Power Electronics

Power Switches

For Switching Power Conversion

Please read
pages 16-31 in Chapter 2
Pages 546-661 Chapter 21-26
of the textbook

Typical Controllable Power Switches.

There are several different electronic devices used for switching appreciable amounts of electrical power. Those to be examined in the next two lectures are:

1.Thyristors (Silicon Controlled Rectifiers; SCRs) 晶闸管 (half-controlled)

2. GTOs (Gate turn-off Thyristors) 可关断晶闸管 (fully controlled)

3. TRIACs 双向晶闸管

4. MOSFETs (Metal Oxide Semiconductor Field Effect Transistors) (fully controlled)

5. GTR (Giant Transistor)大功率晶体管 (fully controlled)

6. IGBT (Insulated Gate Bipolar Transistors) 绝缘栅极双极性晶体管 (fully controlled)

Pictures courtesy of International Rectifier

Practical Considerations for Switch Selection:

I. How much control do we have (or need)?

→ Controllability

I. How much voltage will it drop when on?

→ Conduction Resistance

I. How much voltage can it block 阻断 when off?

→ Voltage Rating

I. How much current can it carry承受?

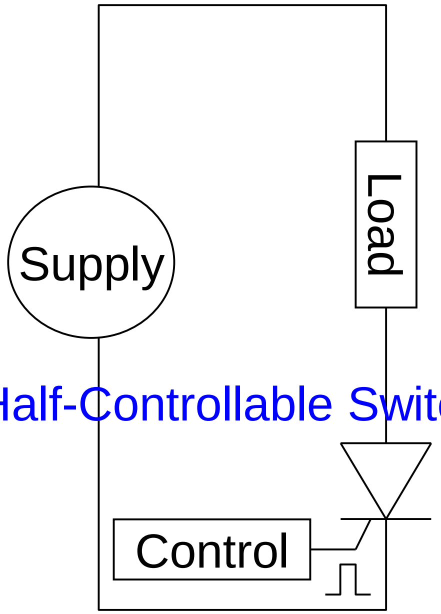
→ Current Rating

I. How long does it take to turn on and off?

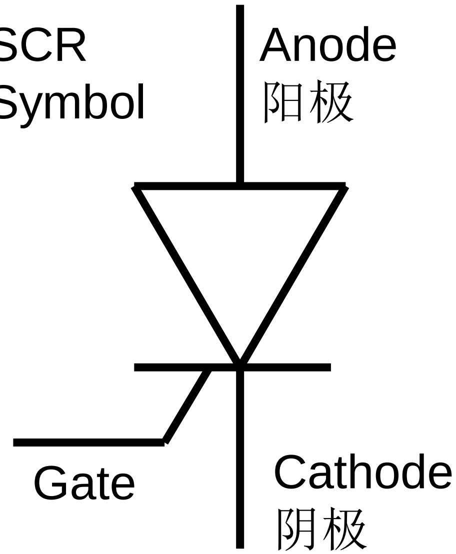
→ Switching Frequency

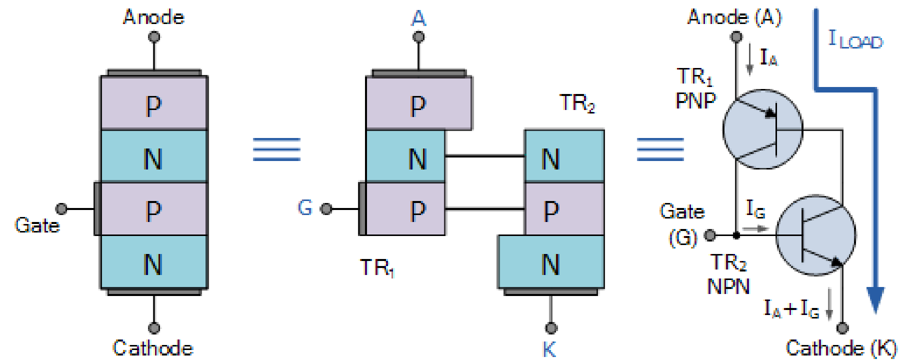
The Thyristor (SCR – Silicon-Controlled-Rectifier) 晶闸管

If the anode voltage is higher than the cathode voltage, a brief pulse on the gate will turn on the device. Once the device is conducting, it stays on ("Latches"闩锁) until the current through it falls to zero. Once on, the gate looses all control.



Half-Controllable Switch





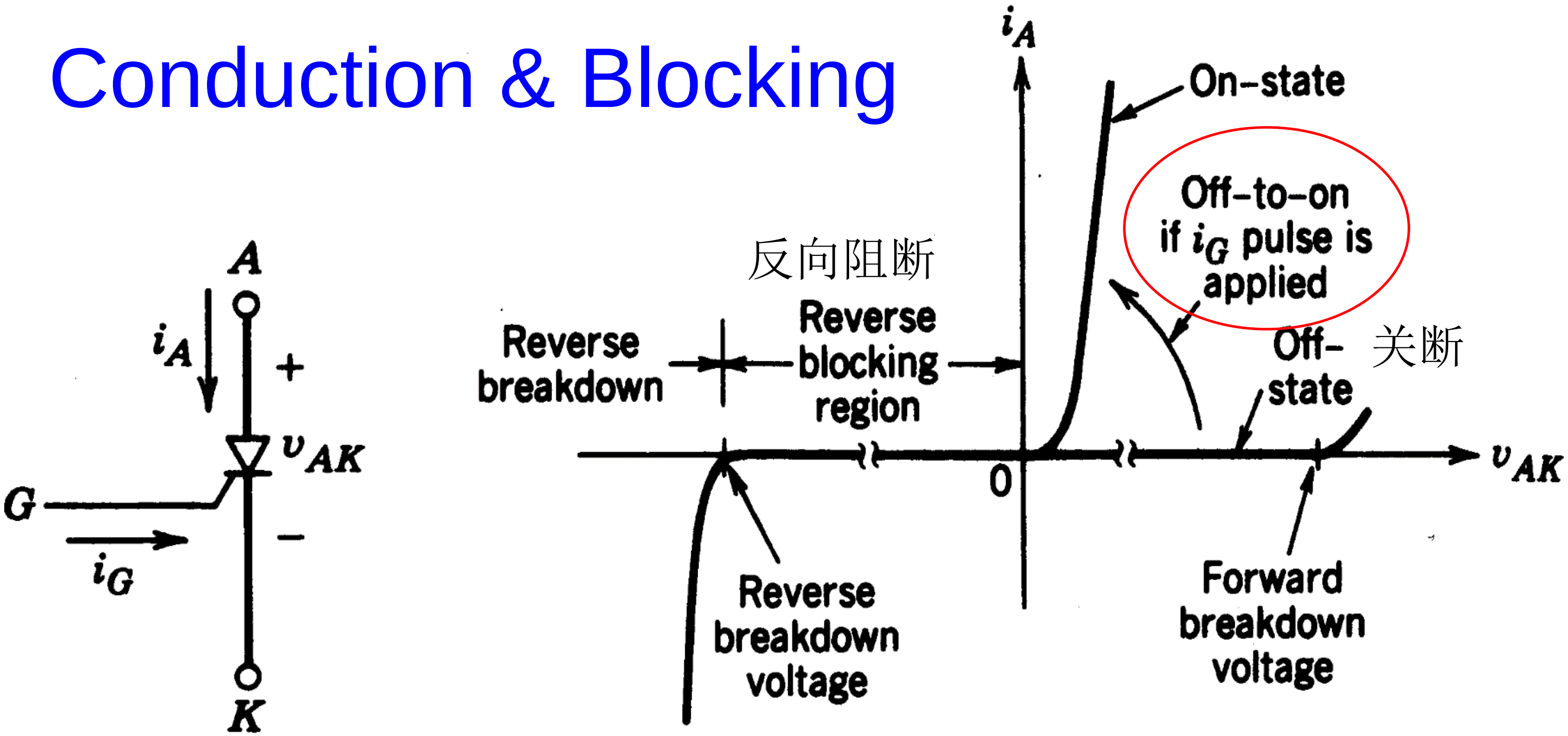
The gate needs a few volts and a few milliamps to switch the device on.

The device can pass thousands of amps and block thousands of volts.

When on, the forward voltage drop is low (Approximate 1V).

Turn-on is slow, taking a few 10's to a few 100's of microseconds, depending on the size of the device. **They are used in very high power applications!!!**

Conduction & Blocking

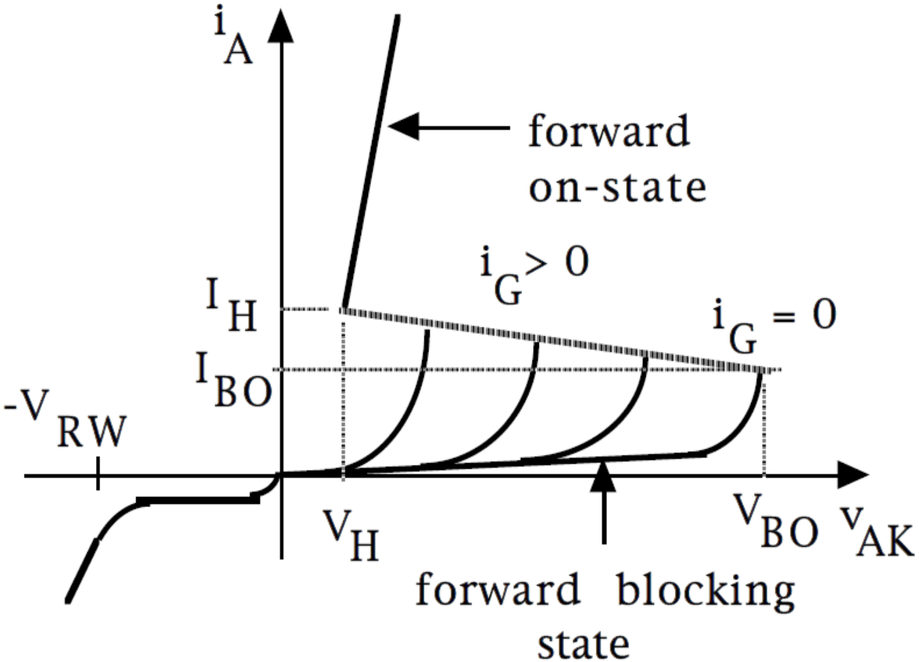


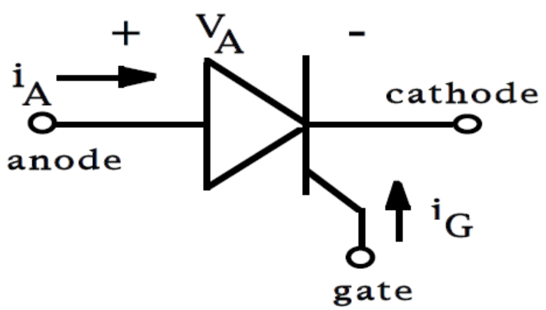
Half-Controllable Switch 半控开关

The thyristor can be turned on by applying a pulse of positive gate current i_G for a short duration when the device in its forward-blocking 前向阻断 state.

