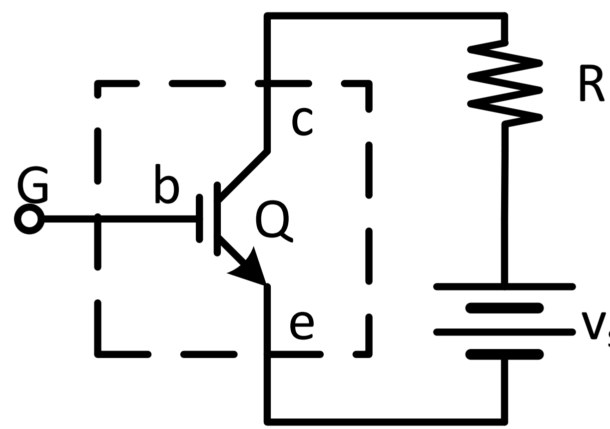




Diode??

X

It is not a 3-terminal device & cannot be controlled



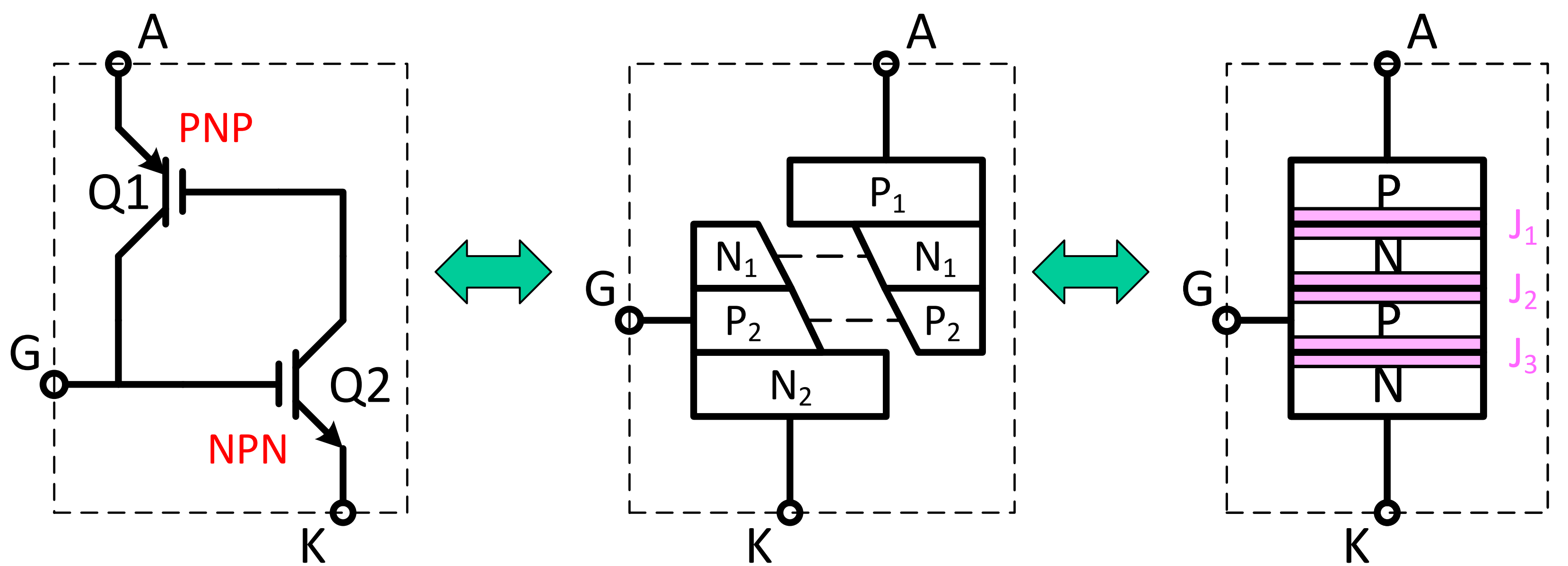
Transistor??

Possible!

But, it cannot hold the conduction without control signal

Combined structure – Two transistors

- A PNP and NPN transistors connected back-to-back as shown below.
- They form a four-layer, 3 junction structure.

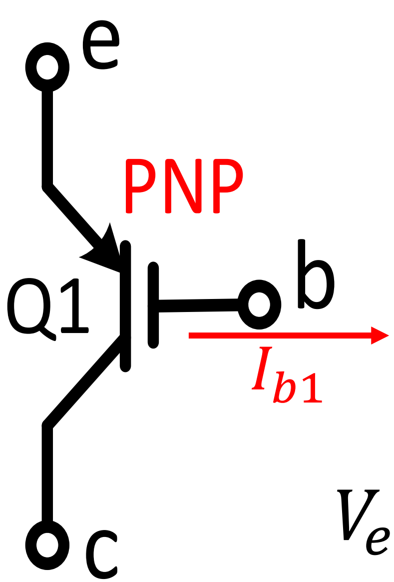


- When $V_{AK} > 0$, J1 & J3 are forward biased, J3 is reverse biased, so SCR cannot conduct.
- When $V_{AK} < 0$, J2 is forward biased, J1 & J3 are reverse biased, still SCR cannot conduct.
- Therefore, *without trigger, this device won't conduct at all!!*

Two transistors forming a SCR

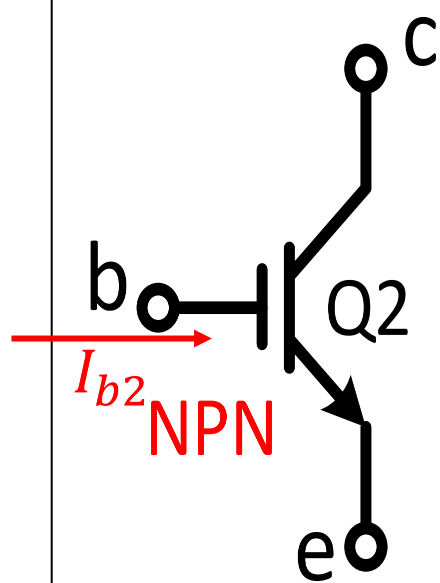
- Recall the knowledge of transistors
  - When the transistors are conducting:

For a PNP transistor:



$V_e > V_b > V_c$

For a NPN transistor:



$V_c > V_b > V_e$

Turn–ON and turn–OFF procedures

- 1. Turn-on stage:
  - Forward biased $V_A > V_K$
  - Trigger current I_G:

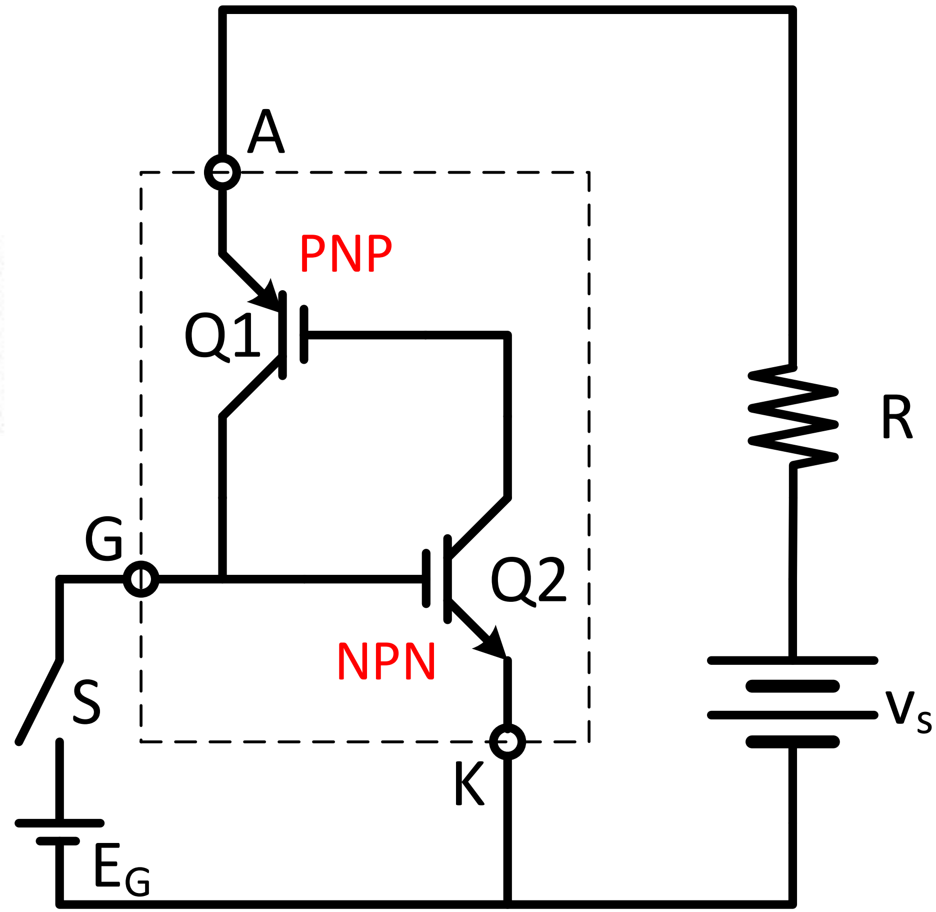
$$I_G \rightarrow I_{b2} \rightarrow Q2 \begin{cases} \rightarrow I_{e2} \\ \rightarrow I_{c2} \rightarrow I_{b1} \rightarrow Q1 \begin{cases} \rightarrow I_{e1} \\ \rightarrow I_{c1} \end{cases} \end{cases}$$

- 2. Stable stage
  - Forward biased
  - No I_G:

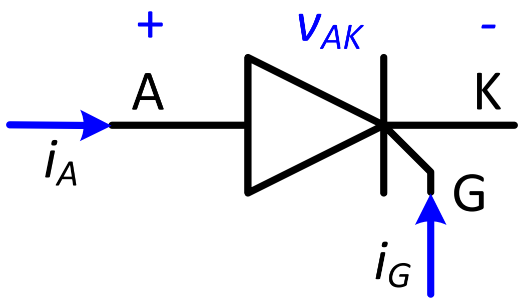
$$\begin{tikzcd} I_{c1} \arrow[r] & I_{b2} \arrow[d, "Q2"] \\ I_{b1} \arrow[u, "Q1"] & I_{c2} \arrow[l] \end{tikzcd}$$

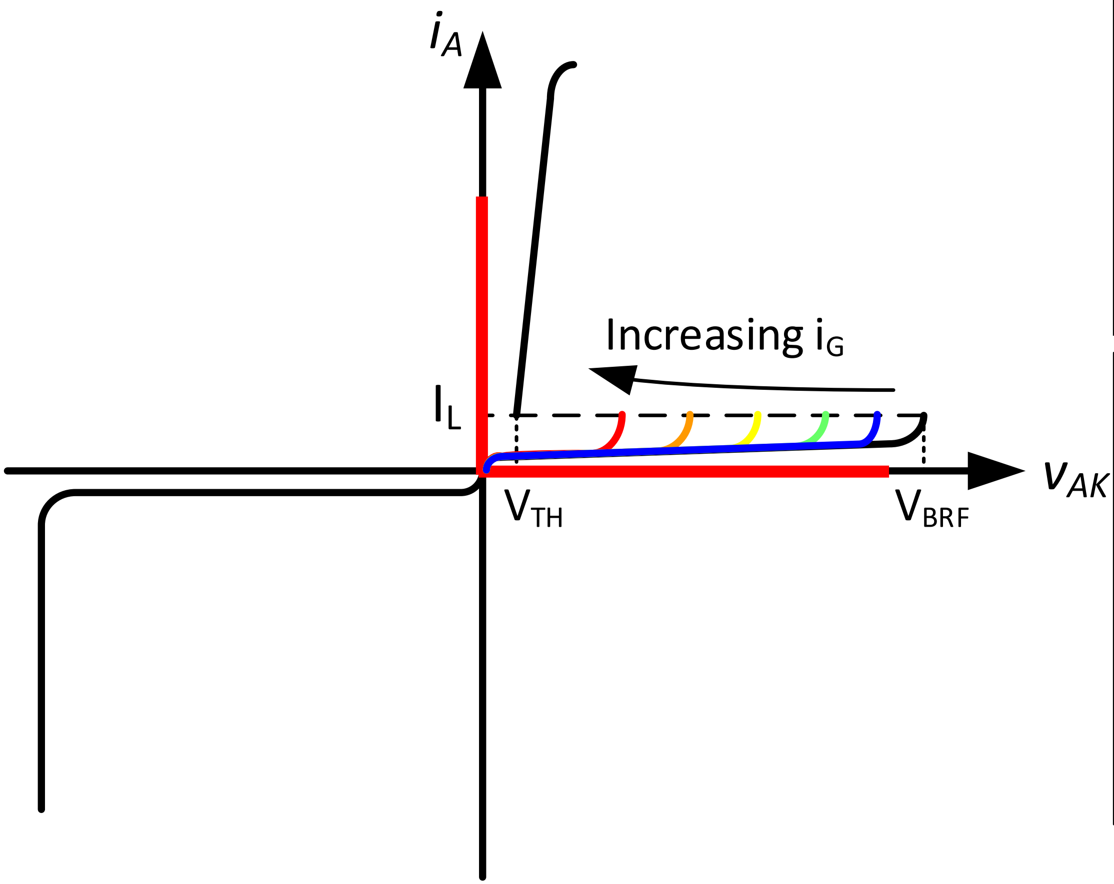
- 3. Turn-off stage:
  - When I_A drops small enough

$$i_A(I_{e1})\downarrow \;\rightarrow\; \underset{\substack{\Downarrow \\ Q2 \text{ off}}}{I_{c1}(I_{b2})\downarrow} \;\rightarrow\; \underset{\substack{\Downarrow \\ Q1 \text{ off}}}{I_{c2}(I_{b1})\downarrow}$$



Static characteristics (I-V curve)





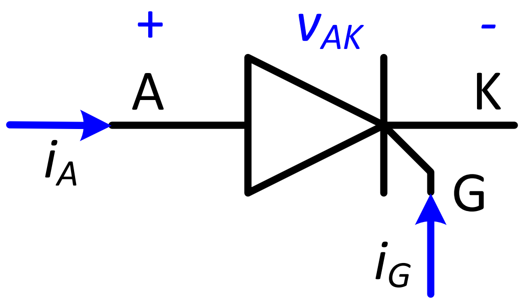
Turn-on:

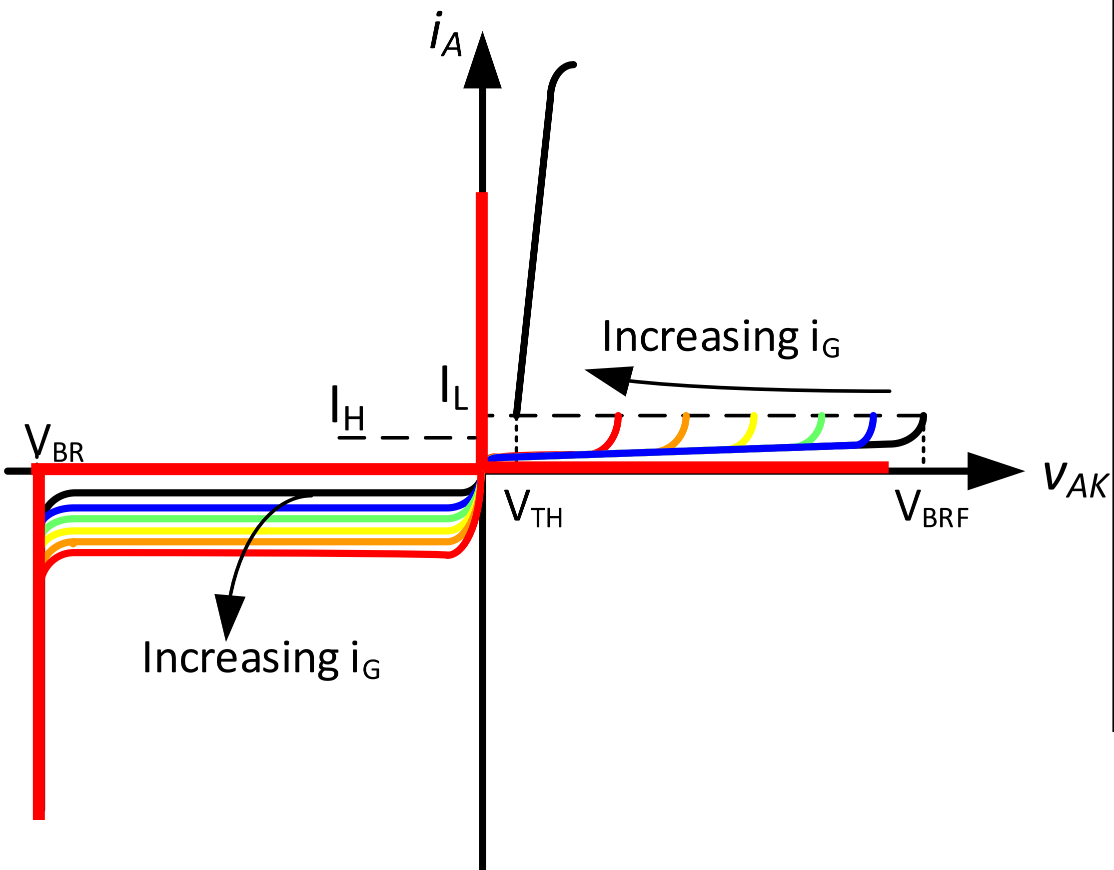
- When $i_G = 0$, no trigger current, forward biased but not conducting;
  - When v_{AK} increases to V_{BRF}, it conducts;
- With $i_G \neq 0$, thyristor can be turned on with smaller v_{AK};
  - Larger i_G, smaller v_{AK};
  - Larger v_{AK}, smaller i_G.

Notice:

- Voltage drop on the thyristor is V_{TH}, a constant value;
- Forward conduction loss is the slope of the I-V line;
- Latching current is the lowest value of i_A to support the conduction.

Static characteristics (I-V curve)





Turn-off:

- Not controllable via i_G;
- Turns off when i_A has fallen small enough, below the holding current I_H
  - $I_H < I_L$;
  - Reducing v_{AK} helps, but not crucial.

Reverse biases (blocked):

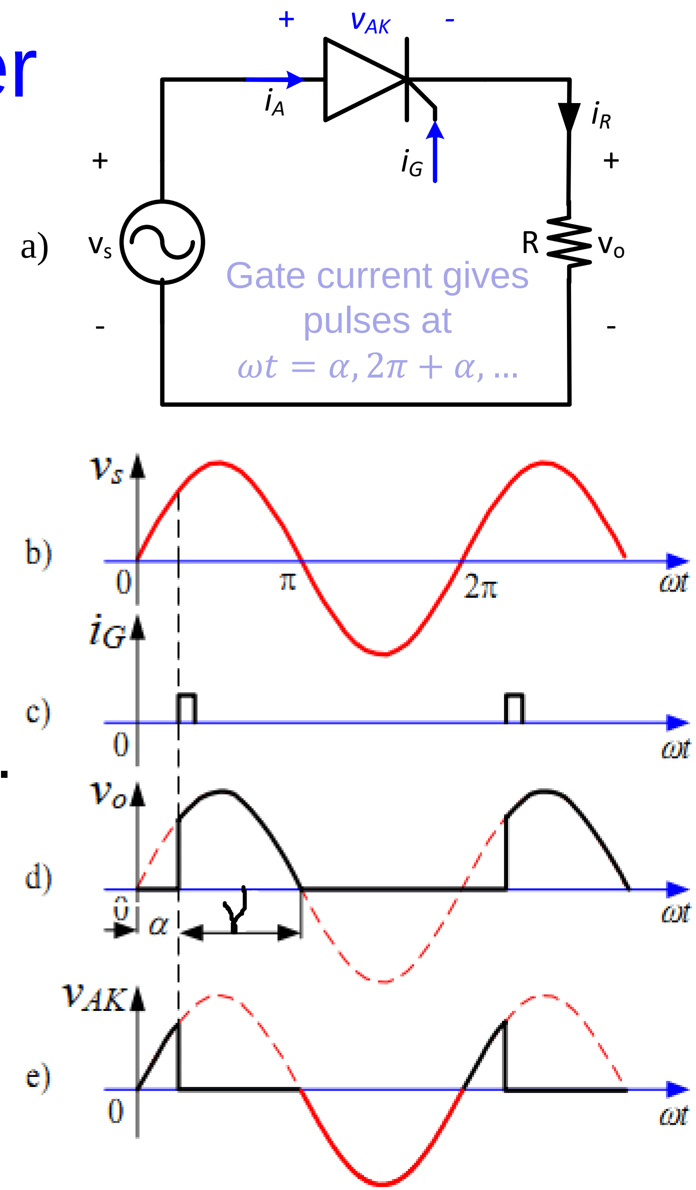
- Not conducting, regardless of i_G;
- Reverse saturation current I_{RS};
  - Larger i_G, larger I_{RS};
- When v_{AK} reaches reverse breakdown voltage $-V_{BR}$, thyristor breaks down.

2.1 Basic thyristor circuits I (R loading)

- 1. Half-wave *controlled* rectifier
  - – In the positive half
    - $[0, \alpha]$: i_R is zero, v_o is zero;
    - $[\alpha, \pi]$: $v_o = v_s = V_m \sin \omega t$;

$$i_A = i_R = \frac{V_m}{R} \sin \omega t.$$

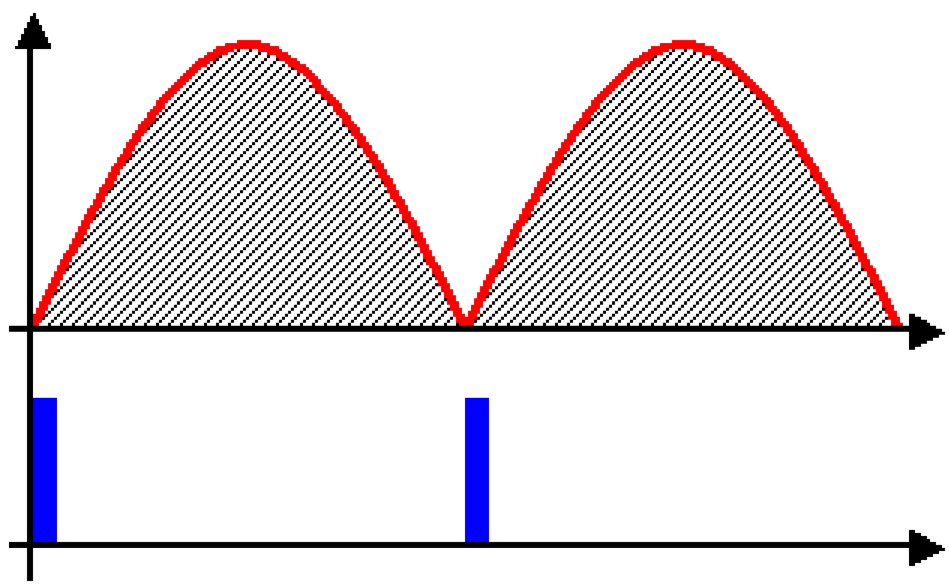
  - – In the negative half
    - $[\pi, 2\pi]$: i_R drops to zero, v_o is zero.



