EEE213 Power Electronics and Electromechanism

4. Controlled Rectifier – Single Phase

Outline

- Power Electronic Devices
  - Thyristor
    - SCR (Silicon Controlled Rectifier)
    - Triac
    - GTO (Gate Turn-Off)
  - Basic thyristor circuits
- Single phase controlled rectifier
  - Half-wave
  - Bridge fully controlled
    - Rectification: power flows to the load
    - Inversion: power flows to the grid/source
  - Bridge half controlled

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

Mercury arc rectifier

thyratron

High f & p

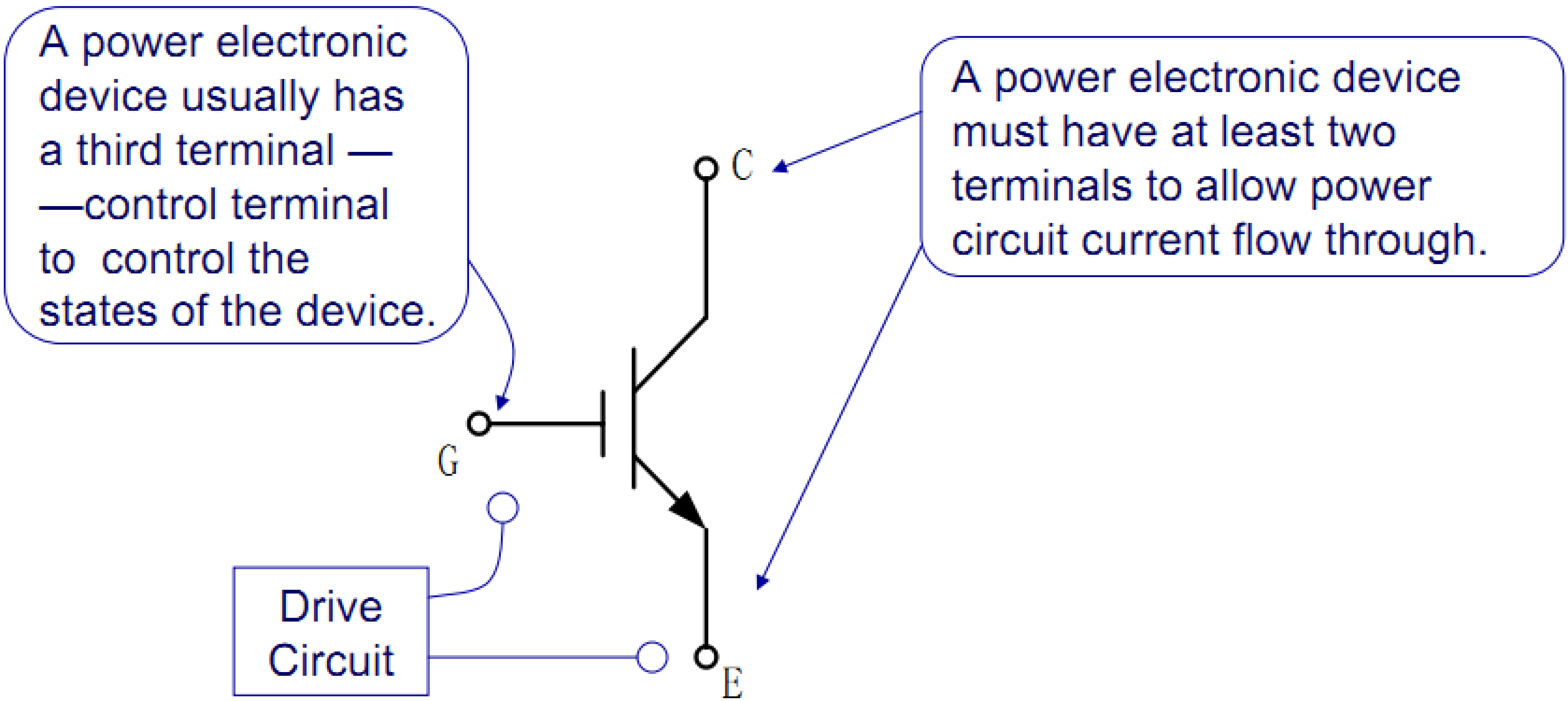
Power electronic devices $\left\{ \begin{array}{l} \text{Vacuum devices} \\ \text{Semiconductor devices} \end{array} \right.$

- Very often:

Power electronic devices = Power semiconductor devices

1.1.1 Power Electronic Devices

- Terminals of a controllable power electronic device



1.1.2 Power semiconductor devices

- Power Diode – uncontrollable
- Thyristor (晶闸管)
  - **SCR (Silicon Controlled Rectifier)** – on controllable
  - TRIAC (Triode ac switch)
  - GTO (Gate turn-off thyristor) – on/off controllable
- Power Transistors
  - Power BJT (Bipolar Junction Transistor)
  - Power MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor)
  - IGBT (Insulated Gate Bipolar Transistor)

1.1.2 Power semiconductor devices

- Uncontrollable: has only two terminals and can not be controlled by control signal. The on and off states of the device are determined by the power circuit.
- Half-controllable: is turned-on by a control signal and turned-off by the power circuit.
- Fully controllable: The on and off states of the device are controlled by control signals.

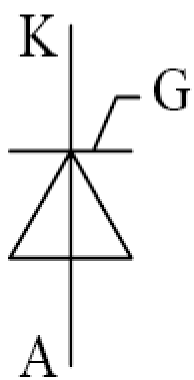
- In the broad sense, thyristors are defined as a larger set of devices with at least four layers of alternating N and P-type material. It is a family name of
- Silicon-controlled rectifiers (SCR)
- Triode ac switch (TRIAC)
- Gate turn-off Thyristors (GTO)
- In a narrow sense, it is considered as synonymous of SCR.
- Thyristor Opened the power electronics era
- – 1956, invention, Bell Laboratories
- – 1957, development of the 1st product, GE
- – 1958, 1st commercialized product, GE

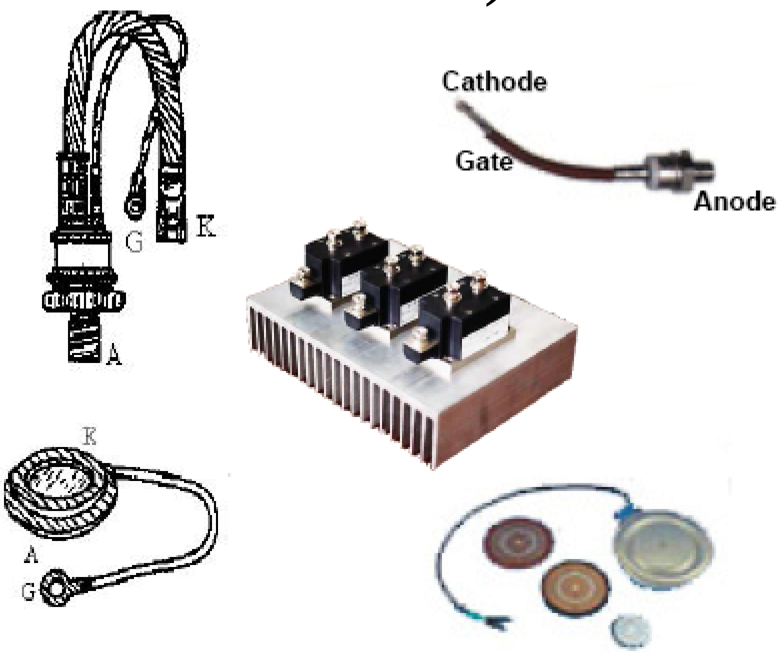
» Thyristor replaced vacuum devices in almost every power processing area.

1.1.3 Silicon Controlled Rectifier

- Three-terminal devices: anode, cathode, gate
- 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).