Once the device begins to conduct, it is latched on and I_G can be removed. It cannot be turned off by gate. It will turn off until anode current i_A go to zero.

Trigger On





Current to several kiloamps for V(on) of about 1 volts.

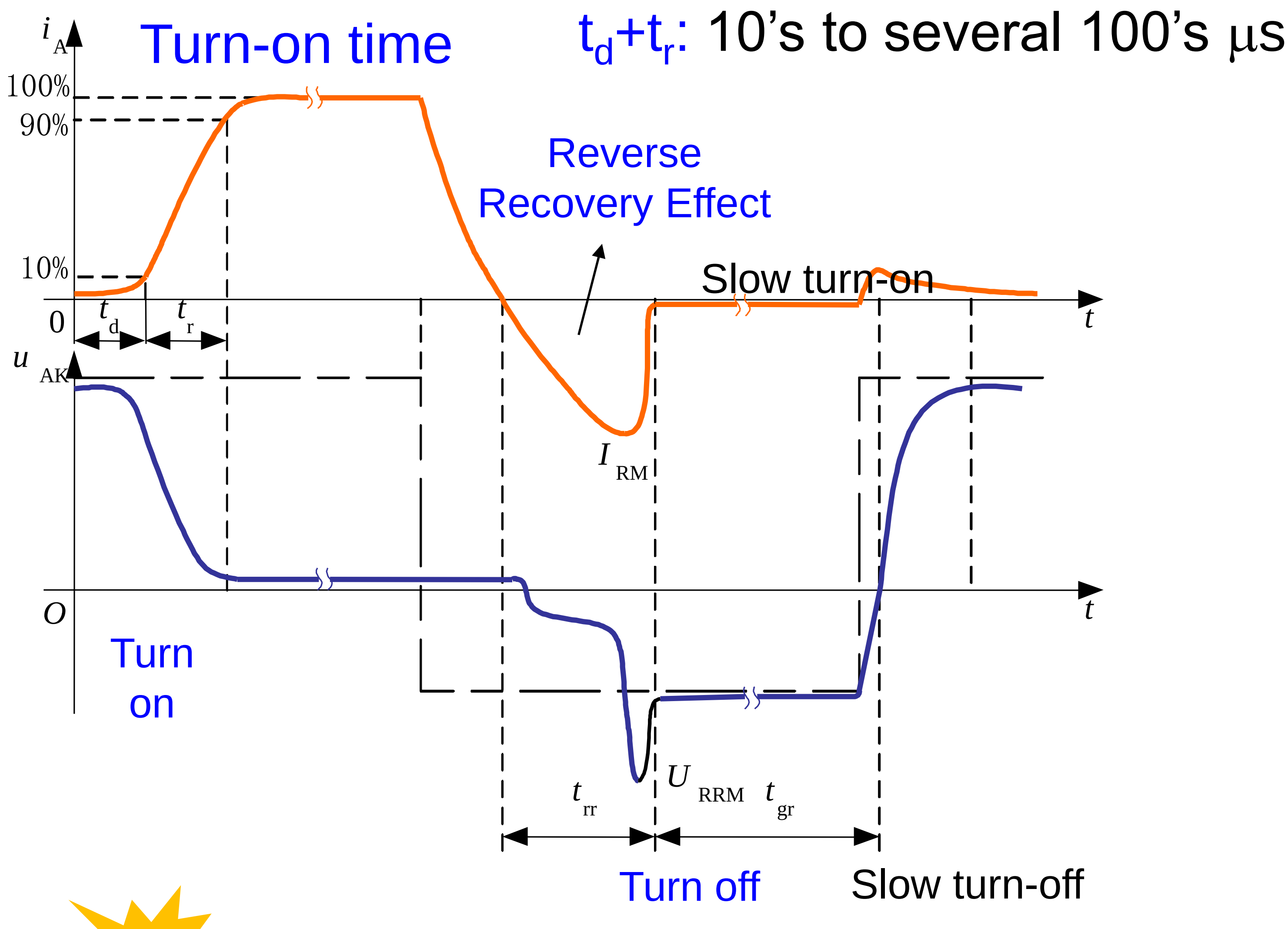
Blocking voltages to 5-8 kilovolts.

Maximum junction temperature = 125 °C

Higher i_G leads to shorter turn-on time

High efficient for high voltage high current applications (e.g. HVDC)

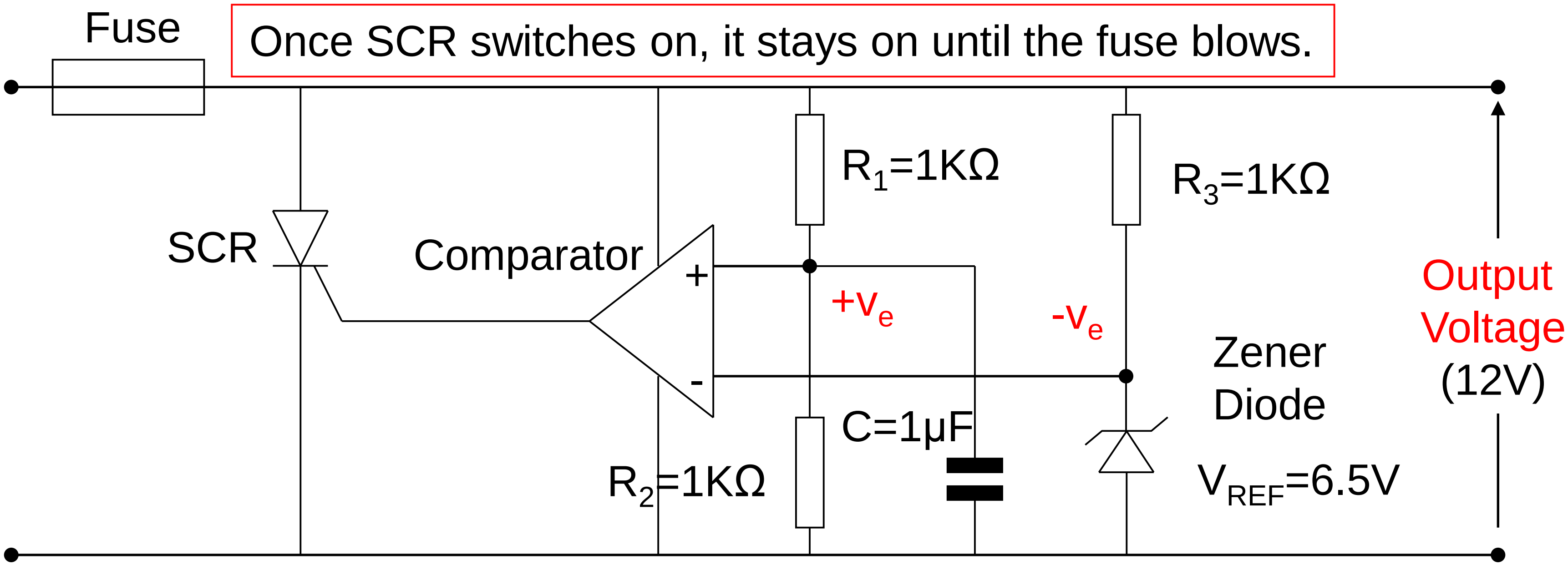
Turn-on/off of Thyristor (SCR)



Turn-off time t_{rr}+t_{gr}: several hundred μs

Example application of SCRs in DC circuits

The diagram below shows a power supply with an SCR used to prevent the output from exceeding a pre-defined value.



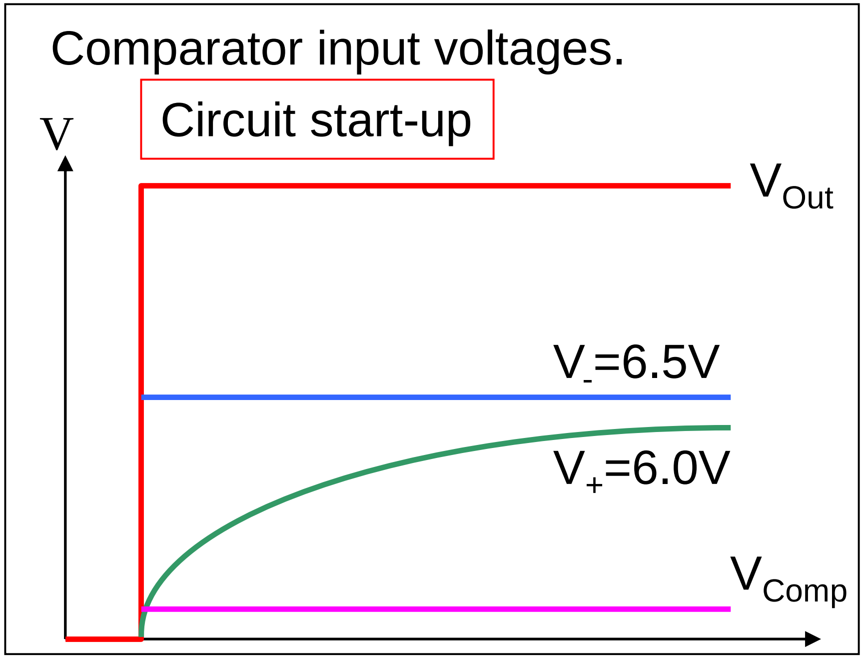
This is called an *over-voltage crowbar circuit.*

Comparator truth table

+ve > -ve	Output ↑
+ve < -ve	Output ↓

If the comparator + input is more positive than the – input, the output (V_{Comp}) is "on".