> - Firing angle: α
> - Conduction angle: $\gamma = \pi - \alpha$

Phase Control

- 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:



Parameter evaluation (I)

1. Average output voltage V_0:

$$V_0 = \frac{1}{2\pi}\int_0^{2\pi} v_o \, d\omega t = \frac{1}{2\pi}\int_\alpha^{\pi} V_m \sin\omega t \, d\omega t$$

$$= \frac{V_m}{2\pi}\left(-\cos\omega t\Big|_\alpha^\pi\right) = \frac{V_m}{2\pi}(\cos\alpha + 1)$$

- When $\alpha = 0$, $V_0 = \frac{V_m}{\pi} = 0.318V_m$

  This is the maximum possible V_0;

  The same as simple diode rectifier;
- When $\alpha = \pi/2$, $V_0 = \frac{V_m}{2\pi} = 0.159V_m$

  Half of the maximum possible V_0;

$V_0 > 0$

- When $\alpha = \pi$, $V_0 = 0$

  No trigger current in the positive half, so *no conduction* at all.

Parameter evaluation (II)

2. RMS output voltage V_{RMS}

$$V_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} v_o^2 d\omega t} = \sqrt{\frac{1}{2\pi}\int_\alpha^{\pi} V_m^2(\sin\omega t)^2 d\omega t}$$

$$= \sqrt{\frac{V_m^2}{2\pi}\int_\alpha^{\pi}\frac{1-\cos 2\omega t}{2} d\omega t} = \frac{V_m}{2}\sqrt{\frac{1}{\pi}\int_\alpha^{\pi}(1-\cos 2\omega t) d\omega t}$$

$$= \frac{V_m}{2}\sqrt{\frac{1}{\pi}\left(\omega t\Big|_\alpha^{\pi} - \frac{1}{2}\sin\delta\Big|_{2\alpha}^{2\pi}\right)} = \frac{V_m}{2}\sqrt{\frac{1}{\pi}\left[(\pi-\alpha) - \frac{1}{2}(0-\sin 2\alpha)\right]}$$

$$= \frac{V_m}{2}\sqrt{\frac{2(\pi-\alpha)+\sin 2\alpha}{2\pi}}$$

Parameter evaluation (III)

3. Rectification efficiency

$$\eta = \frac{P_0}{P_{RMS}} = \frac{V_0^2}{V_{RMS}^2}$$

4. Transformer utilisation factor

$$f_T = \frac{P_0}{P_S} = \frac{V_0 I_0}{V_S I_S} = \frac{V_0^2}{V_S V_{RMS}}$$

5. Form factor and ripple factor

$$f_F = \frac{V_{RMS}}{V_0} \qquad f_R = \sqrt{f_F^2 - 1}$$

2.2 Basic thyristor circuits II (RL loading)

2. Inductive load (RL)

$[\mathbf{0}, \boldsymbol{\alpha}]$**:** i_o is zero, v_o is zero;

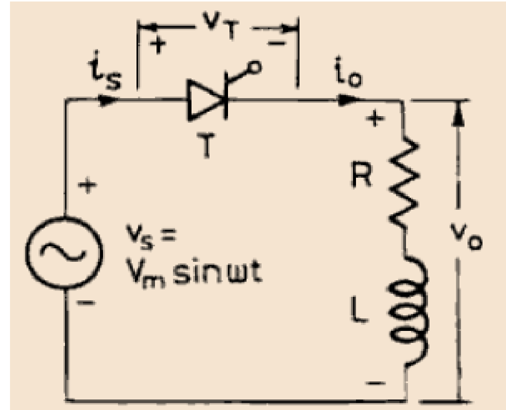
$[\boldsymbol{\alpha}, \boldsymbol{\beta}]$**:** $v_o = v_s = V_m \sin \omega t$

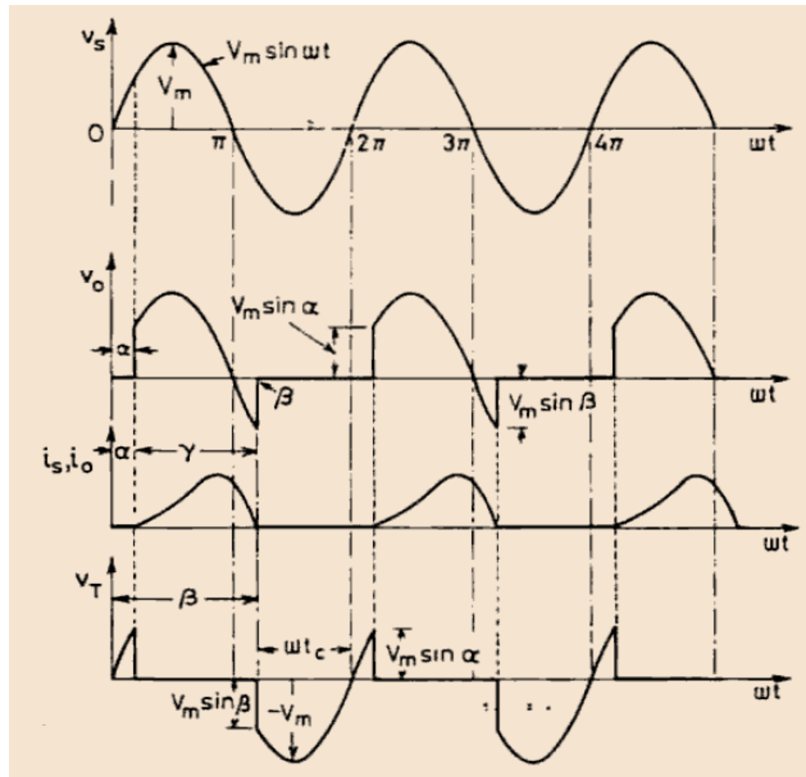
Inductance L forces the load current i_o *to rise gradually, after sometime, it reaches maximum value and then begins to decrease. At* $\omega t = \pi$, $v_o = 0$, *but* $i_o \neq 0$ *due to inductance. After* $\omega t = \pi$, *SCR is subjected to reverse anode voltage, but it will not be turned OFF.*

$[\boldsymbol{\beta}, \mathbf{2\pi}]$**:** At angle $\beta \rightarrow i_o$ is zero, turns OFF.

- Firing angle: α
- Termination/extinction angle: β

  Conduction angle: $\gamma = \beta - \alpha$





Notice that $\beta > \pi$.

Key Parameters

- Average output voltage

$$V_0 = \frac{1}{2\pi}\int_{\alpha}^{\beta} V_m \sin\omega t \, d\omega t = \frac{V_m}{2\pi}(\cos\alpha - \cos\beta)$$

- RMS output voltage

$$V_{RMS} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta} V_m^2 (\sin\omega t)^2 d\omega t} = \frac{V_m}{2}\sqrt{\frac{2(\beta-\alpha)+\sin 2\alpha - \sin 2\beta}{2\pi}}$$

2.2 Basic thyristor circuits II (RL loading)

Calculation is not required

- The voltage equation when SCR is conducting:

$$L\frac{di_o}{dt} + Ri_o = V_m \sin\omega t$$

with the initial state conditions $\omega t = \alpha$ and $i_o = 0$, get:

$$i_o = i_{steady}(t) + i_{transient}(t) = \frac{V_m}{Z}\sin(\omega t - \varphi) - \frac{V_m}{Z}\sin(\alpha - \varphi)\, e^{-\frac{R}{\omega L}(\omega t - \alpha)}$$

where $Z = \sqrt{R^2 + (\omega L)^2}$ and $\varphi = \arctan(\omega L/R)$

- Substitute $\omega t = \beta$ and $i_o = 0$ in the equation, get:

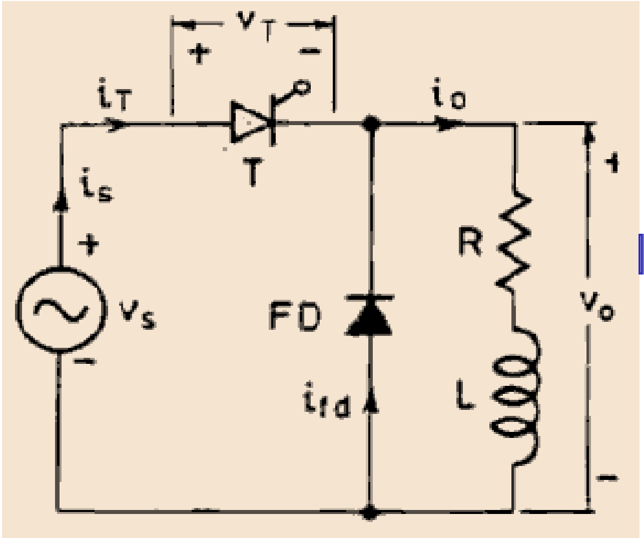
$$\boxed{\sin(\alpha - \varphi)e^{-\frac{\beta-\alpha}{\tan\varphi}} = \sin(\beta - \varphi)}$$

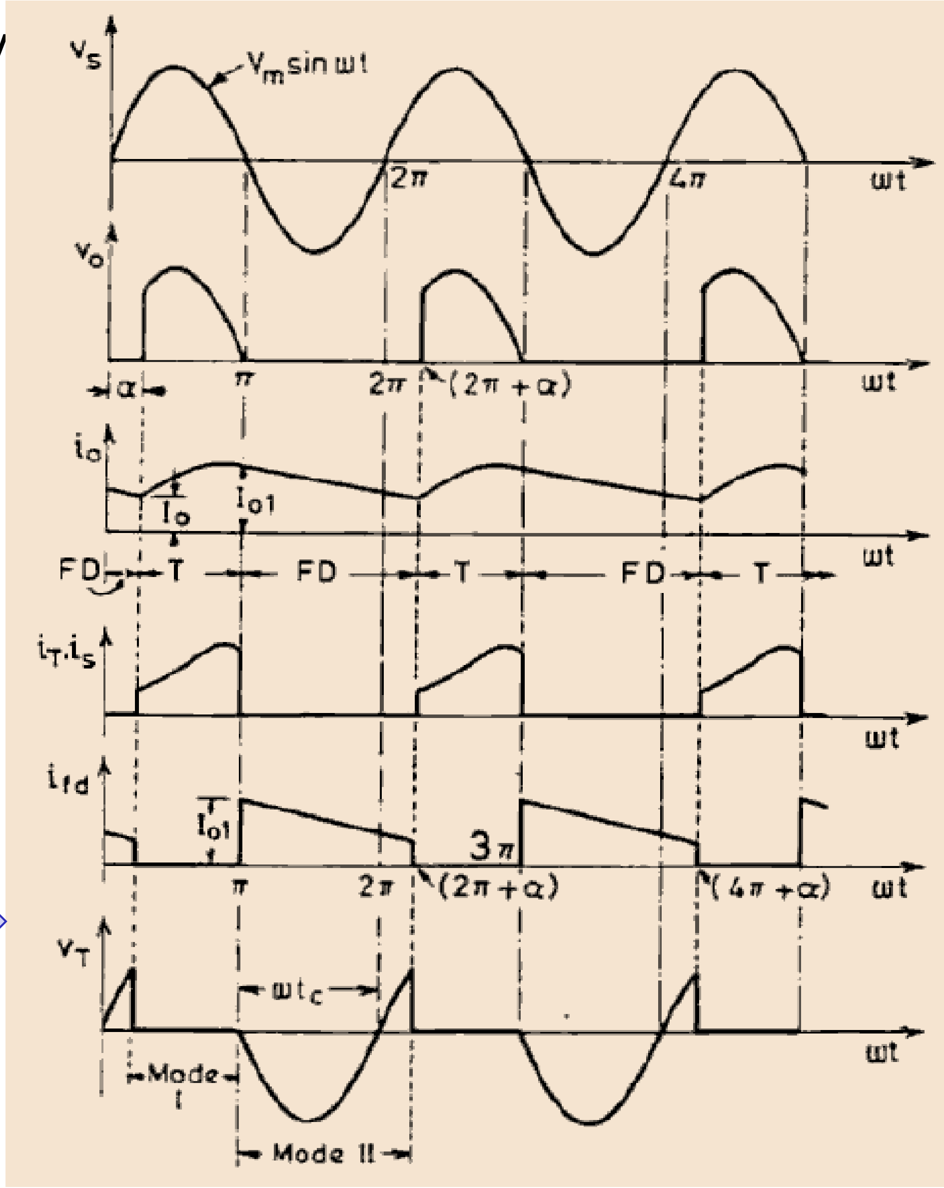
with the knowledge of angles α and φ, the termination angle β can be calculated.

2.2 RL load with freewheeling diode

- Load current i_o (earlier) can be improved by connecting freewheeling diode across load.

1) At $\omega t = \alpha, v_s$ appears across load as v_o.
2) At $\omega t = \pi$, $v_s = 0$. After $\omega t = \pi$, diode FD is forward-biased through conducting SCR. As a result, i_o is immediately transferred from SCR to FD as v_s tends to reverse. At the same time, SCR is turned OFF due to reverse voltage.
3) It is assumed that the inductor L is quite large, energy stored in L is enough to support the conduction in the freewheeling path until next period starts, i.e,. $2\pi + \alpha$.



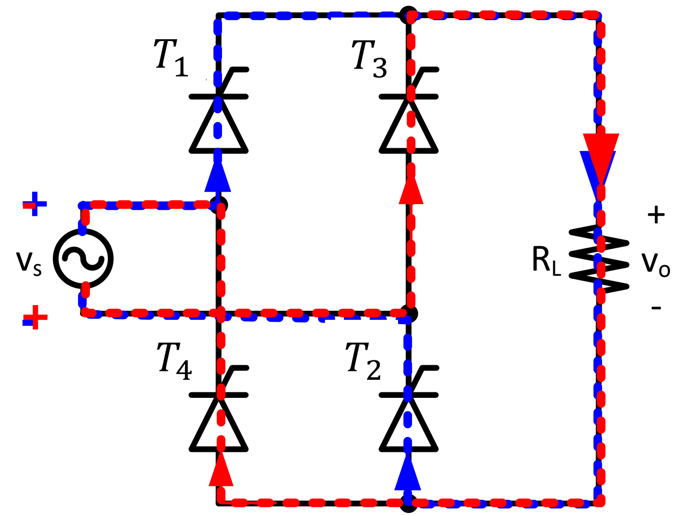


Summary – Half-wave Circuit

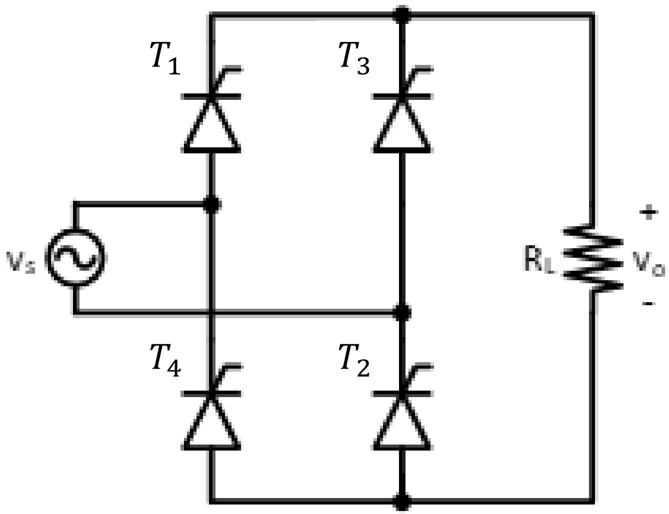
- Triggering delay angle α of SCR could vary from 0 to π;
- V_0 and V_{RMS} are smaller than the corresponding circuits using diode;
- The circuit is simple, but form factor and ripple factor are quite large;
- These circuits are hardly used in practice;
- For SCR: Maximum forward voltage and maximum reverse voltage are two parameters for device selection;
- Disadvantage:
  - Only single pulse in one line cycle