Symbol

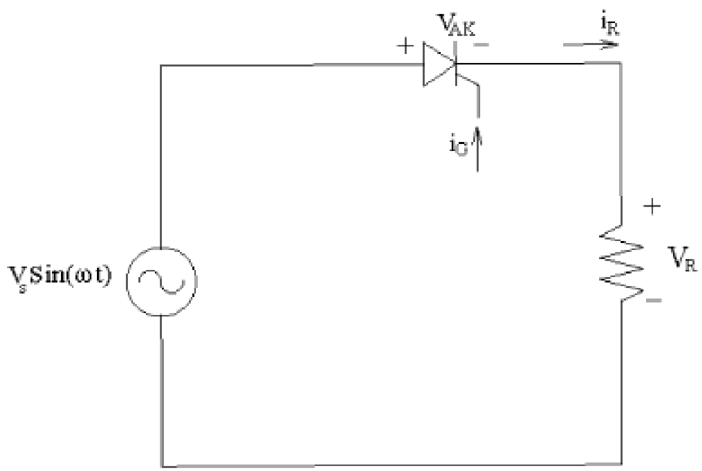


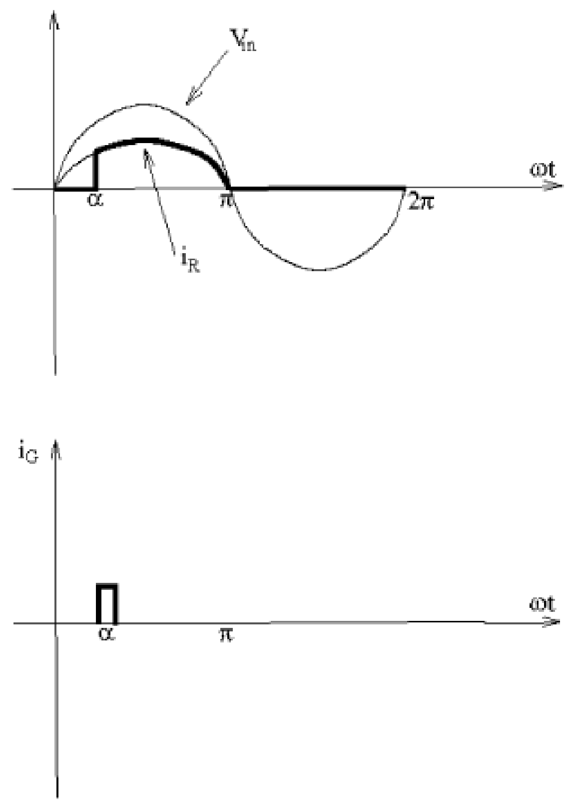


1.1.3 Silicon Controlled Rectifier

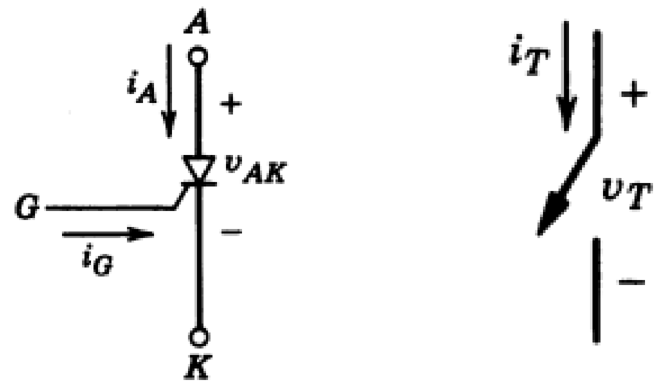
- SCR: Acts like a diode where you can select when conduction will start, but not when it stops.
  - Semi-controlled: we control the turn on point, but only turns off when circuit conditions force it to.

Stay off until a gate pulse is applied while $V_{AK} > 0$.
Once on, behaves like a diode and does not turn off until $\boldsymbol{i} \rightarrow 0$.
To stay off (after $V_{AK} > 0$ again) must have $\boldsymbol{i}$ stay at 0 for a short time *t*, (10-100us)





Generic Switch Symbol

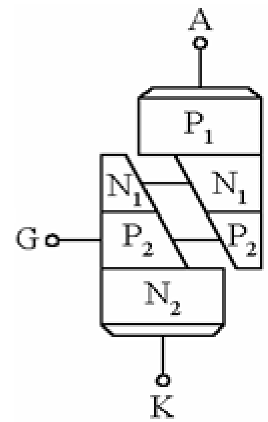


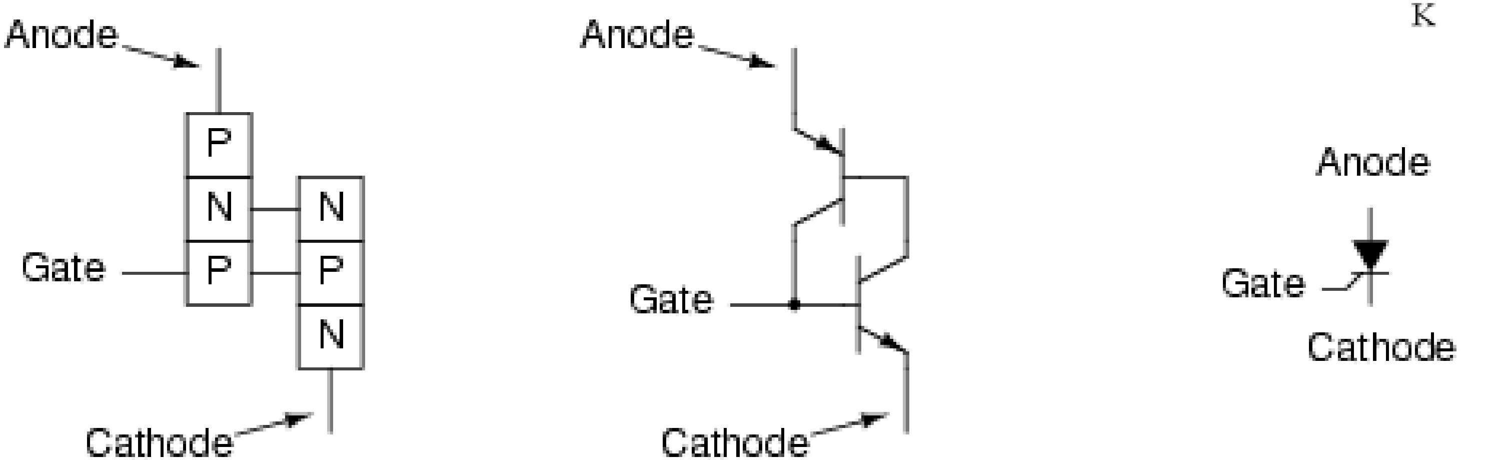
- Idealized switch symbol
  - When on, current can flow only in the direction of the arrow
  - Instantaneous switching from one state to the other
  - Zero voltage drop in on-state
  - Infinite voltage and current handling capabilities

Physics of thyristor operation

Not required

- Four-layer three-junction P-N-P-N devices
- Blocks voltage in both directions

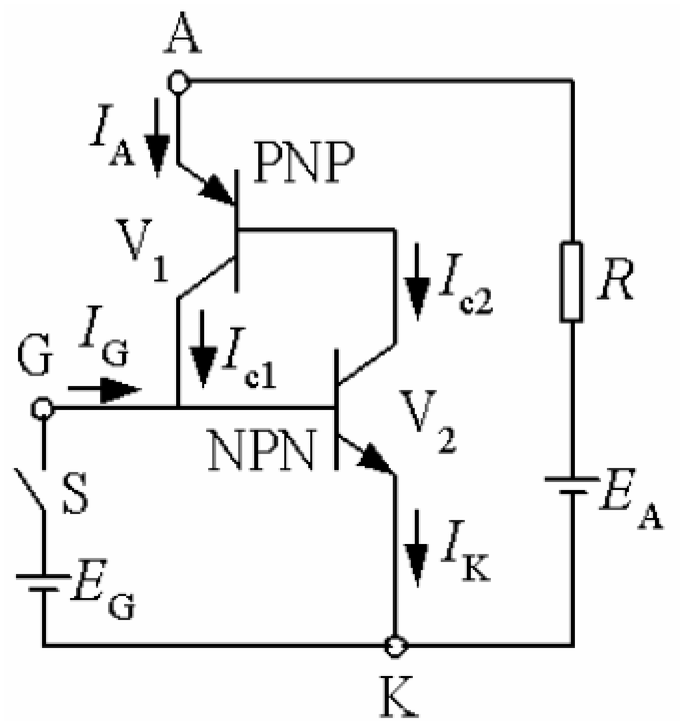




Physical diagram *Equivalent schematic* *Schematic symbol*

Physics of thyristor operation

Not required



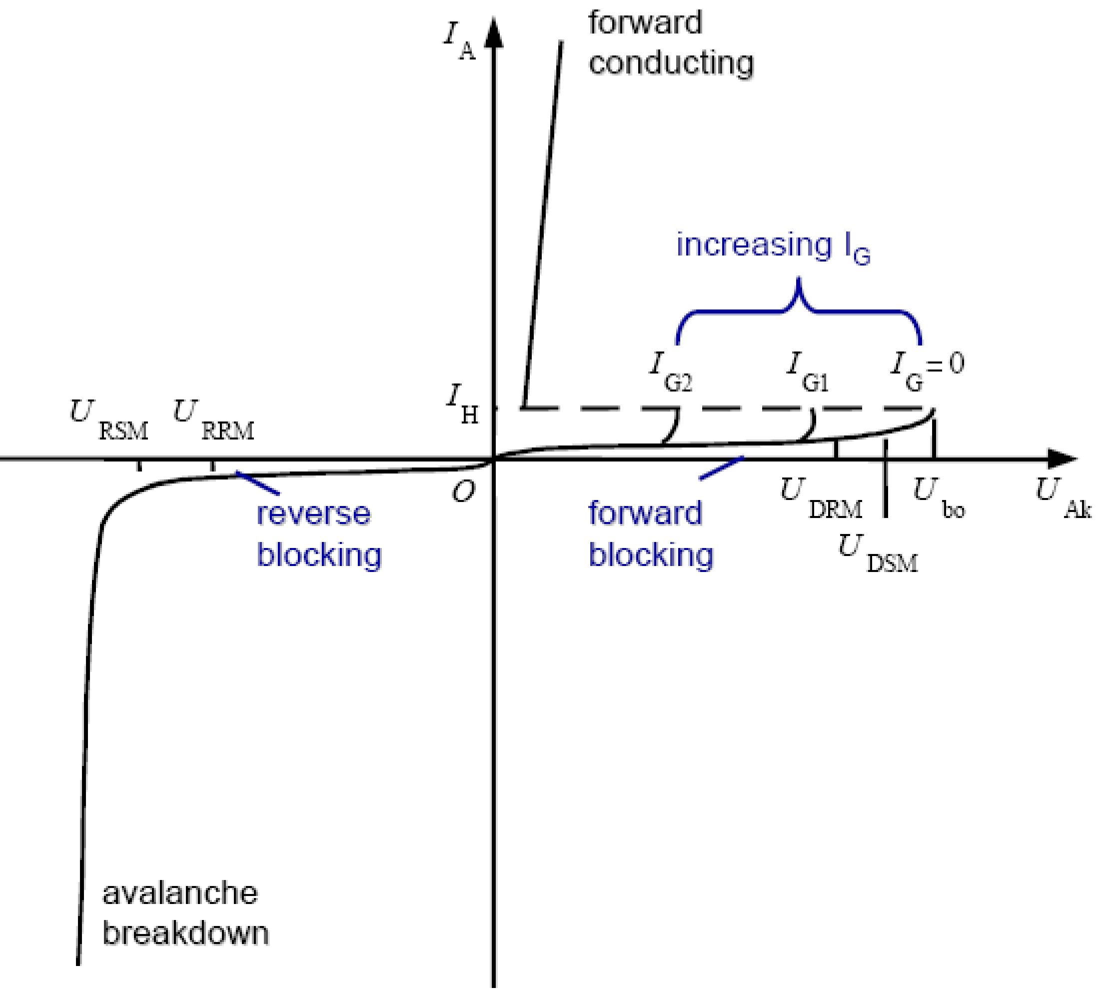
Equivalent circuit

- Equivalent circuit: A PNP transistor and an NPN transistor interconnected together
- Positive feedback
- Trigger
- Half-controllable

- On-state
  - Forward-biased, and triggered
- Off-state
  - Reverse-biased, or
  - Forward-biased, but not triggered

When I_G=0, α1+α2 is small.
When I_G>0, α1+α2 will approach 1, I_A will be very large.