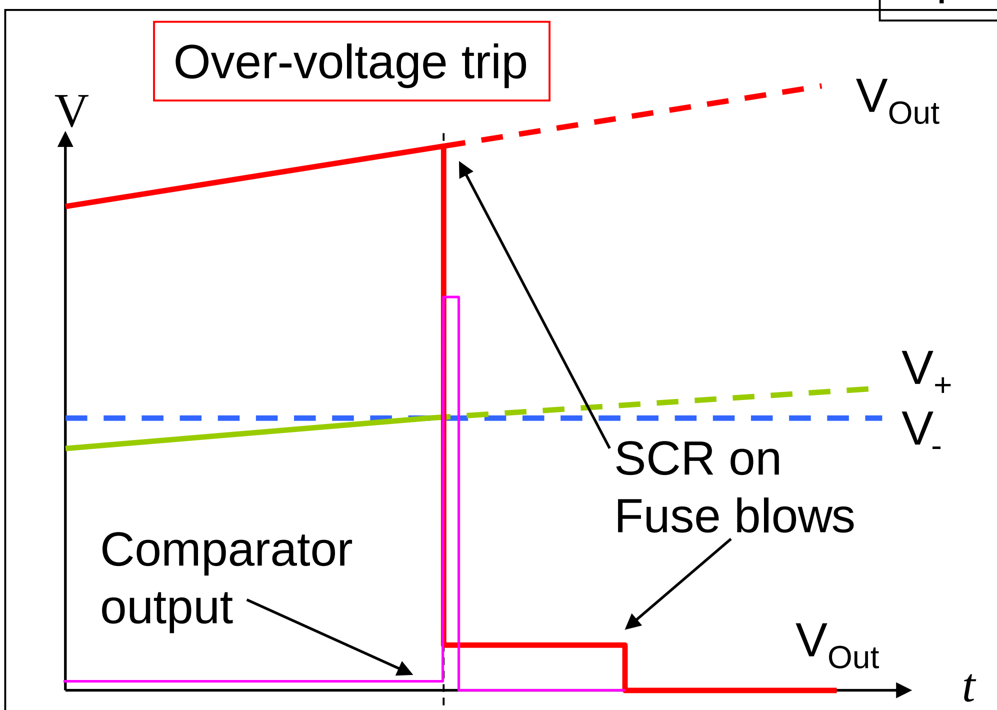
If the comparator + input is more negative than the – input, the output is "off".



The capacitor holds the voltage on the +ve comparator input down whilst the supply voltages stabilise, preventing false triggering 触发 of the SCR. This also provides noise immunity when operating. $T=RC$=1 second.

R_1 & R_2 form a potential divider 分压电路 holding the +ve input at half the output voltage (6V).

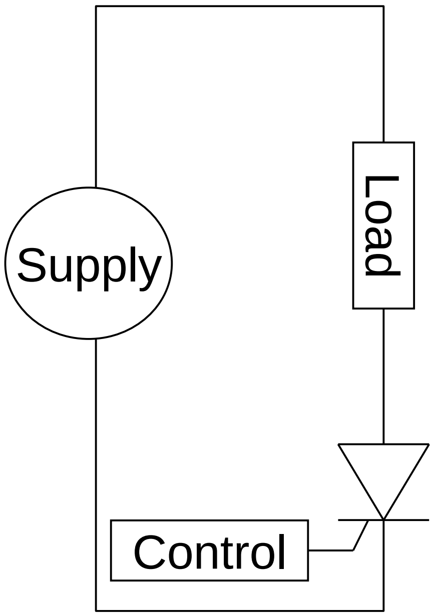
R_3 quickly biases the zener diode 齐纳二极管 into the conduction region so that the –ve input is held at 6.5V.

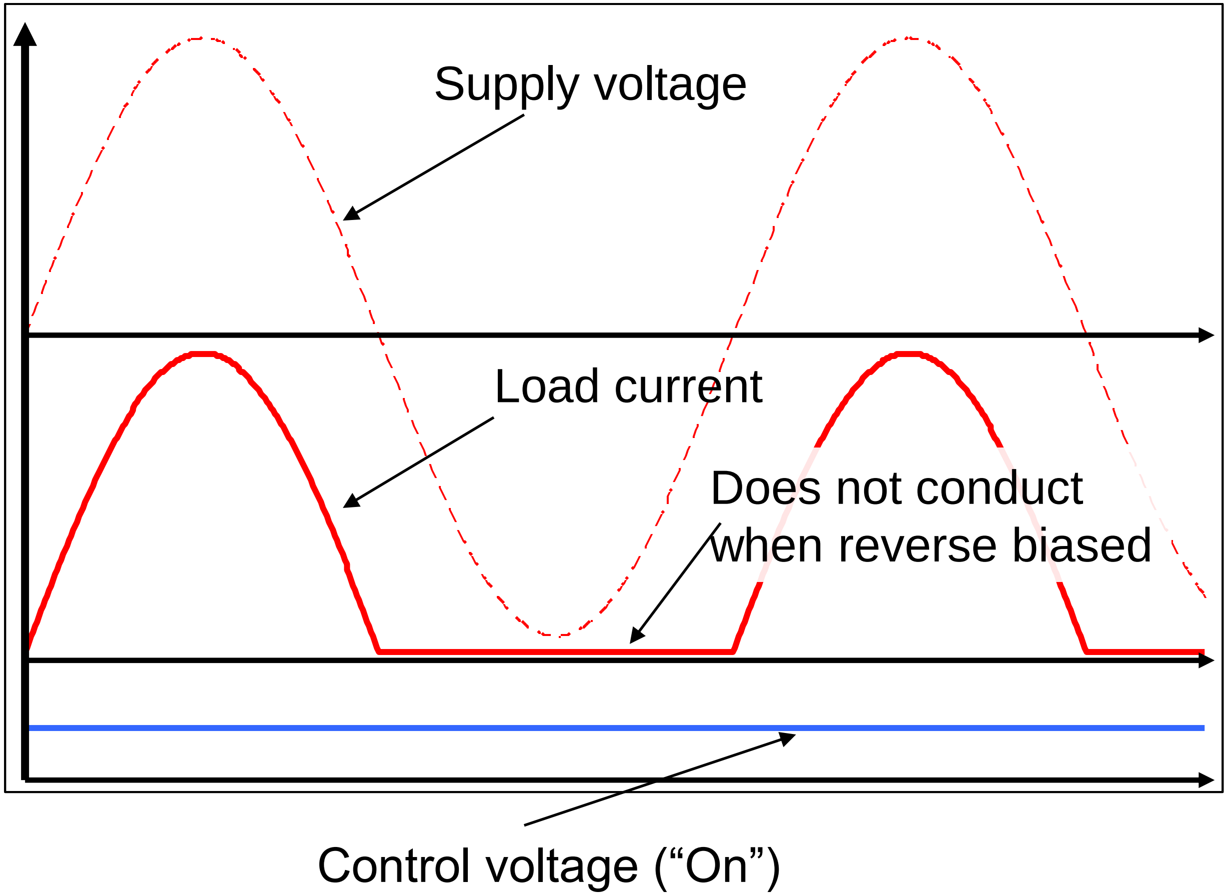


If the output voltage starts to rise, the potential divider also starts to rise but the zener voltage is fixed. When V+ is greater than V- the comparator output switches on, fires the SCR which then latches on. This presents a short circuit across the supply, protecting the load. The fuse then blows 熔断 to protect the transformer etc. After the fuse blows the SCR resets itself.

Thyrisitor Switching

The previous showed how an SCR can be used as switch in a DC circuit to protect the equipment connected to the output of a power supply. This took advantage of the fact that once an SCR is on, it stays on until the current through it falls to zero. We would also like to be able to use SCRs in AC circuits because of their huge power control capacity.

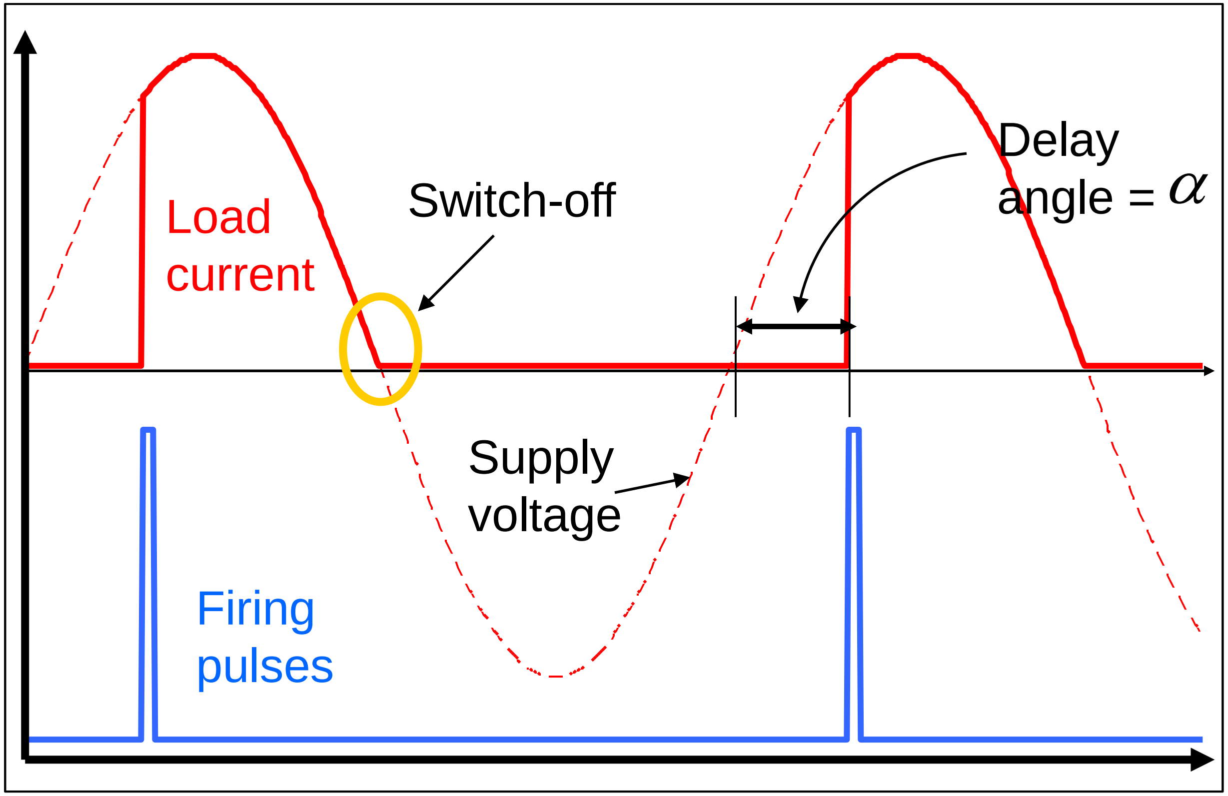




Thyristor behaving as a half-wave rectifier. The SCR turns off ("commutates"换流) automatically at the end of each positive half cycle.

Phase control of SCRs

If we delay the firing pulse 触发脉冲 for the SCR relative to the zero-crossing points, we can use the SCR as a means 手段 of regulating the power applied to the load.