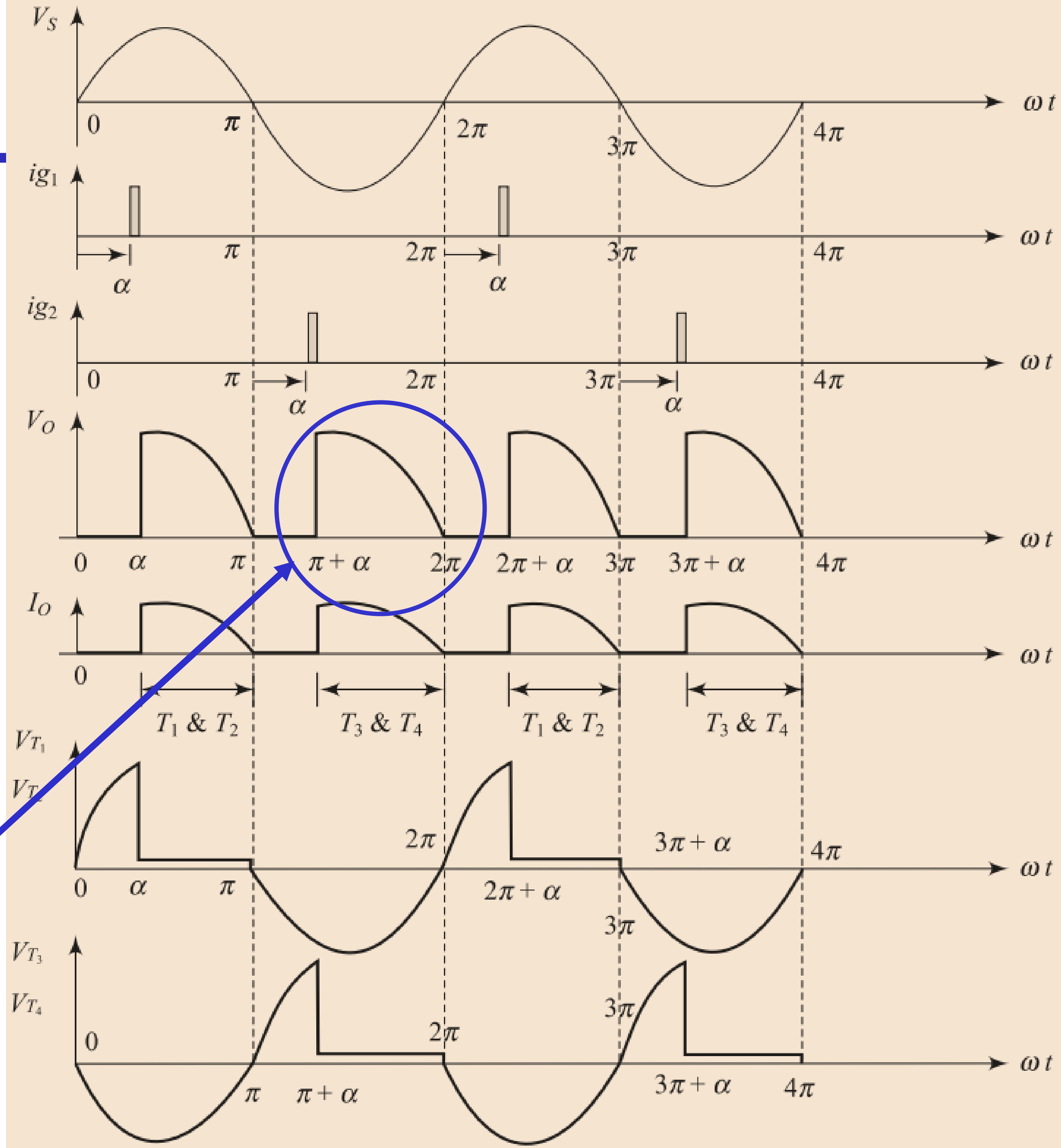
3.1 Full-bridge rectifier (R)

- Resistive load (R)
  - T_1 and T_2 is a pair of bridge arm: In the positive half of v_s, they start to conduct when triggered by a pulse, and will be closed when v_s passes 0 to negative.
    - → Blue current path
  - T_3 and T_4 is another pair of bridge arm: In the negative half of v_s, they start to conduct when triggered by a pulse, and will be closed when v_s passes 0 to positive.
    - → Red current path



3.1 Full-bridge rectifier (R)





V_o is still positive, why?

Parameter evaluation (I)

- Average output (rectified) voltage

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t = \frac{V_m}{\pi}(\cos\alpha + 1)$$

- RMS output voltage

$$V_{RMS} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 (\sin\omega t)^2 d\omega t} = \frac{V_m}{2}\sqrt{\frac{2(\pi-\alpha)+\sin 2\alpha}{\pi}}$$

- Rectification efficiency

$$\eta = \frac{V_0^2}{V_{RMS}^2} = \frac{4(\cos\alpha+1)^2}{\pi(2(\pi-\alpha)+\sin 2\alpha)}$$

Parameter evaluation (II)

- Average output current

$$I_0 = \frac{V_0}{R} = \frac{V_m}{\pi R}(\cos\alpha + 1)$$

- RMS output current

$$I_{RMS} = \frac{V_{RMS}}{R} = \frac{V_m}{2R}\sqrt{\frac{2(\pi - \alpha) + \sin 2\alpha}{\pi}}$$