Static characteristics

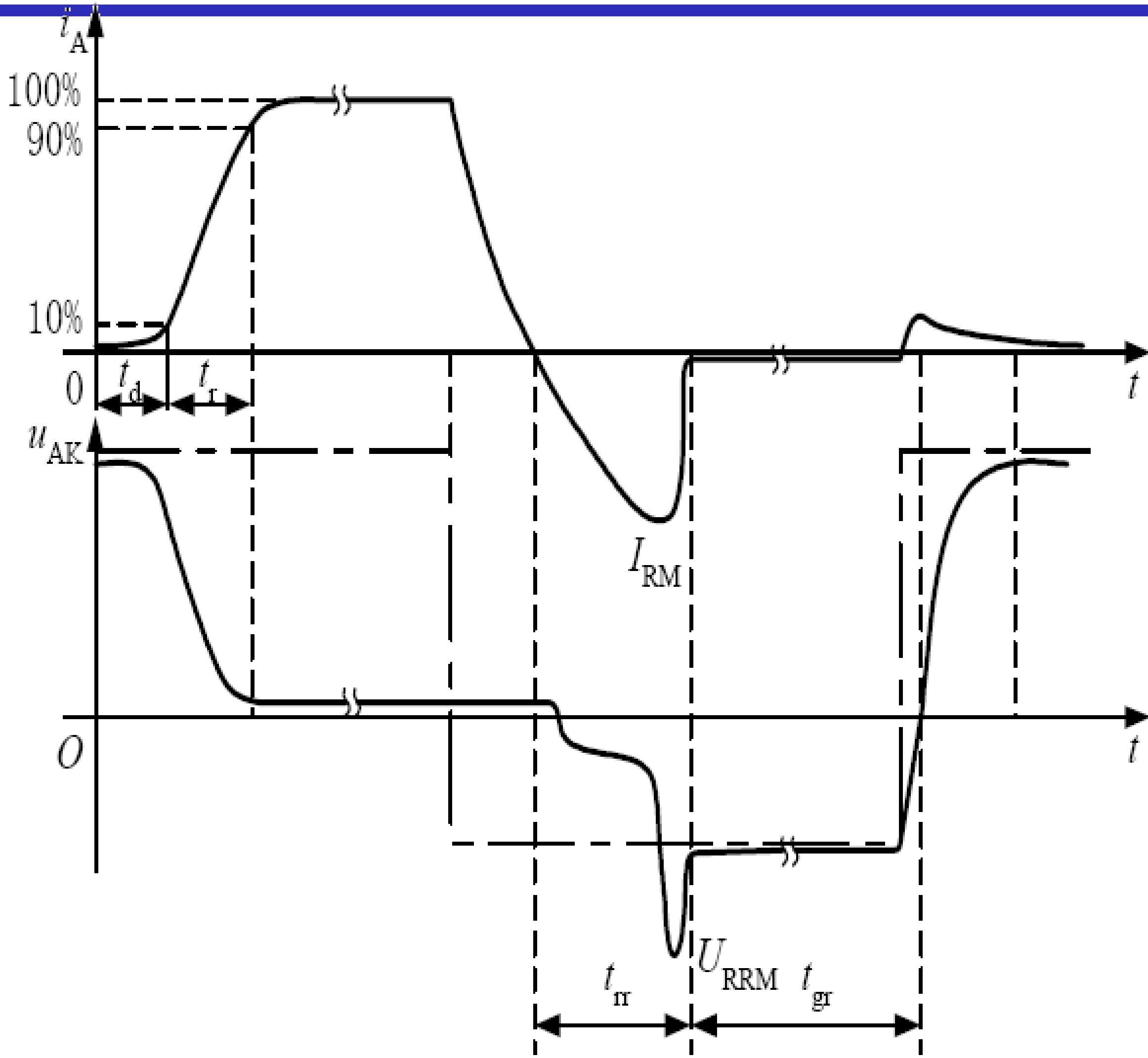


- Turn-on: controllable
  - *when forward-biased*
  - *the latching current i_L: the minimal anode current to guarantee a successful turn-on*
  - *gate pulse i_G to trigger*
  - *conducting in one direction: anode to cathode*

- Turn-off
  - Not controllable via the gate pulse
  - Turns off when the current has fallen small enough
  - The holding current i_H: in the order of *mA* and $i_L > i_H$
  - Recovery: similar to a diode

Dynamic characteristics

Not required

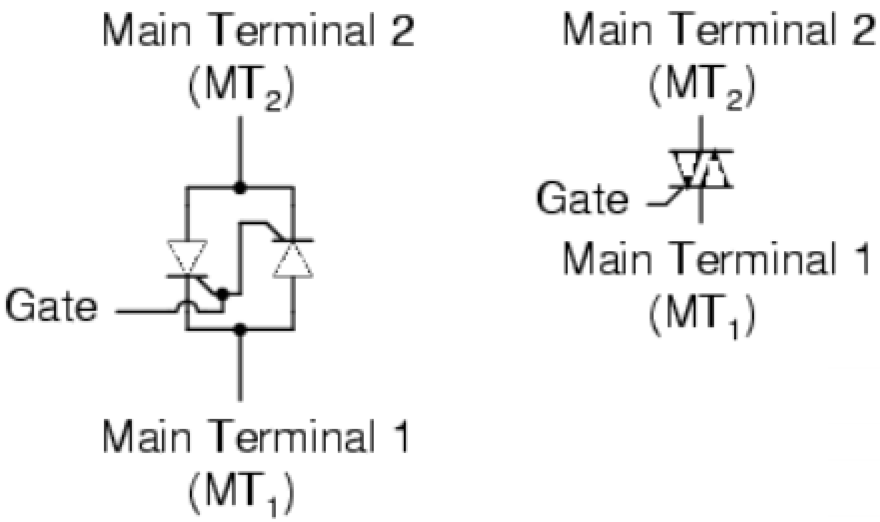


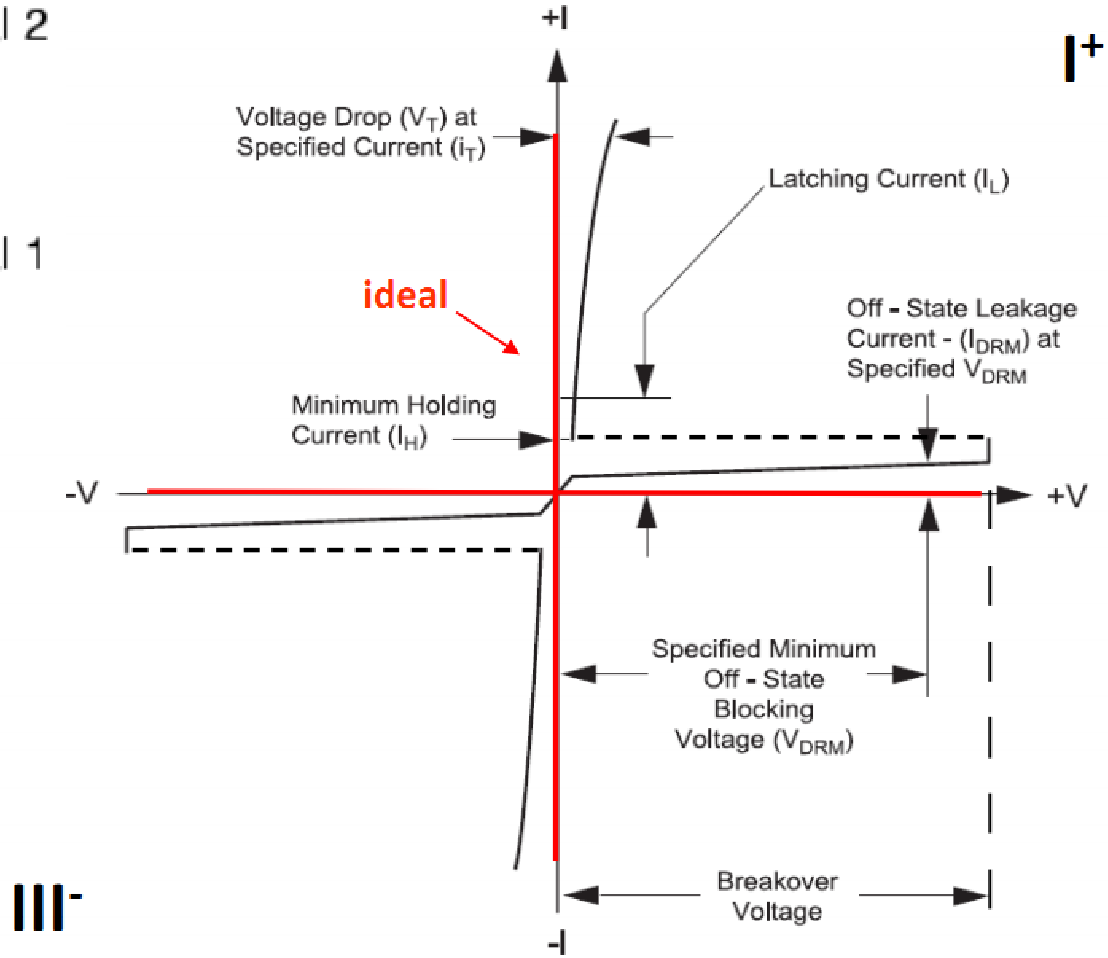
- Turn-on transient
  - Delay time t_d
  - Rise time t_r
  - Turn-on time tgt