The period of time before the current flows in the SCR is called the delay angle, α

Calculation of average and RMS voltages for half-wave SCR phase angle control

$$V_{AVE} = \frac{1}{2\pi}\left[\int_0^\alpha 0.d\omega t + \int_\alpha^\pi \hat{V}\sin(\omega t)d\omega t\right]$$

$$= \frac{\hat{V}}{2\pi}\left[-\cos(\omega t\right]_\alpha^\pi$$

$$= \frac{\hat{V}}{2\pi}\left[-\cos(\pi) + \cos(\alpha)\right]$$

$$= \frac{\hat{V}}{2\pi}\left[1 + \cos(\alpha)\right]$$

$$V_{RMS}^2 = \frac{1}{2\pi}\left[\int_0^\alpha 0.d\omega t + \int_\alpha^\pi \left(\hat{V}\sin(\omega t)\right)^2 d\omega t\right]$$

$$= \frac{\hat{V}^2}{2\pi}\int_\alpha^\pi\left[\frac{1}{2}\left(1 - \cos(2\omega t)\right)d\omega t\right]$$

$$= \frac{\hat{V}^2}{4\pi}\left[\omega t - \frac{1}{2}\sin(2\omega t)\right]_\alpha^\pi$$

$$= \frac{\hat{V}^2}{4\pi}\left[\pi - \alpha + \frac{1}{2}\sin(2\alpha)\right]$$

Examples

For V_{MAX} = 100V

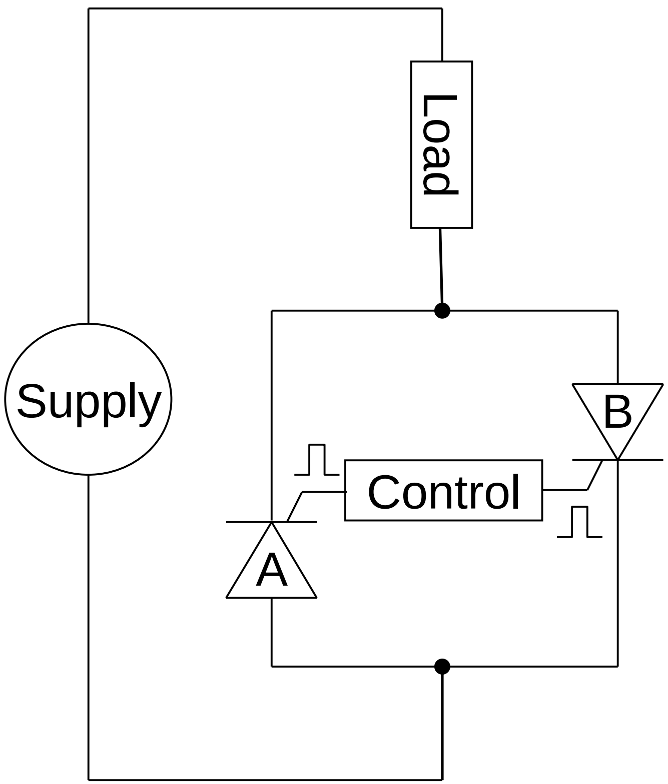
α = 45°: V_{AVE} = 27.17V, V_{RMS} = 47.67V

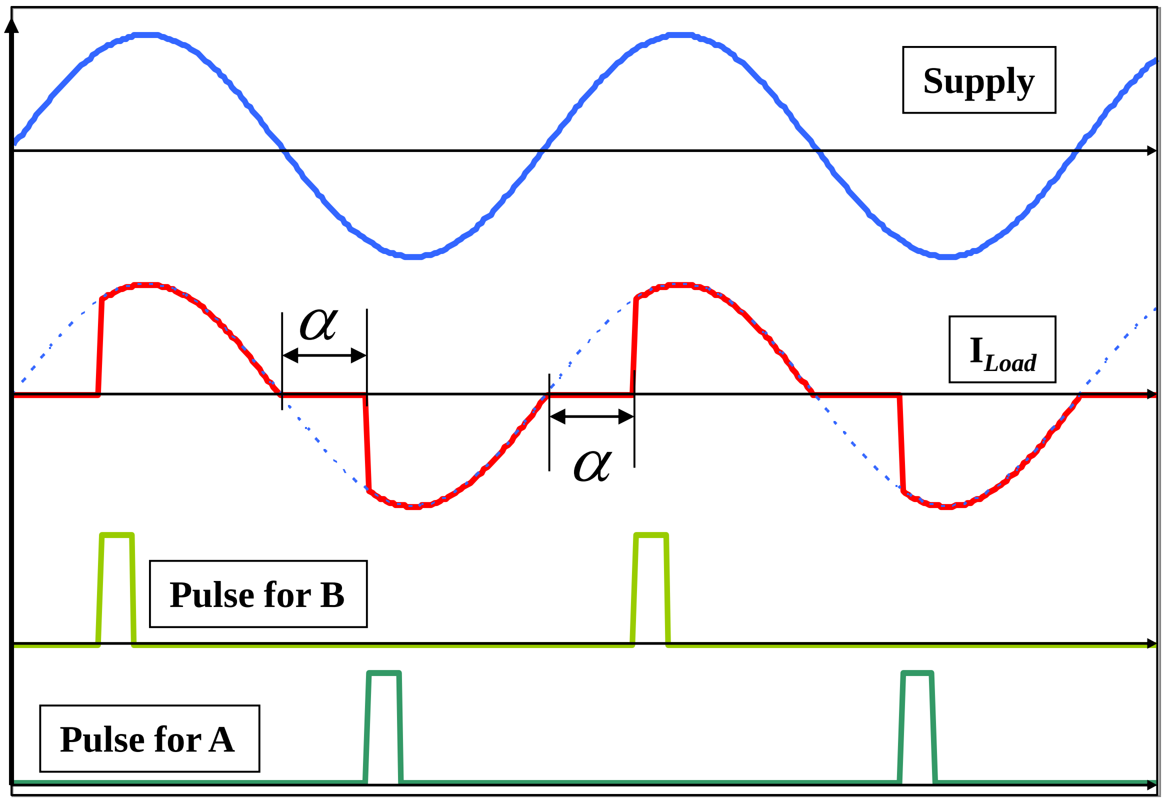
α = 90°: V_{AVE} = 15.92V, V_{RMS} = 35.36V

α = 135°: V_{AVE} = 4.66V, V_{RMS} = 15.07V

Back to back SCRs for full wave control

If we want to be able to control both halves of the mains waveform with SCRs we need to use a pair of SCRs.





By varying α we can change the firing point and therefore vary the power in the load.

Calculation of average and RMS voltages for full-wave SCR phase angle control

$$V_{AVE} = \frac{1}{\pi}\left[\int_0^{\alpha} 0.d\omega t + \int_{\alpha}^{\pi} \hat{V}\sin(\omega t)d\omega t\right]$$

$$= \frac{\hat{V}}{\pi}\left[-\cos(\omega t)\right]_{\alpha}^{\pi}$$

$$= \frac{\hat{V}}{\pi}\left[-\cos(\pi)+\cos(\alpha)\right]$$

$$= \frac{\hat{V}}{\pi}\left[1+\cos(\alpha)\right]\ ;\ 0 \le \alpha \le \pi$$

$$V_{RMS}^2 = \frac{1}{\pi}\left[\int_0^{\alpha} 0.d\omega t + \int_{\alpha}^{\pi} \left(\hat{V}\sin(\omega t)\right)^2 d\omega t\right]$$

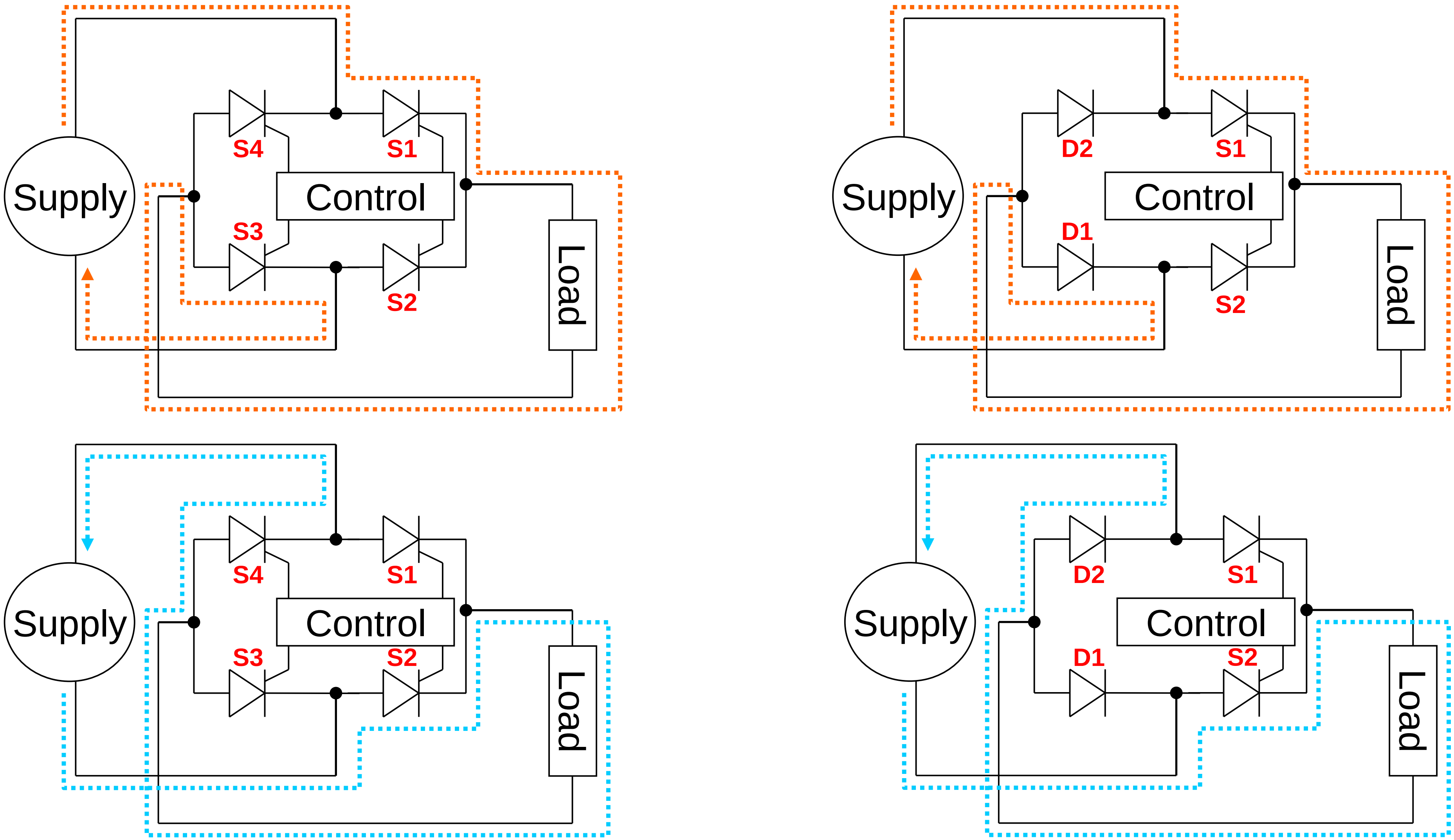
$$= \frac{\hat{V}^2}{\pi}\int_{\alpha}^{\pi}\left[\frac{1}{2}\left(1-\cos(2\omega t)\right)d\omega t\right]$$

$$= \frac{\hat{V}^2}{2\pi}\left[\omega t - \frac{1}{2}\sin(2\omega t)\right]_{\alpha}^{\pi}$$