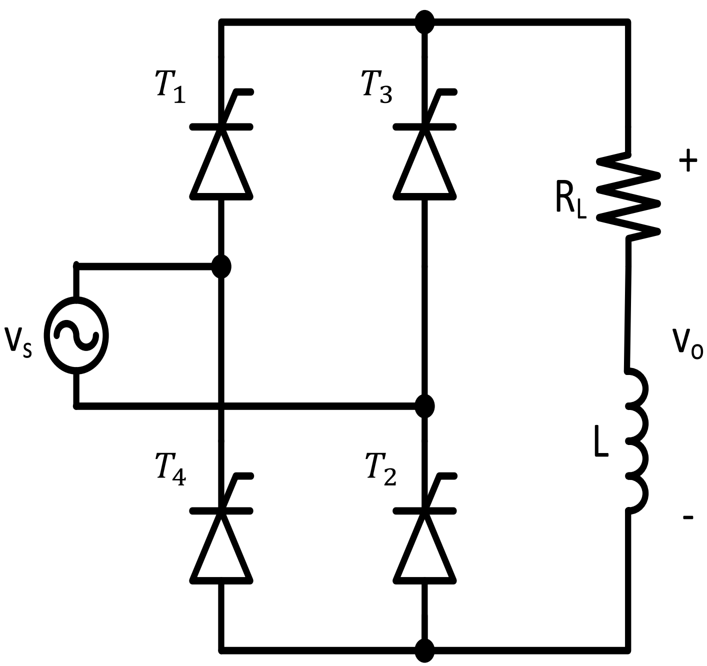
- Average current of each SCR

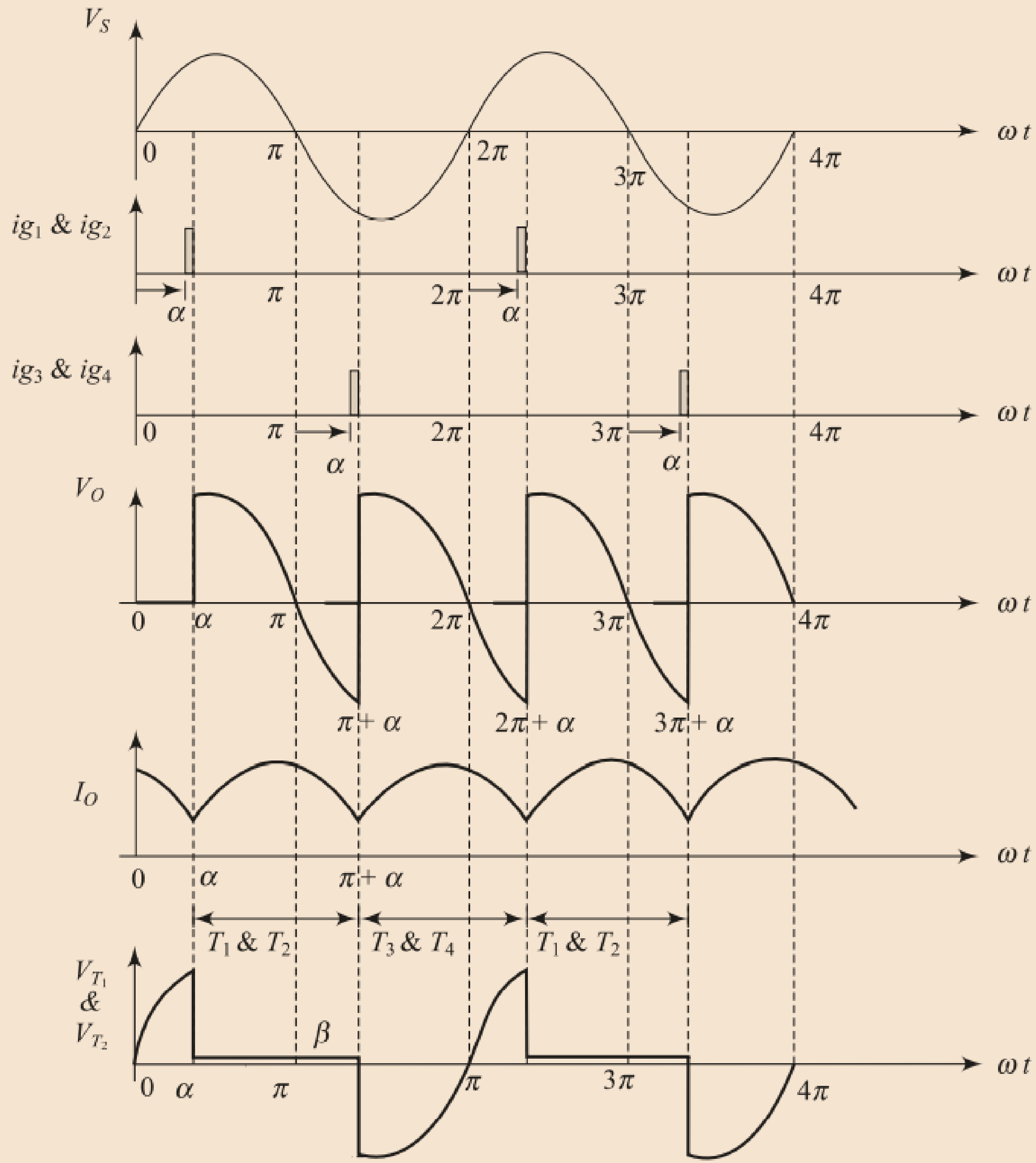
- Effective current of each SCR

Calculate!

3.2 Full-bridge rectifier (RL)

- Inductive load (L is very large)



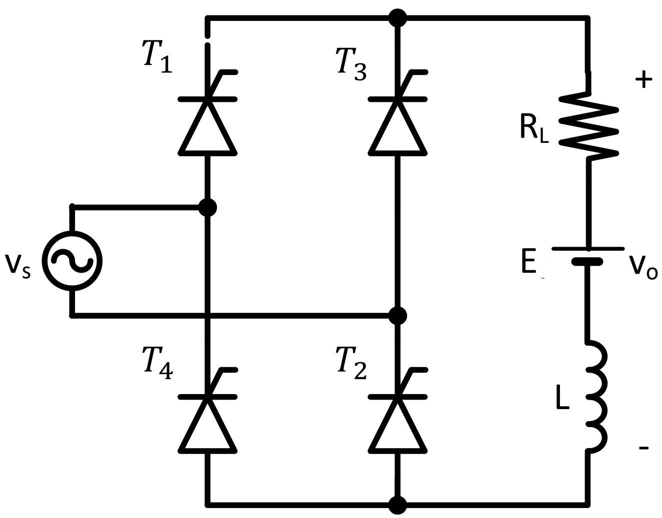


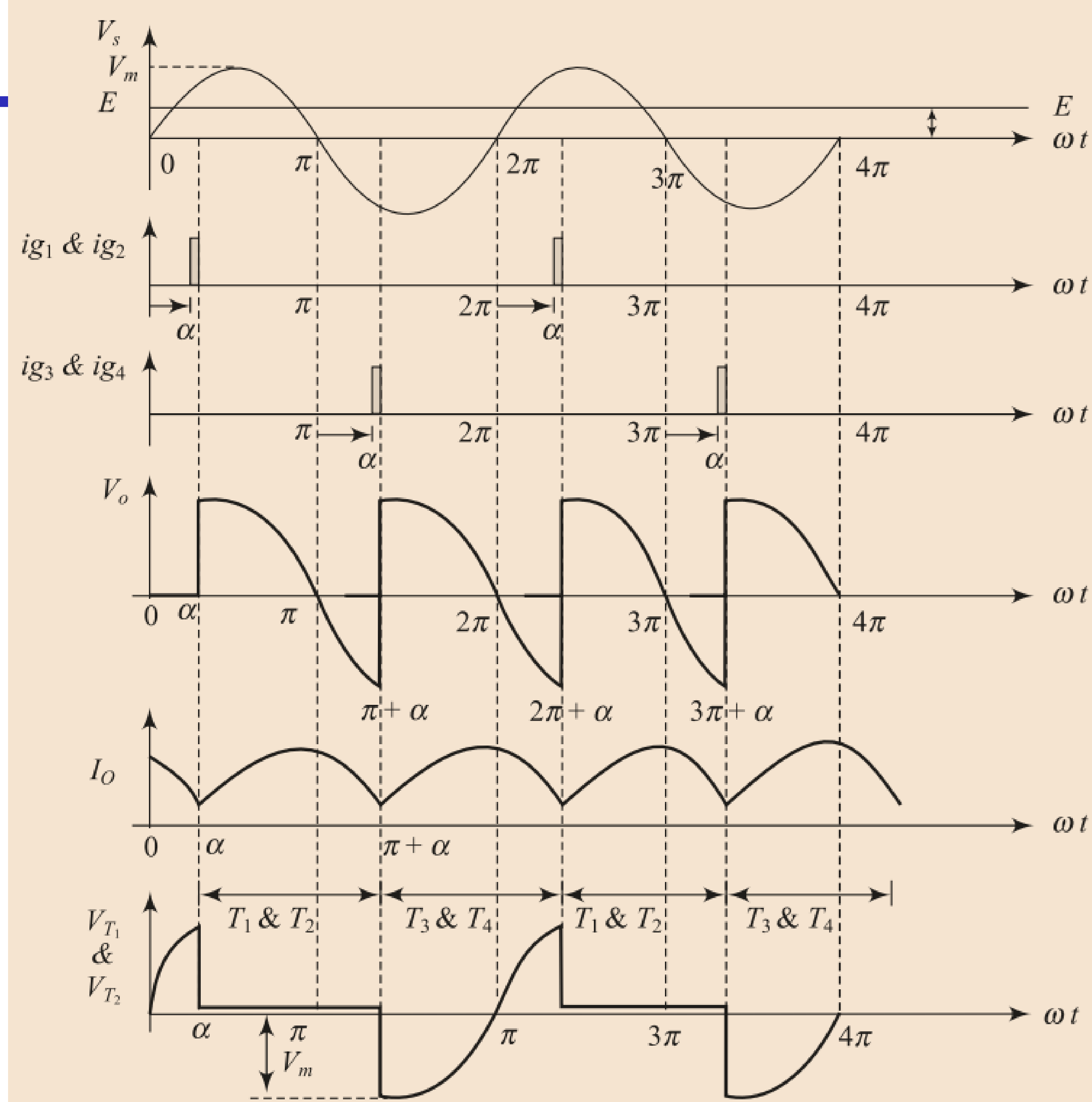
3.4 Full-bridge rectifier (RLE)

Continuous Load Current

With inductive load, the thyristor can still conduct when $V_s < E$ (even when V_s is negative);

- If L is large enough, then the current is continuous;
- Otherwise, discontinuous.