- Turn-off transient
  - Reverse recovery time t_{rr}
  - Forward recovery time t_{gr}
  - Turn-off time t_q

1.1.4 Triacs

- Two SCRs connected in anti-parallel with a common gate
- Can conduct in both ways

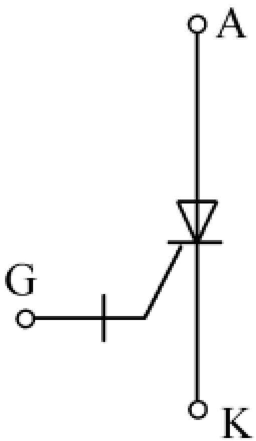




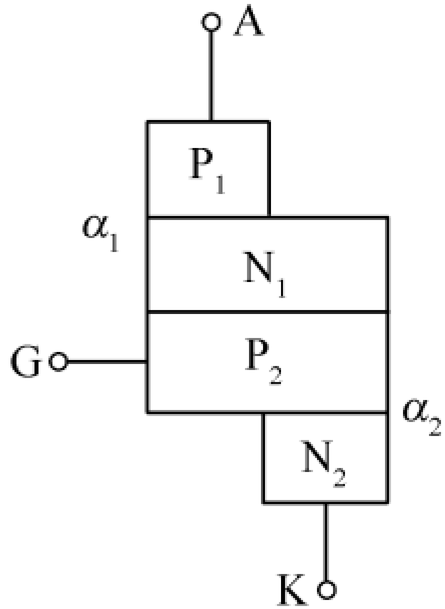
1.1.5 GTO

Not required

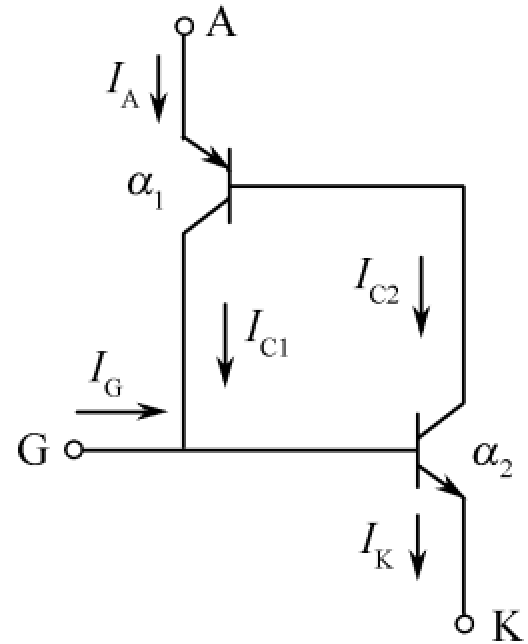
(a) symbol



(b) structure

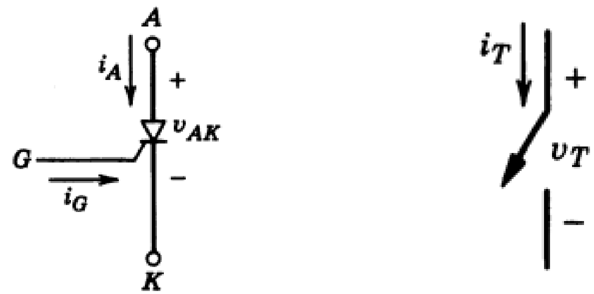


(c) equivalent circuit



- GTO: Gate Turn-off Thyristor, is a thyristor-type device
  - Turn-on: by a positive gate voltage pulse
  - Turn-off: by a relatively large negative gate current pulse

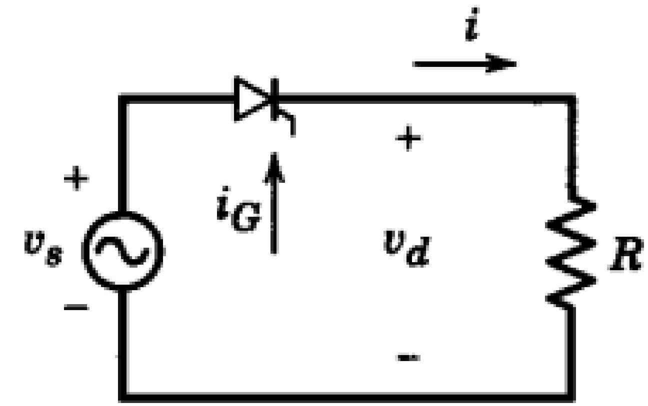
1.2 Thyristor



- 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 and does not turn off until i_{TH} -> 0.
- Ideally:
  - Instantaneous switching from one state to the other
  - Zero voltage drop in on-state
  - Infinite voltage and current handling capabilities

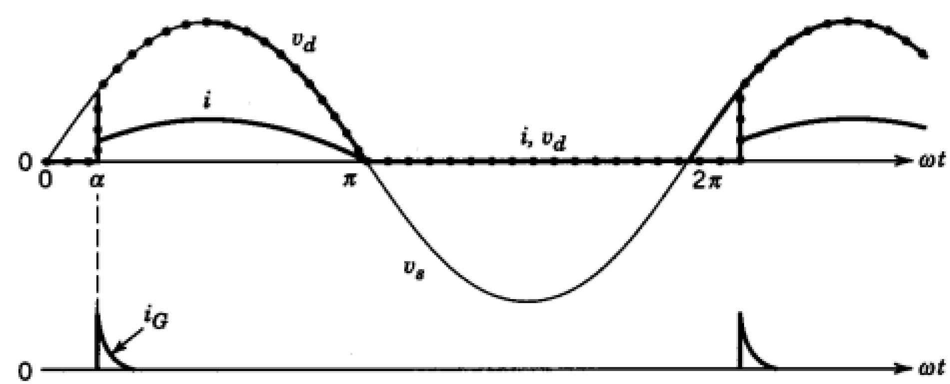
1.2 Basic thyristor circuits I

- 1. Resistive load (R)
  - In the positive half
    - $[0, \alpha]$: i is zero, v_d is zero;
    - $[\alpha, \pi]$: $v_d = v_s$, $i = v_d / R$.



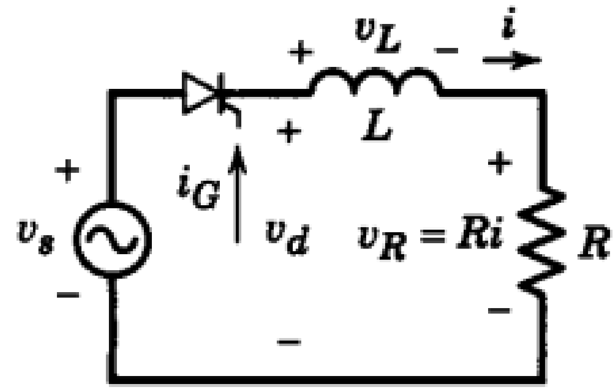
  - In the negative half
    - $[\pi, 2\pi]$: i is zero, v_d is zero.

    Because the thyristor blocks the current



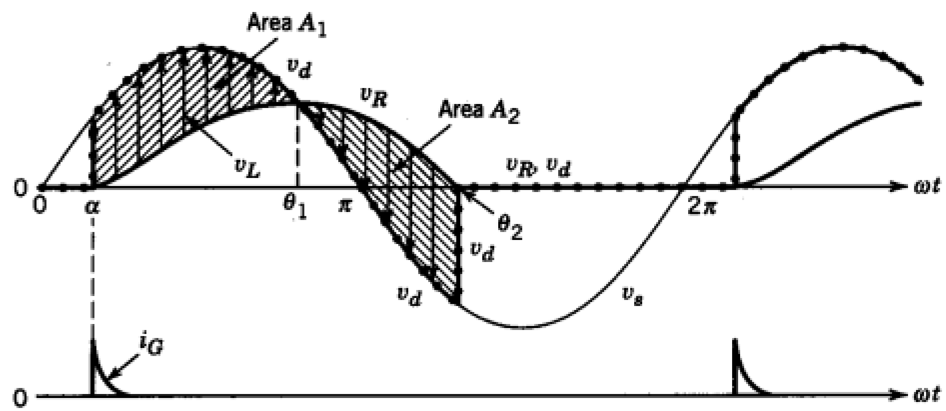
1.2 Basic thyristor circuits II

- 2. Inductive load (RL)
  - $[0, \alpha]$: i is zero, v_d is zero;
  - $[\alpha, \theta_2]$: $v_d = v_s$
    - $[\alpha, \theta_1]$: $v_d > v_R$, i increases.
    - $[\theta_1, \theta_2]$: $v_d < v_R$, i decreases.
  - $[\theta_2, 2\pi]$: i is zero, v_d is zero.