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

Thyristor Bridges

We can replace the diodes in a bridge rectifier with a pair of (or four) SCRs:

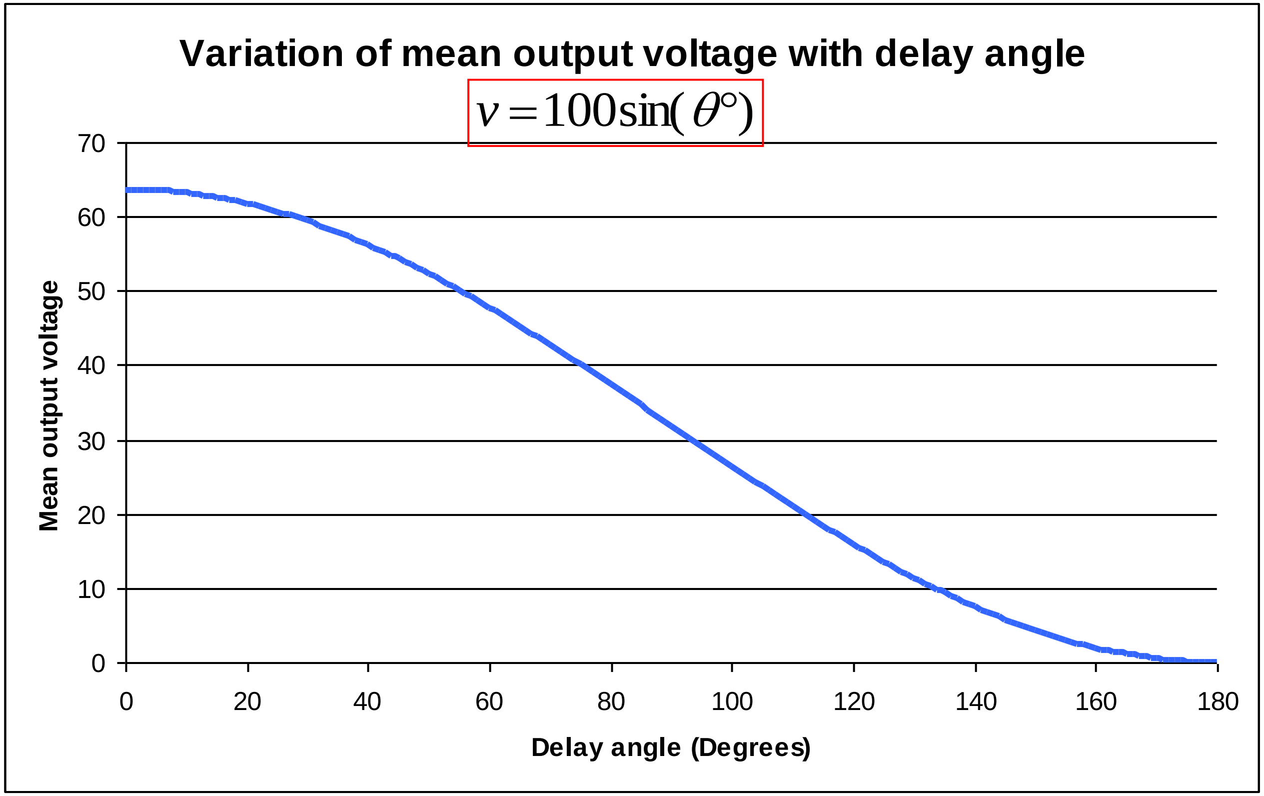


Positive & negative half-cycle current flows through SCRs and diodes.

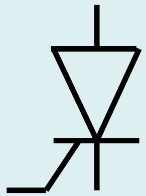
When we introduce phase control into the bridge, the average voltage is given by the integral of the waveform from the delay angle to the end of the half-cycle.

$$\boxed{V_{AVE} = \frac{\hat{V}}{\pi}\left[1 + \cos(\alpha)\right] \; ; 0 \le \alpha \le \pi}$$

The thyristor bridge allows us to vary the mean DC output voltage directly. The following chart of delay angle vs mean DC voltage is for a *resistive load only.*

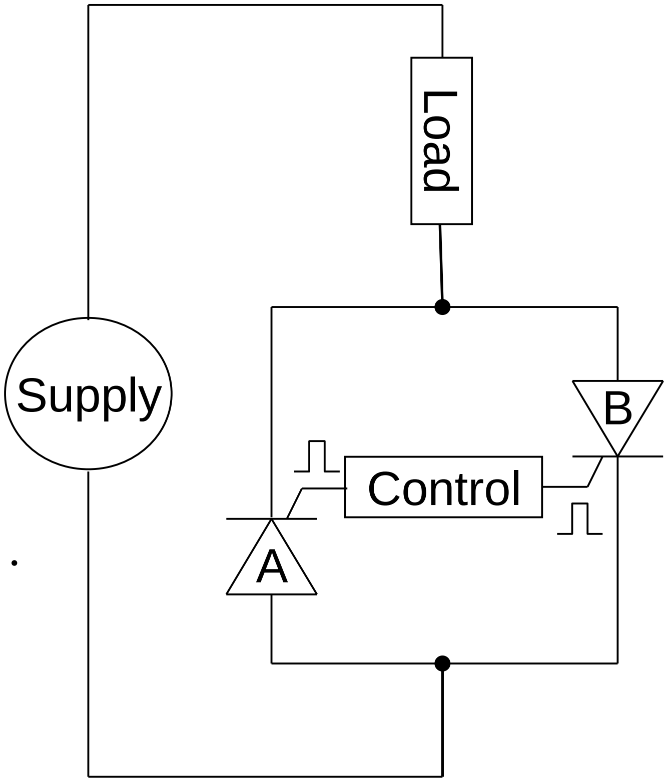


Device selection chart

Device	Symbol	Control	Power Rating	Switch speed
SCR		Partial	Very high	Slow
TRIAC & SSR				
MOSFET				
IGBT				
GTO				

Example

If V_{Supply} = 415V $_{RMS}$ and the load is a resistor of value 25Ω, what power is dissipated in the load for delay angles of 30°, 90° and 150°? What is the maximum load power when the SCRs are permanently switched on?



Maximum power = $V^2/R = 415^2 / 25$ = 6.889KW.

$$\text{For } \alpha = 30°,\ V^2_{\text{RMS}} = \frac{(415\sqrt{2})^2}{2\pi}\left[\pi - \frac{\pi}{6} + \frac{1}{2}\sin(60°)\right] = 167259.$$

$$P = \frac{V_{RMS}^2}{R} = 6690\ \text{W}$$

$$\text{For } \alpha = 90°,\ V^2_{\text{RMS}} = \frac{(415\sqrt{2})^2}{2\pi}\left[\pi - \frac{\pi}{2} + \frac{1}{2}\sin(180°)\right] = 86112.5$$

$$P = \frac{V_{RMS}^2}{R} = 3444.5\text{W}$$

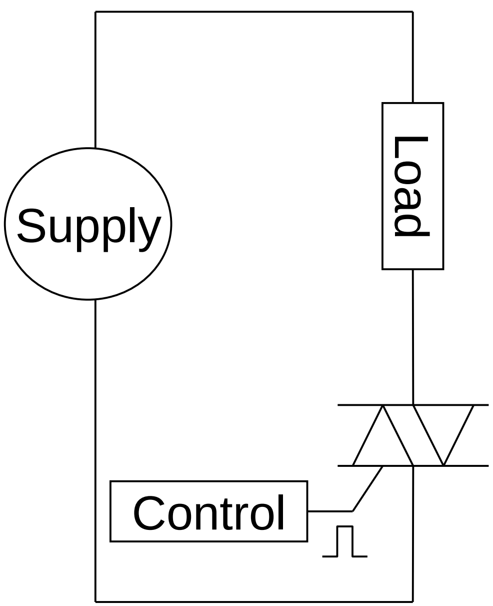
This is exactly half the full power, which makes sense since the SCRs are on for exactly half the time.

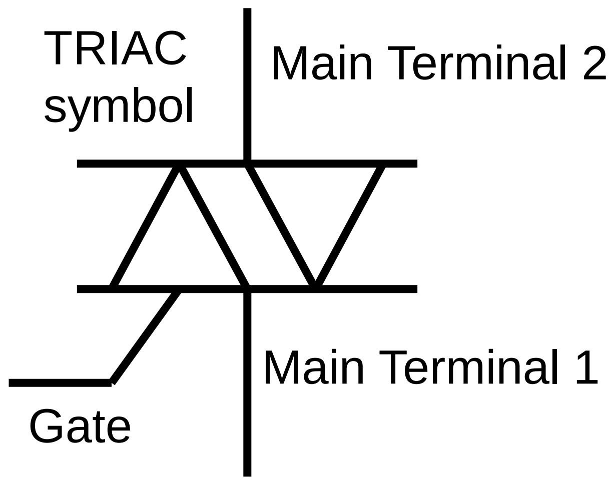
$$\text{For } \alpha = 150°,\ V^2_{\text{RMS}} = \frac{(415\sqrt{2})^2}{2\pi}\left[\pi - \frac{5\pi}{6} + \frac{1}{2}\sin(300°)\right] = 4966$$

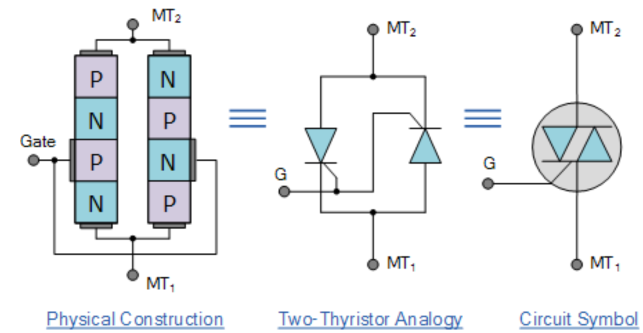
$$P = \frac{V_{RMS}^2}{R} = 198.6\text{W}$$

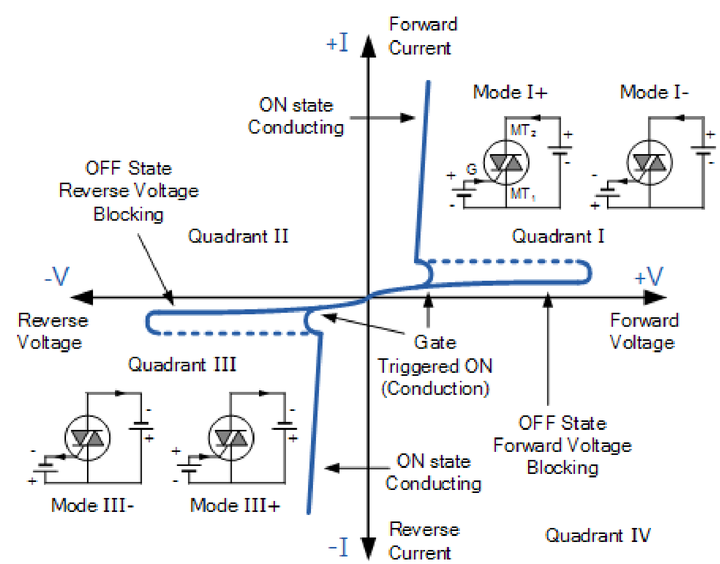
The TRIAC(triode for alternating current) 双向晶闸管

From a functional point of view the TRIAC is basically a pair of back to back 背靠背 SCRs sharing a common gate. As with the SCR, the TRIAC can be switched on by a short pulse applied to the gate. Once on, the device is latched until the current flowing through it falls to zero – usually the end of the AC half cycle.