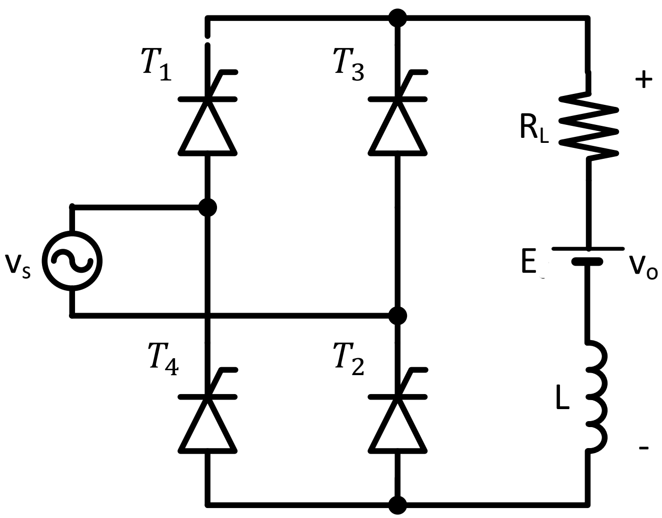


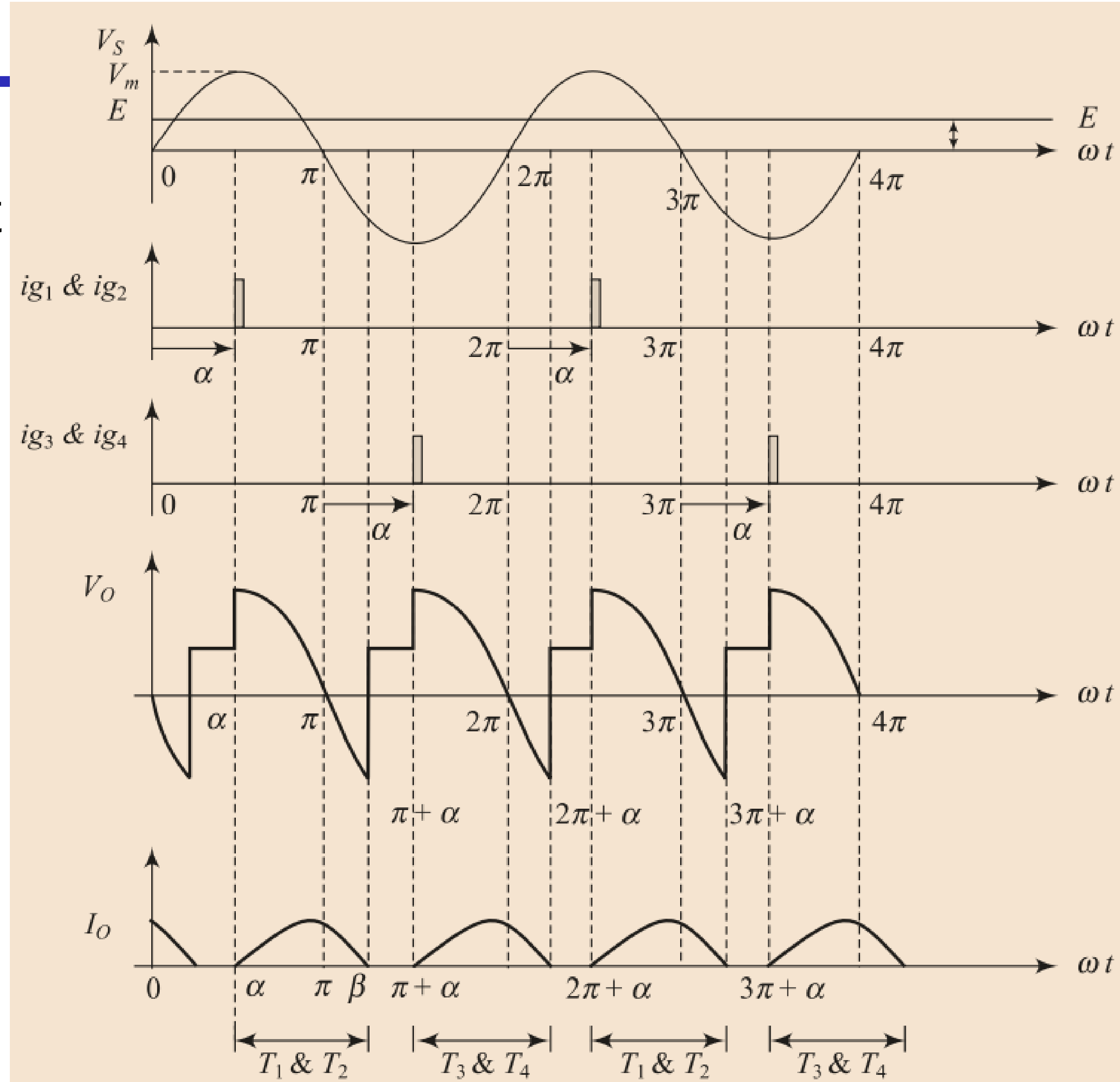
3.4 Full-bridge rectifier (RLE)

Discontinuous Load Current

With inductive load, the thyristor can still conduct when $V_s < E$ (even when V_s is negative);

- If L is large enough, then the current is continuous;
- Otherwise, discontinuous.





Summary of some important points

- When analysing a thyristor circuit, start from a diode circuit with the same topology. The behaviour of the diode circuit is exactly the same as the thyristor circuit when firing angle is 0.
- A power electronic circuit can be considered as different simple circuits when the power semiconductor devices are in different states.
- Take different principles when dealing with different kinds of load.
  - For resistive load: current waveform of a resistor is the same as the voltage waveform.
  - For inductive load with a large inductor: the inductor current can be considered constant.

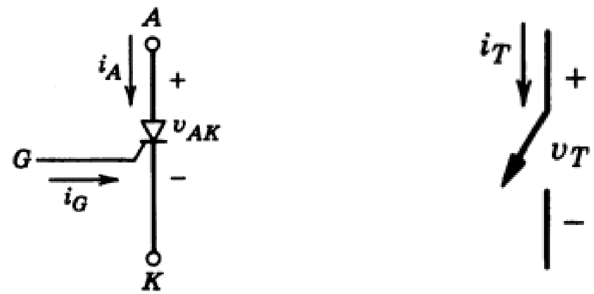
Exercise – Try to solve!

- A single-phase half-wave controlled rectifier with R load is supplied from a 230 V, 50 Hz AC source. When average dc output voltage is 50% of maximum possible average dc output voltage, determine

  1) Firing angle of SCR.
  2) Average dc output voltage.
  3) RMS output voltage.
  4) Average and RMS output currents.
  5) Average and RMS currents of SCR.

  [Assume $R = 20\ \mathbf{\Omega}$]

Summary



- Narrow sense: Thyristor = SCR (Silicon Controlled Rectifier)
- Acts as controlled diode:
  - Stay off until a gate pulse i_G is applied while $v_{AK} > 0$;
  - Once on, behaves like a diode & does not turn off until $i_A \rightarrow 0$.
- Ideally:
  - Instantaneous switching from one state to the other.
  - Zero voltage drop in on-state.
  - Infinite voltage and current handling capabilities.

See you in the next class (March 17th)