$$v_L = L\frac{di}{dt} = v_d - v_R$$

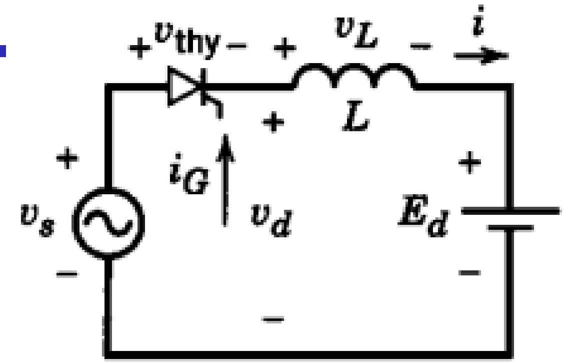
$$i(\omega t) = \frac{1}{\omega L}\int_{\alpha}^{\omega t} v_L(\omega\tau)\,d(\omega\tau)$$



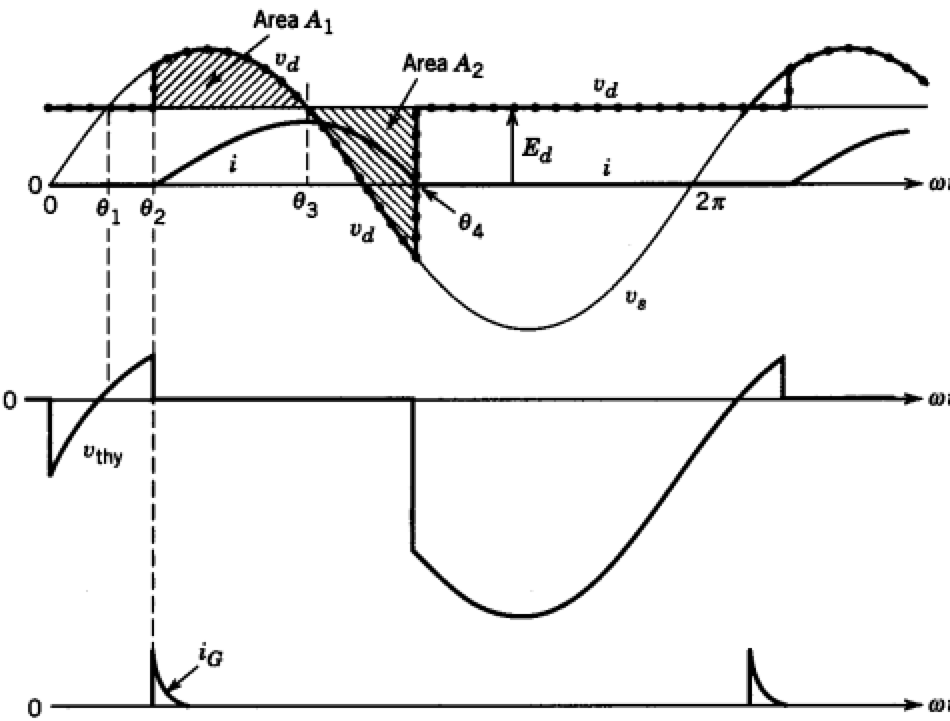
For inductor: voltage can jump, but current must be continuous.

1.2 Basic thyristor circuits III

- 3. Inductive load (LE)
  - $[0, \theta_1]$: i is zero, v_d is zero, thyristor is reverse biased, so $v_{TH}=v_s-E_d$;
  - $[\theta_1, \theta_2]$: i is zero, v_d is zero, thyristor is forward biased but not triggered, so $v_{TH}=v_s-E_d$;
  - $[\theta_2, \theta_3]$: $v_s > E_d$, i increases.
  - $[\theta_3, \theta_4]$: $v_s < E_d$, i decreases.
    - At , thyristor stops conduction.
  - $[\theta_4, 2\pi]$: i is zero, v_d is zero, thyristor is reverse biased, so $v_{TH}=v_s-E_d$

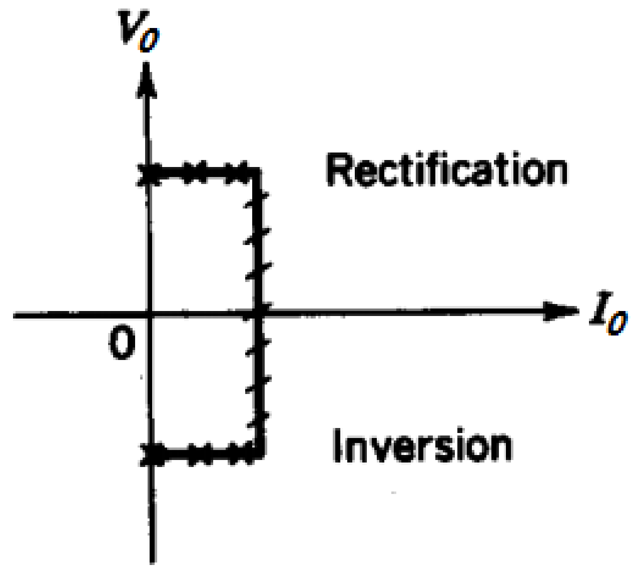


$$v_L = L\frac{di}{dt} = v_d - E_d$$



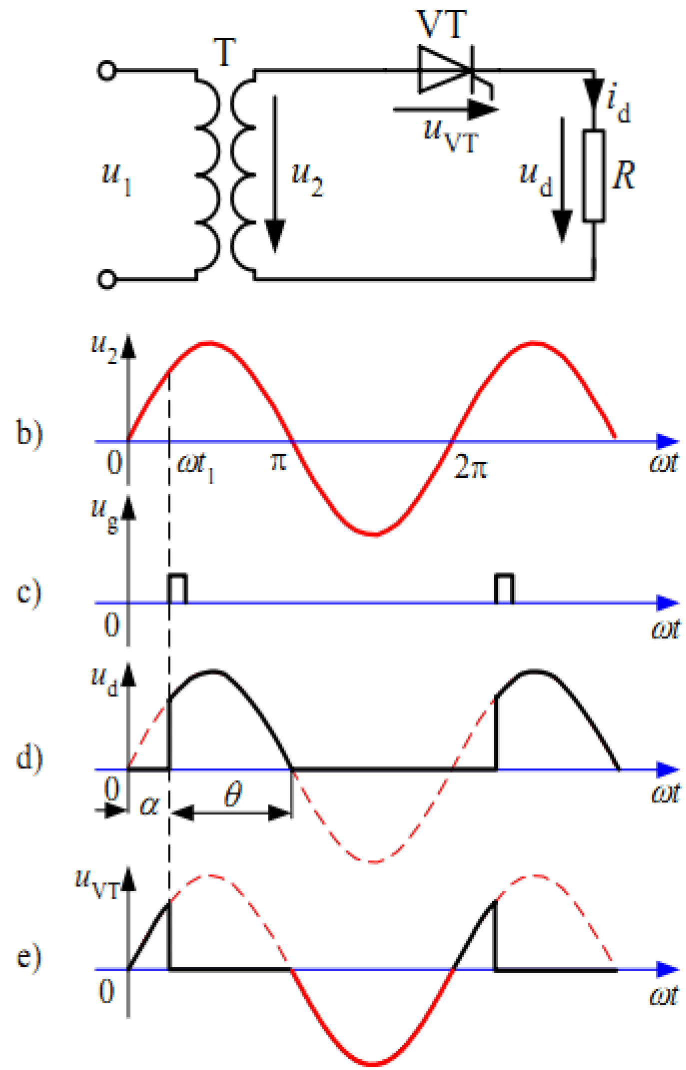
2. Controlled Rectifiers

- Types of controlled rectifiers: According to the directions of the output voltage V_0 and the current I_0, there are three types:
  - Semi-converter (one-quadrant):
    - V_0 + and I_0 + (Rectification)
  - Full converter (two-quadrant):
    - V_0 +/- and I_0 + (Rectification + inversion)
  - Dual converter (four-quadrant):
    - V_0 +/- and I_0 +/- (Bi-directional rectification + inversion)



2.1 Single-phase half-wave controlled rectifier

- 1. Resistive load (R):
  - Half-wave, single-pulse
  - Triggering angle α
    - Delay angle
    - Firing angle
  - Conduction angle θ
    - $\theta = \pi - \alpha$



Controlling the output DC voltage by modifying the triggering pulse phase is called **Phase Control**

Parameter evaluation

- (1) Average output voltage

$$U_{\mathrm{d}} = \frac{1}{2\pi}\int_{\alpha}^{\pi}\sqrt{2}U_2 \sin\omega t \mathrm{d}(\omega t) = \frac{\sqrt{2}U_2}{\pi}\frac{1+\cos\alpha}{2} = 0.45U_2\frac{1+\cos\alpha}{2}$$

- (2) RMS output voltage

$$U_{RMS} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi}\left(\sqrt{2}U_2 \sin\omega t\right)^2 \mathrm{d}(\omega t)} = U_2\sqrt{\frac{1}{4\pi}\sin 2\alpha + \frac{\pi-\alpha}{2\pi}}$$

- (3) Rectification efficiency

$$\eta = \frac{P_d}{P_{RMS}} = \frac{U_d^2}{U_{RMS}^2}$$

- (4) Transformer utilisation factor

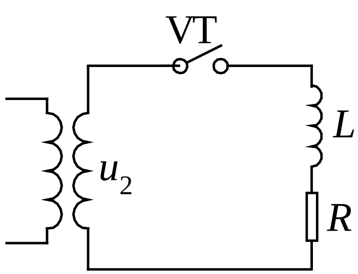
$$TUF = \frac{P_d}{V_s I_s} = \frac{U_d^2}{V_s I_{RMS}}$$

- (5) Form factor and ripple factor

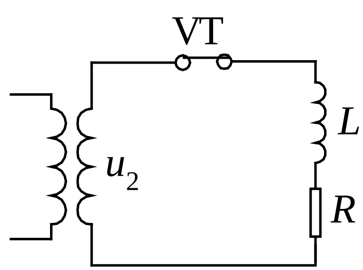
$$FF = \frac{U_{RMS}}{U_d} \qquad RF = \sqrt{FF^2 - 1}$$