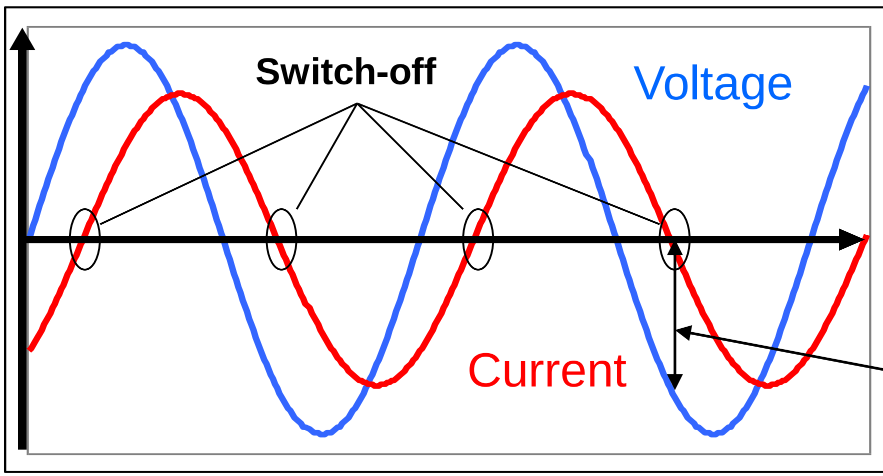


https://www.electronics-tutorials.ws/power/triac.html

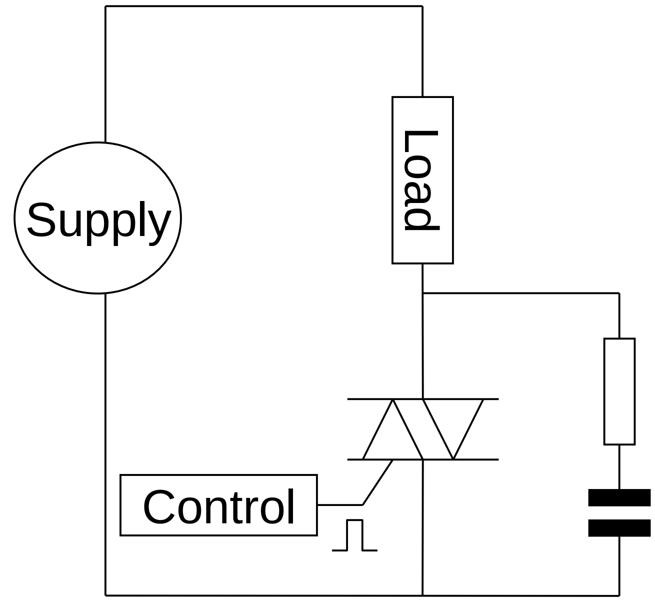
TRIACs are bidirectional devices – they can pass current in either direction. They do not have such high power ratings as the SCR. However, they are very simple to use and find application in things like dimmer 调光 switches, heater controls and the like.

The TRIAC can be turned on by either a positive or negative gate pulse, irrespective of the polarity of the main terminal voltages. Turn-on times are of the order of a few microseconds. The triggering modes are:

Mode I+	MT2 current+	Gate current +
Mode I-	MT2 current+	Gate current –
Mode III+	MT2 current -	Gate current +
Mode III-	MT2 current -	Gate current -

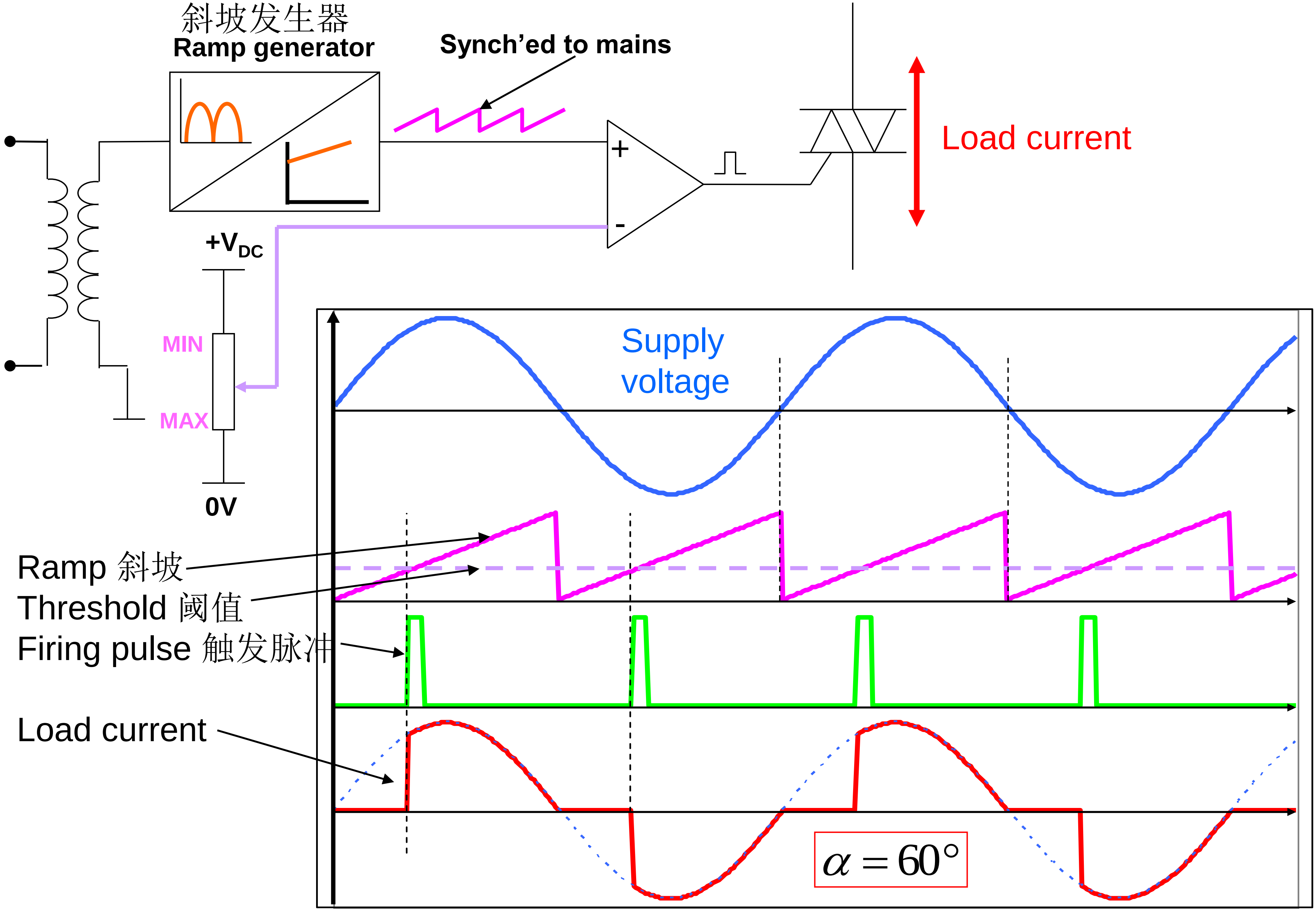


dV/dt high @ commutation



When using a TRIAC to drive an inductive load such as a motor, at each half cycle as the ***current*** falls to zero the line voltage can be quite high. The rate of change of this commutation voltage can be fast enough to interact with parasitic capacitances in the TRIAC and cause it to switch on again. This can lead to the device being permanently locked on. To circumvent this problem a RC snubber 阻容缓冲电路 should be used across the device to limit dV/dt to about 1V/μS.

Generating the firing pulse for phase control



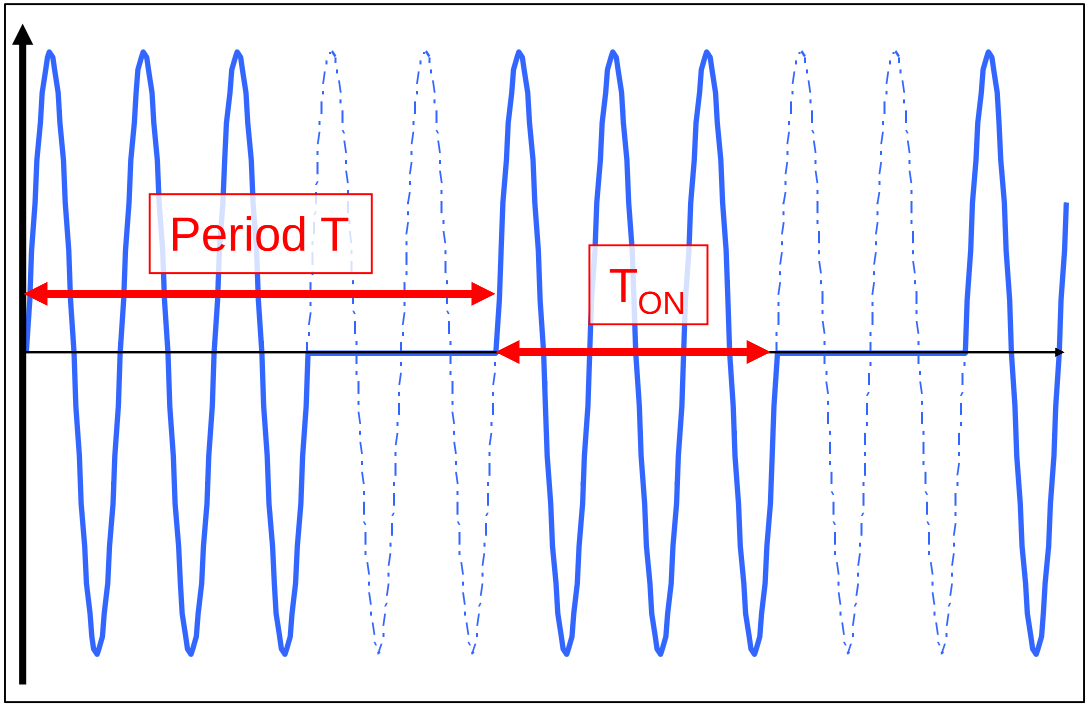
Burst control (instead of phase angle control)

Burst control is the technique where bursts of pulses are applied to the load. The ratio of the "on" time to the "period" is the duty cycle (same as before). In this instance the period is the interval over which the on/off ratio repeats itself. In the diagram below, the "on" time is 3 cycles and the "off" time is 2 cycles, so ϕ = 60%.

Note in the waveform below the power to the load is switched in complete half cycles. This is called "zero voltage switching" and is used due to Radio Frequency Interference 无线频率干扰 considerations, discussed shortly. Whether or not burst control is an appropriate way of delivering power to the load is largely a matter of the nature of a load.

A heater with a thermal time constant of many minutes is a good candidate for burst control whereas a light bulb is not – there will be significant flicker due to the filament 灯丝 heating and cooling between sets of pulses.

$$\phi = \frac{T_{ON}}{T}\ (As\ before)$$



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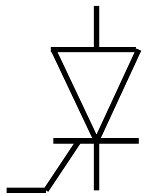
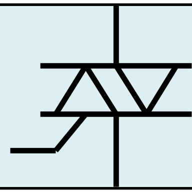
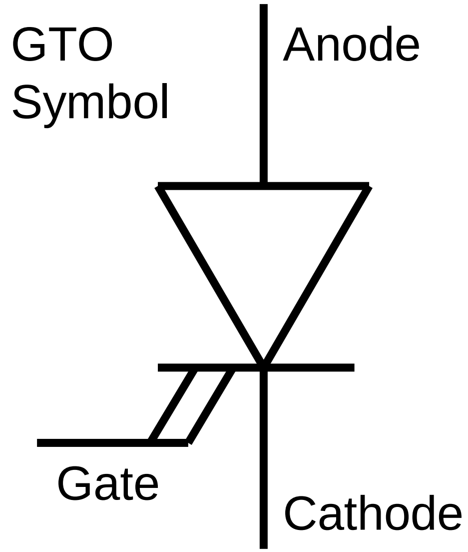
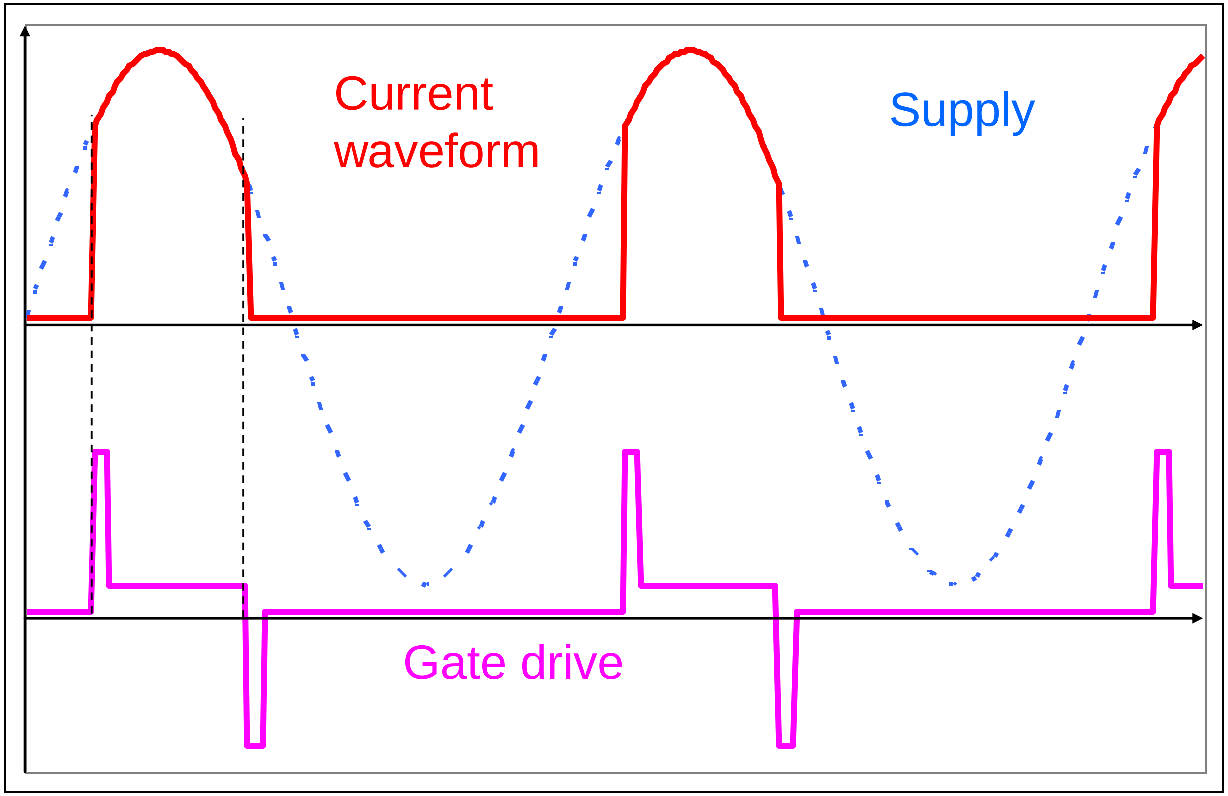
SCR		Partial	Very high	Slow
TRIAC		Partial	Medium	Slow
MOSFET				
IGBT				
GTO				

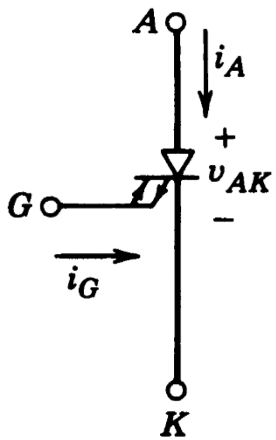
Gate turn-off Thyristors (GTOs)

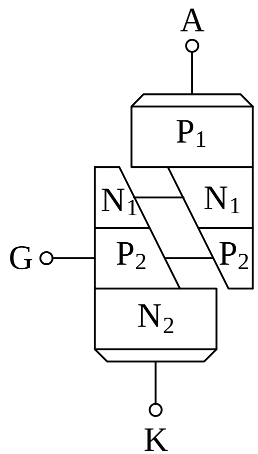
GTOs are fully controllable SCRs. To switch on a GTO a positive pulse is applied to the gate, as in th e case of the SCR. To turn off a GTO a negative pulse is applied to the gate. The turn-on of a GTO is not as reliable as an SCR (the gate sensitivity is approx 10X lower than a comparable SCR) and therefore it is usual to keep a low positive current flowing into the gate the ensure it stays on for the intended duration. GTO turn-off requires an appreciable amount of current to flow during the negative pulse and thus the drive circuitry for a GTO can be quite complex.



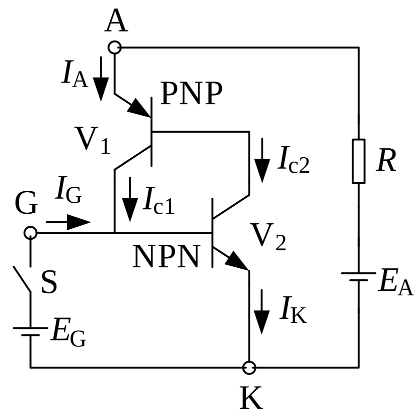


Gate-Turn-Off Thyristor (GTO)

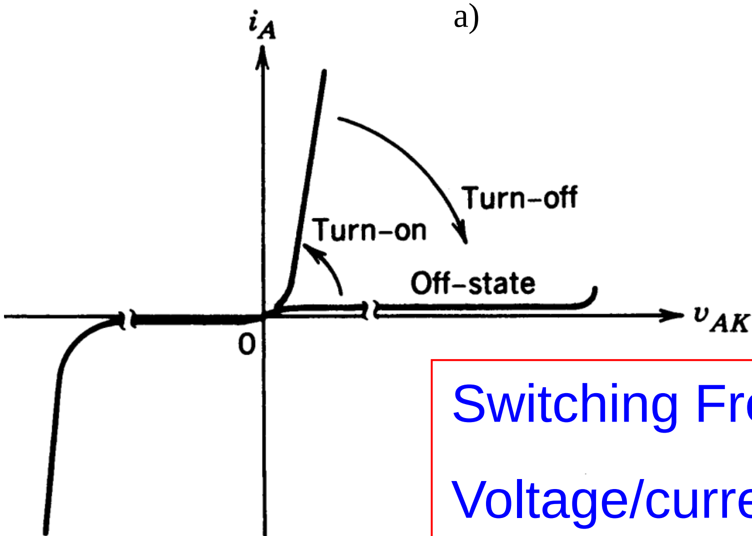




a)



b)



GTO is turned on by a short-duration i_G >0 like Thyristor, GTO can stay on (is latched on) without further gate current.

GTO can be turn off by applying a negative gate-cathode voltage V_{GK} (with i_G<0)

Switching Frequency: up to several kHz

Voltage/current rating: up to 4.5kV/ a few kilo amperes

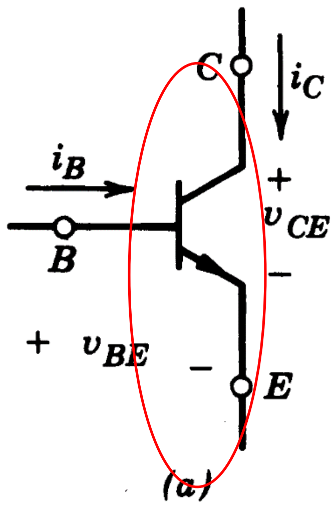
On-state voltage: 2~3V

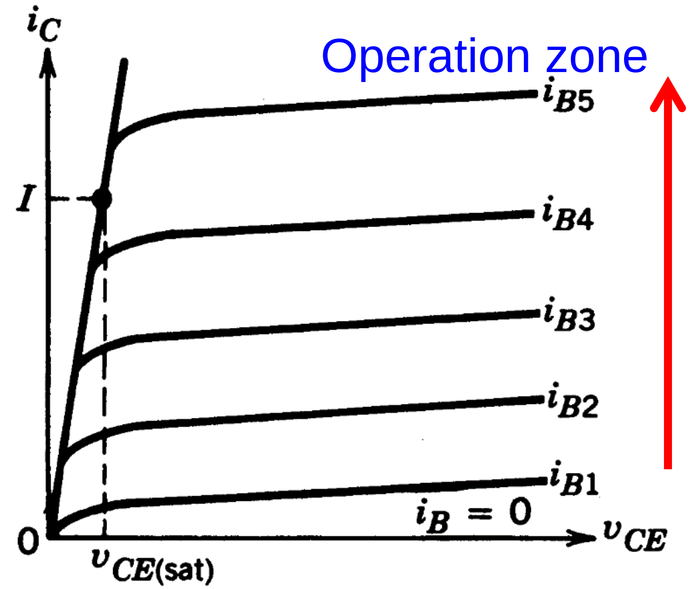
GTO turn-off is quite long, several hundred μS, and this limits the maximum switching frequency to 1KHz or less. During turn-off the voltage must be kept low to prevent over-heating and subsequent device failure. When on, the GTO has a forward voltage drop of about 3V (3X an SCR 三倍于SCR) and this poses additional challenges in keeping it cool.