2.1 Single-phase half-wave controlled rectifier

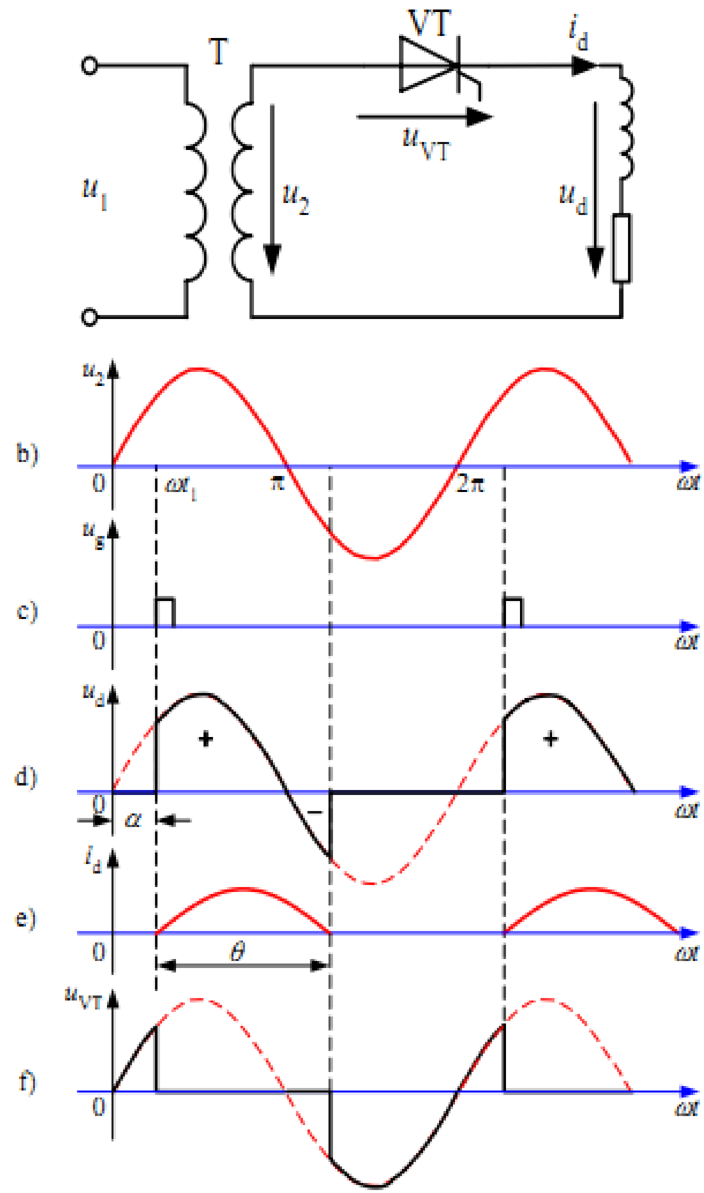
- 2. Resistor-inductor load (RL)
- Time-domain analysis:
  - The time-domain behaviour of a power electronic circuit is actually the combination of consecutive transients of the different linear circuits when the power semiconductor devices are in different states.



a)



b)



2.1 Single-phase half-wave controlled rectifier

- When VT is conducting:

$$L\frac{\mathrm{d}i_{\mathrm{d}}}{\mathrm{d}t}+Ri_{\mathrm{d}}=\sqrt{2}U_2\sin\omega t$$

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

$$i_{\mathrm{d}}=-\frac{\sqrt{2}U_2}{Z}\sin(\alpha-\varphi)e^{-\frac{R}{\omega L}(\omega t-\alpha)}+\frac{\sqrt{2}U_2}{Z}\sin(\omega t-\varphi)$$

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

- Substitute $\omega t=\theta+\alpha$ and $i_d=0$ in the equation, get:

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

with the knowledge of angle α and φ, the conduction angle θ can be calculated by computer.

Calculation is not required

2.1 Single-phase half-wave controlled rectifier

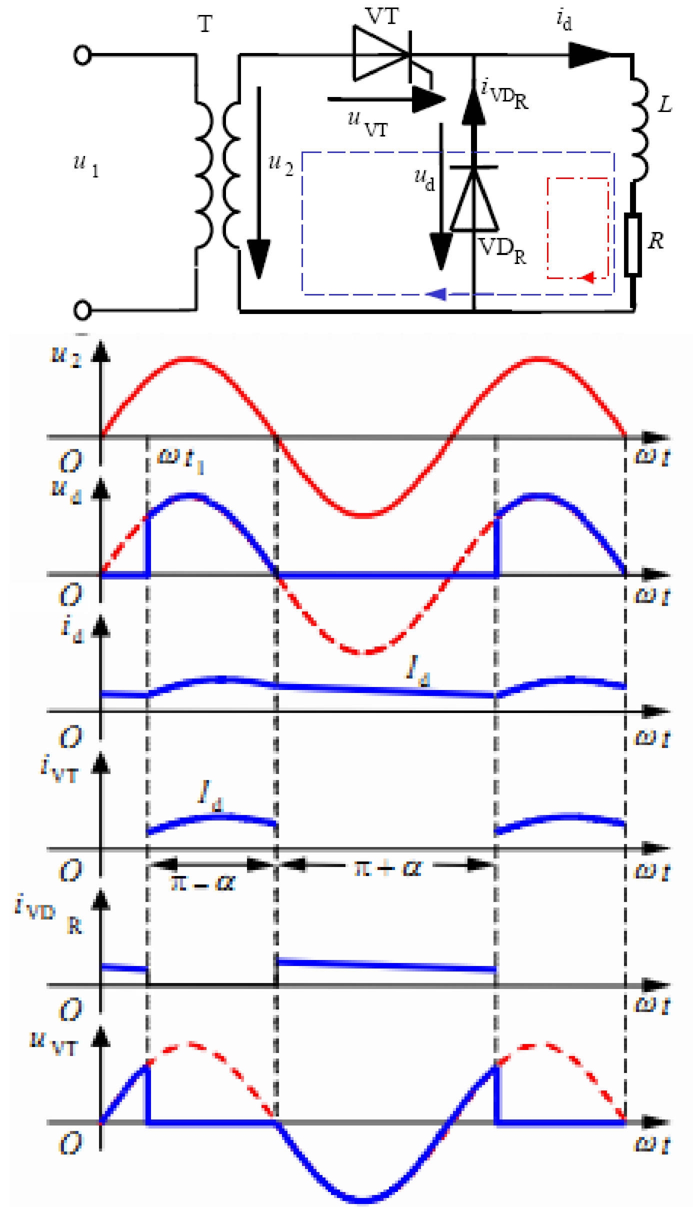
- 3. Inductive load (L is large enough) with freewheeling diode
  - When $u_2 \rightarrow$minus value, V_{DR} starts to conduct; u_d=0, V_T is closed.
  - Energy stored in L keeps the current i_d flowing in the loop L-R-VDR.
- If i_d can be considered as a constant I_d:

$$I_{dVT} = \frac{\pi - \alpha}{2\pi} I_d$$

$$I_{VT} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi} I_d^2 d(\omega t)} = \sqrt{\frac{\pi - \alpha}{2\pi}} I_d$$

$$I_{dVD_R} = \frac{\pi + \alpha}{2\pi} I_d$$

$$I_{VD_R} = \sqrt{\frac{1}{2\pi}\int_{\pi}^{2\pi+\alpha} I_d^2 d(\omega t)} = \sqrt{\frac{\pi + \alpha}{2\pi}} I_d$$

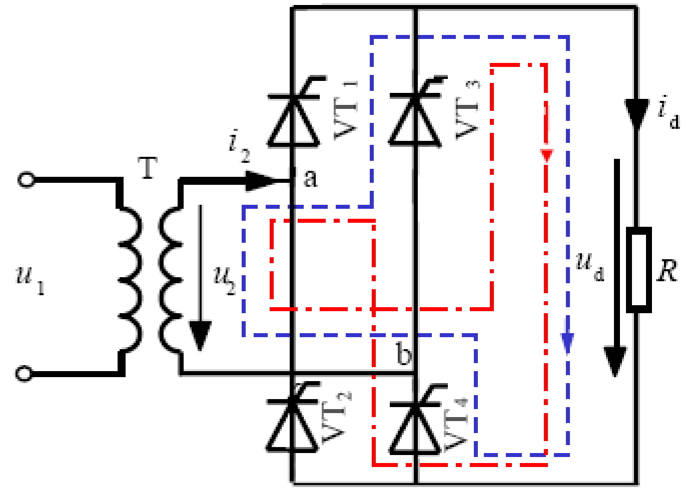


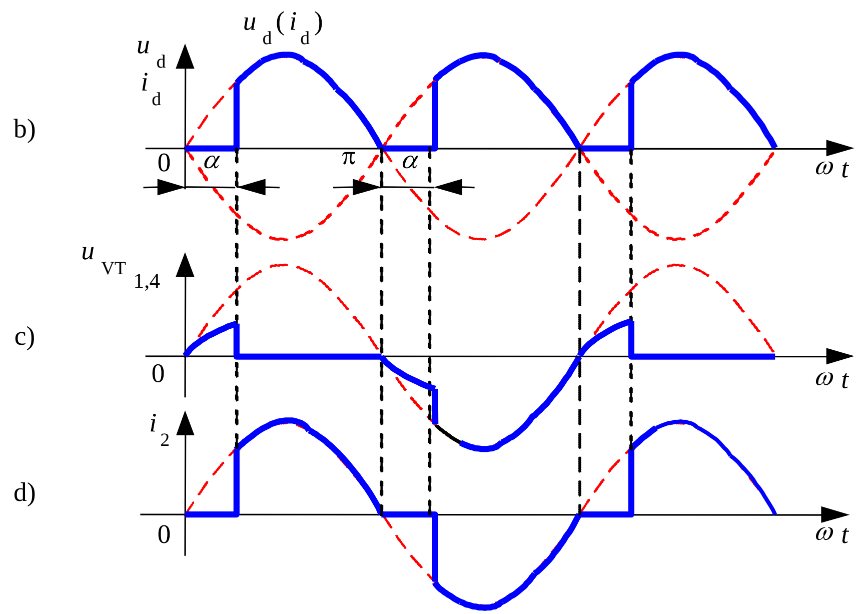
2.1 Single-phase half-wave controlled rectifier

- Summary:
  - Triggering delay angle α of V_T could vary from 0 to π
  - The circuit is simple, but form factor and ripple factor are quite large;
  - These circuits are hardly used in practice;
  - For thyristor: Maximum forward voltage, maximum reverse voltage
  - Disadvantages:
    - Only single pulse in one line cycle
    - DC component in the transformer current

2.2 Single-phase bridge full-controlled rectifier

- 1. Resistive load (R)
  - V_{T1} and V_{T4} is a pair of bridge arm: In the positive half of u_2, they start to conduct when triggered by a pulse, and will be close when u_2 passes 0 to negative.
  - V_{T2} and V_{T3} is another pair of bridge arm: In the negative half of u_2, they start to conduct when triggered by a pulse, and will be close when u_2 passes 0 to positive.





Parameter evaluation

- Average output (rectified) voltage

$$U_{\mathrm{d}} = \frac{1}{\pi}\int_{\alpha}^{\pi}\sqrt{2}U_2 \sin\omega t\,\mathrm{d}(\omega t) = \frac{2\sqrt{2}U_2}{\pi}\frac{1+\cos\alpha}{2} = 0.9U_2\frac{1+\cos\alpha}{2}$$

- Average output current

$$I_{\mathrm{d}} = \frac{U_{\mathrm{d}}}{R} = \frac{2\sqrt{2}U_2}{\pi R}\frac{1+\cos\alpha}{2} = 0.9\frac{U_2}{R}\frac{1+\cos\alpha}{2}$$

- Average current on thyristor

$$I_{\mathrm{dVT}} = \frac{1}{2}I_{\mathrm{d}} = 0.45\frac{U_2}{R}\frac{1+\cos\alpha}{2}$$

- Effective current on thyristor

$$I_{\mathrm{VT}} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi}\left(\frac{\sqrt{2}U_2}{R}\sin\omega t\right)^2\mathrm{d}(\omega t)} = \frac{U_2}{\sqrt{2}R}\sqrt{\frac{1}{2\pi}\sin 2\alpha + \frac{\pi-\alpha}{\pi}}$$

2.2 Single-phase bridge full-controlled rectifier

- Summary
  - Similar to a diode bridge, but with the capability of controlling the output voltage.
  - V_{T1}-V_{T4} pair conducts for the positive half cycle, if triggered; V_{T2}-V_{T3} pair conducts for the negative half cycle, if triggered.
  - V_{T1}-V_{T4} pair or V_{T2}-V_{T3} pair should be triggered at the same time.
  - For thyristor: Half maximum forward voltage, maximum reverse voltage
  - Advantages:
    - 2 pulses in one line cycle
    - No DC component in the transformer current

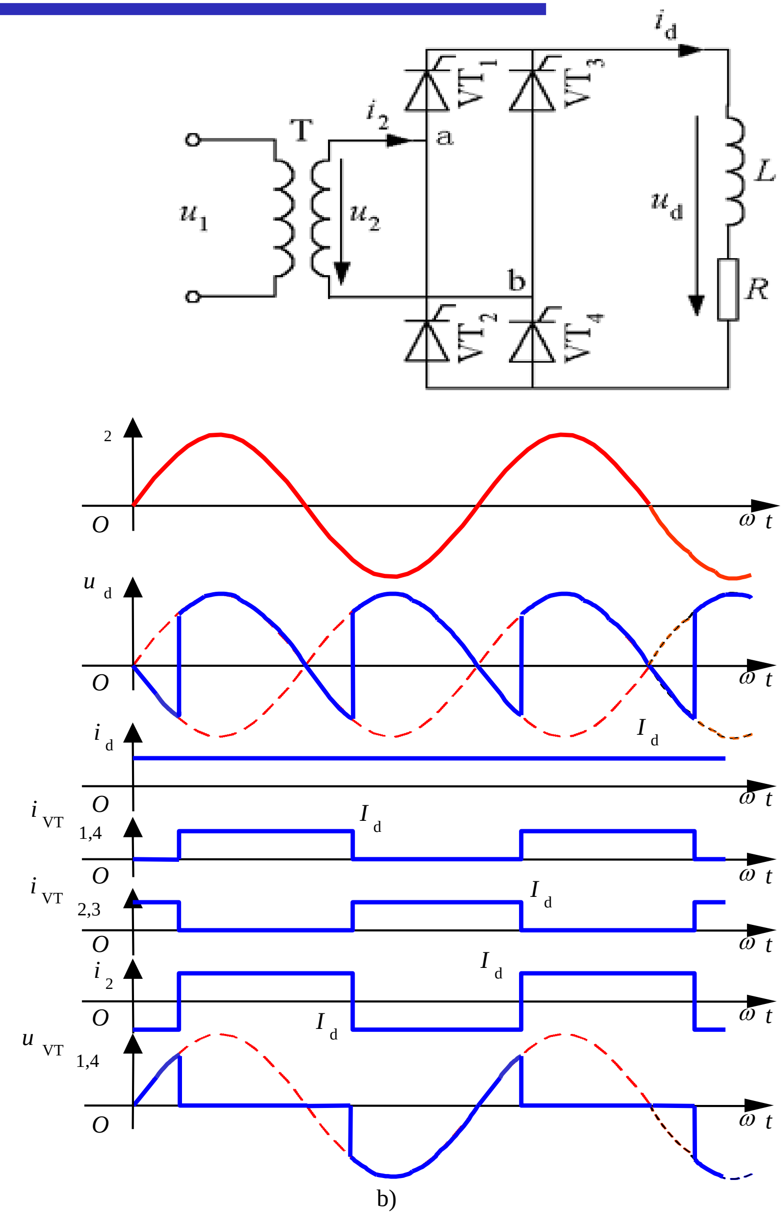
2.2 Single-phase bridge full-controlled rectifier

- 2. Inductive load (L is large enough)
  - Average output (rectified) voltage

$$U_d = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} \sqrt{2}U_2 \sin \omega t \mathrm{d}(\omega t) = 0.9U_2 \cos\alpha$$

  - The voltage can be varied from $0.9V_s$ to 0 by controlling the firing angle α from 0^o to 90^o.
  - Current:

$$I_{dT} = \frac{1}{2} I_d \qquad I_T = \frac{1}{\sqrt{2}} I_d = 0.707 I_d$$

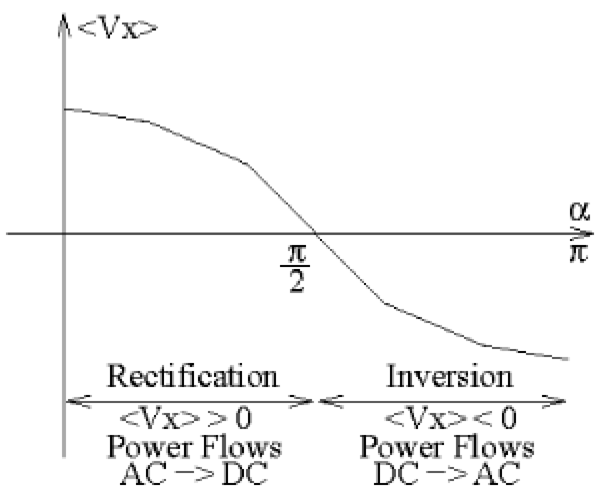


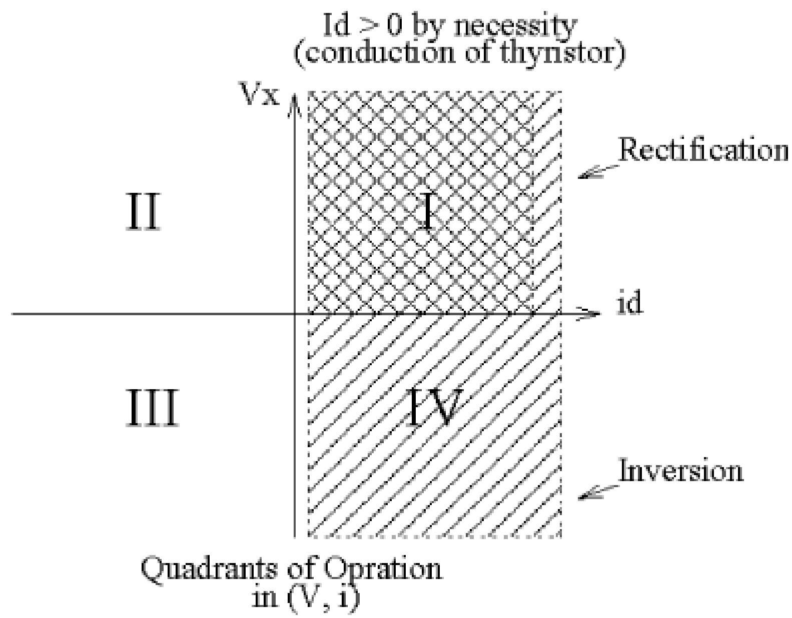
b)

2.2 Single-phase bridge full-controlled rectifier

$$U_d = 0.9U_2 \cos\alpha$$

- Assume that L is large enough and the load can provide energy. Then the output voltage is negative when $\alpha > 90^o$.
- The power is flowing from the load to the supply. This is called inversion.

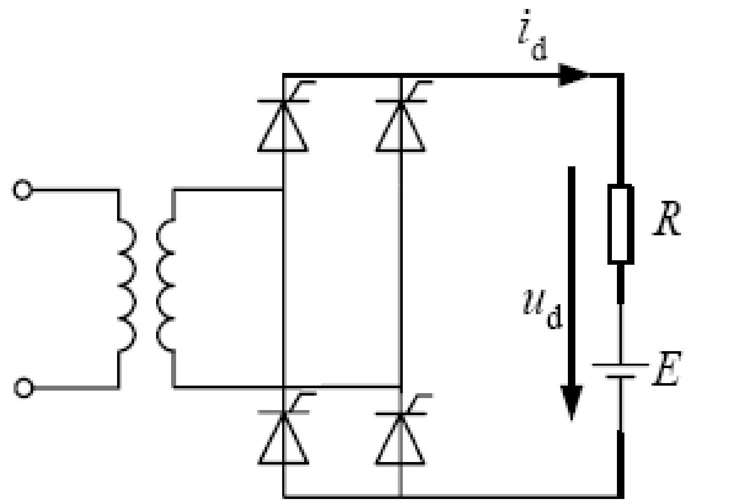


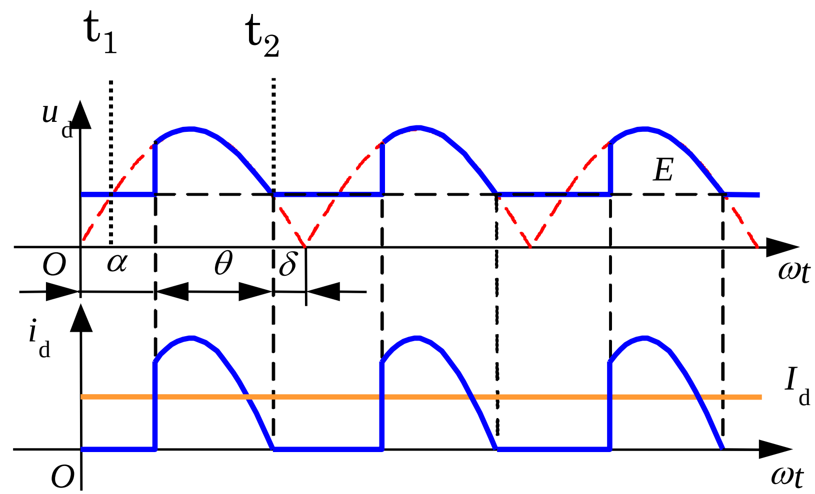


2.2 Single-phase bridge full-controlled rectifier

- 3. Electro-motive-force (EMF) load (With Resistor)
- Operation procedure:
  - At t_1, When $|U_2|>E$, thyristors are positive biased => possible to conduct;
  - Until t_2, $|U_2|$->E again, i_d reduces to 0 to close the thyristors => u_d equals to E afterwards.
  - Comparing with pure R load, thyristor stops conduction δ radians earlier, which is

$$\delta = \sin^{-1}(E / V_m)$$

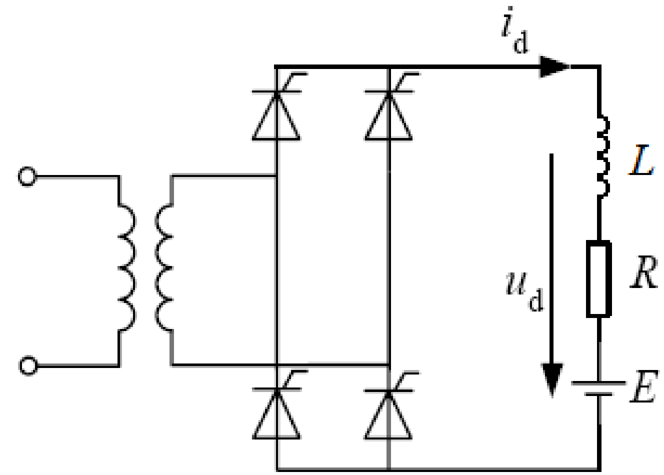


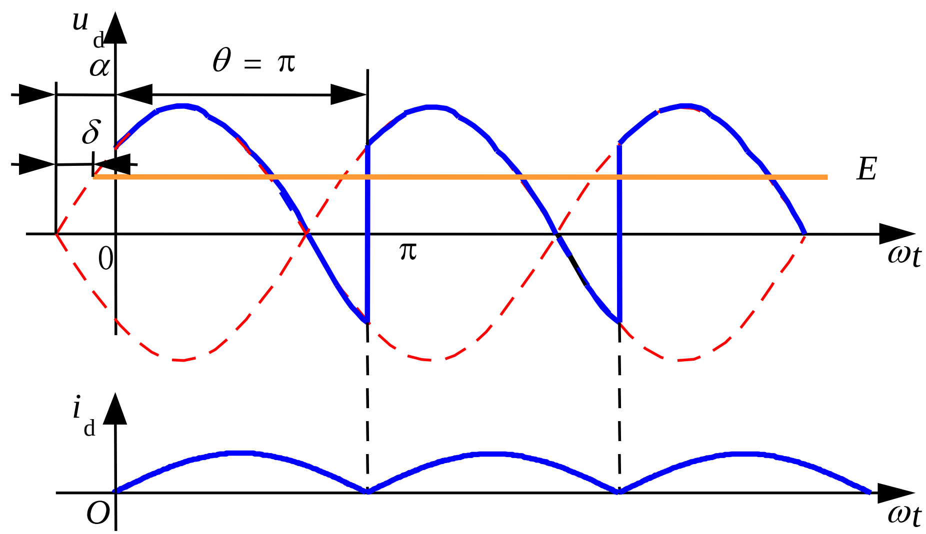


Discontinuous i_d

2.2 Single-phase bridge full-controlled rectifier

- 3.2 Electro-motive-force (EMF) load
  - With Inductive load (R-L-E)
- Operation procedure:
  - With inductive load which can provide energy, the thyristor can still conduct when u2 is smaller than E (even when u2 is negative);
    - If L is large enough, then the current is continuous;
    - Otherwise, it is discontinuous.
  - Waveform with critical value of L is shown on the right.

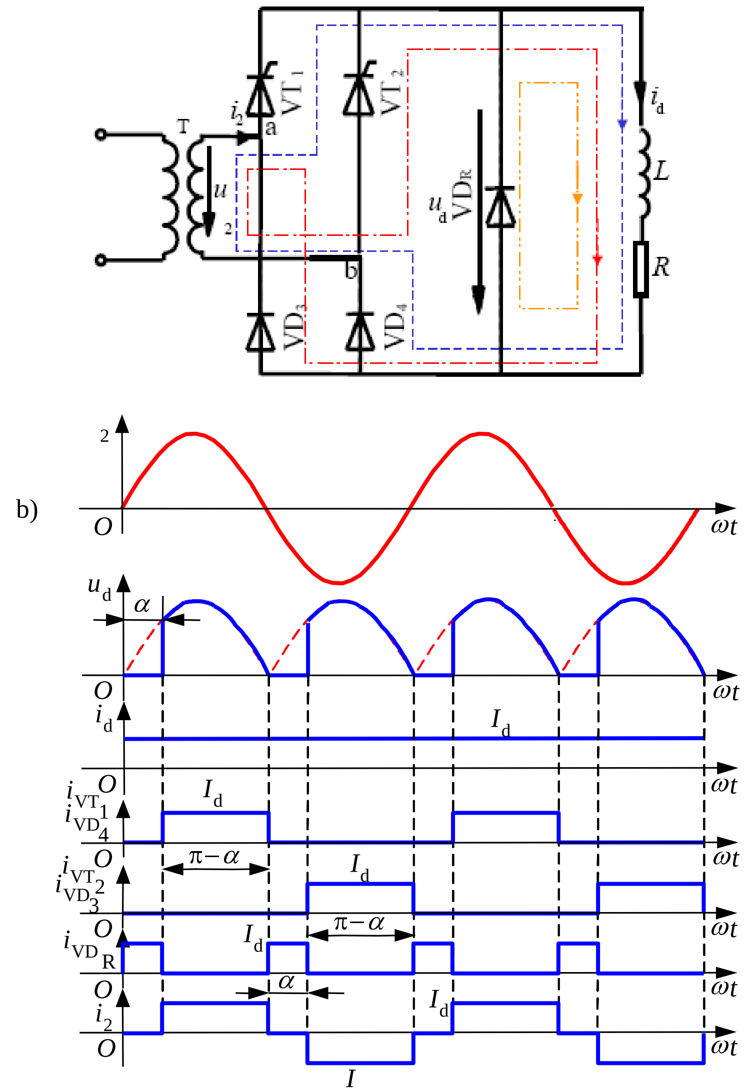




Continuous i_d

2.3 Single-phase bridge half-controlled rectifier

- Inductive load (with freewheeling diode)
- Operation procedure:
  - Positive half after trigger: u_2 -> load through V_{T1} and V_{D4};
  - u_2 passes 0 to negative, the current flows through V_{T1} and V_{D2}, u_d is zero;
  - Negative half after trigger: u_2 -> load through V_{T3} and V_{D2};
  - u_2 passes 0 to positive, the current flows through V_{T3} and V_{D4} , u_d is zero again.



2.4 Summary of some important points in analysis

- When analyzing 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