Despite the difficulties in using a GTO, they are of particular value in high power inverters and DC applications such as traction motor controllers where a reverse voltage (and hence natural commutation) would never occur.

6000A / 6000V GTO (Toshiba)

Bipolar Junction Transistor (BJT or GTR)





$$I_B > \frac{I_C}{h_{FE}}$$

Now GTRs are replaced by MOSFETs, IGBTs

On-State Voltage: 1~2V

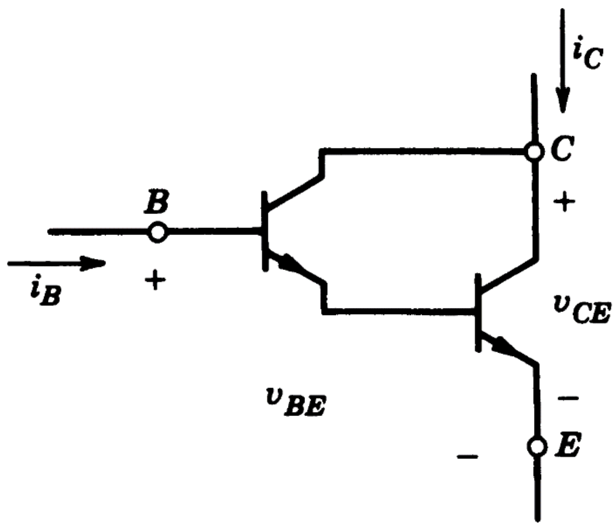
Limited Voltage/Current Rating: 1400V/several hundred A

Limited Switching Frequency: several kHz

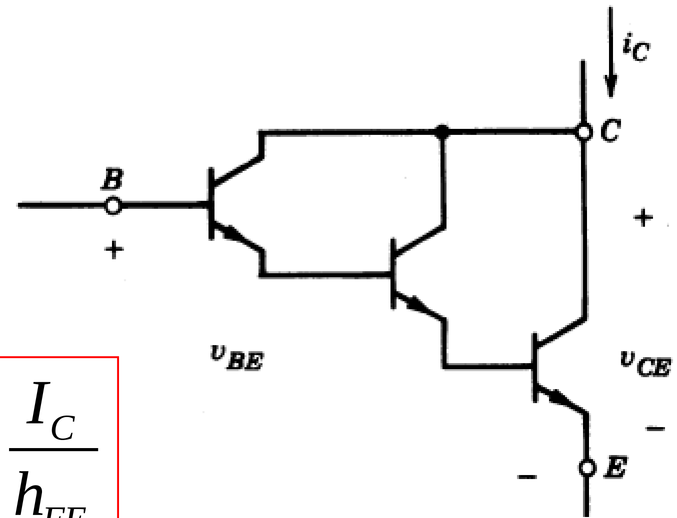
Complex current controlled drive circuit.

The letter *F* indicates that it is a forward transfer characteristic, and the letter **E** indicates it is for a common emitter configuration.

Darlington Configuration GTR

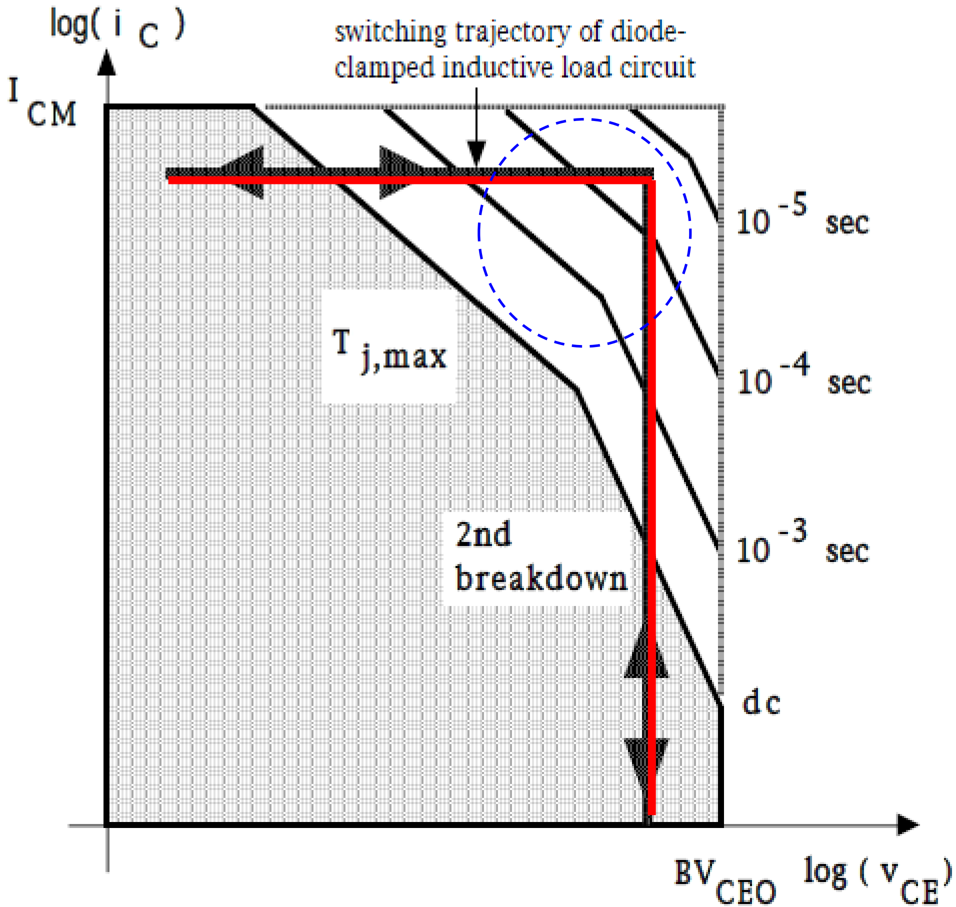


$$\boxed{I_B > \frac{I_C}{h_{FE}}}$$



BJTs are current controlled (fully-controllable) devices, base current i_B must be supplied continuously to keep them in the on state. To increase the dc current gain h_{FE} and reduce the gate current loss, BJTs usually adopt Darlington configuration达林顿结构 at cost of slightly higher $V_{CE(sat)}$ and slower switching speed. Driver circuit is also complex.

GTR Safe Operation Area
安全工作区

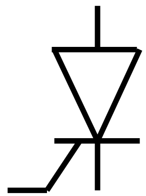
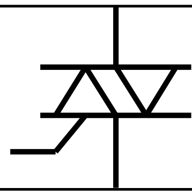
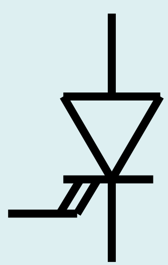


Forward bias 前置 safe operating area (FBSOA)

Snubber Circuit 缓冲电路 is needed for fully-controllable devices to shape its transient i_C-V_{CE} trajectory during the switching On/Off procedure.

Actually snubber is used to limit dv/dt and di/dt during switching transition.

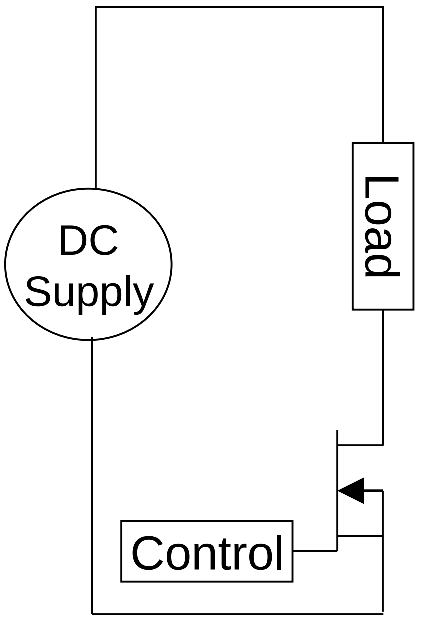
Device selection chart

Device	Symbol	Control	Power Rating	Switch speed
SCR		Partial	Very high	Slow
TRIAC & SSR		Partial	Medium	Slow
MOSFET				
IGBT				
GTO		Full	High	Slow

The MOSFET

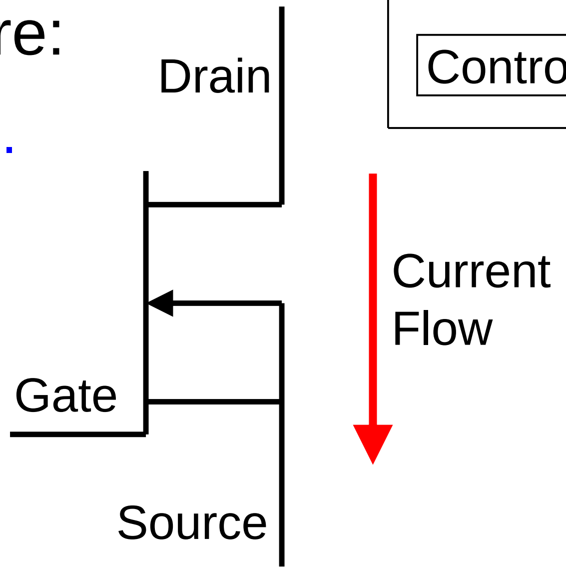
MOSFETs come in many varieties 型式 and sizes 尺寸. Some of their advantages include:

- Fast switching (10’s → 100’s nS).
- Huge power gain (Very simple gate control).
- Easily paralleled for higher current handling.



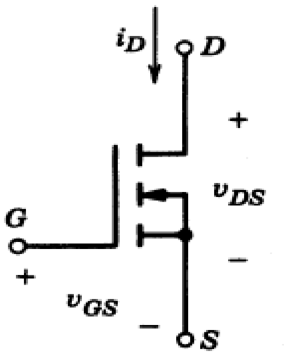
Their three main disadvantages are:

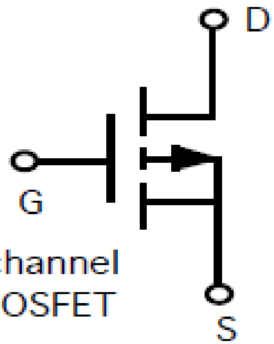
- Relatively low blocking voltage (1000V).
- Relatively low current handling (100A).
- Power dissipation can be high.



Metal Oxide Semiconductor Field-Effect Transistor (MOSFET)

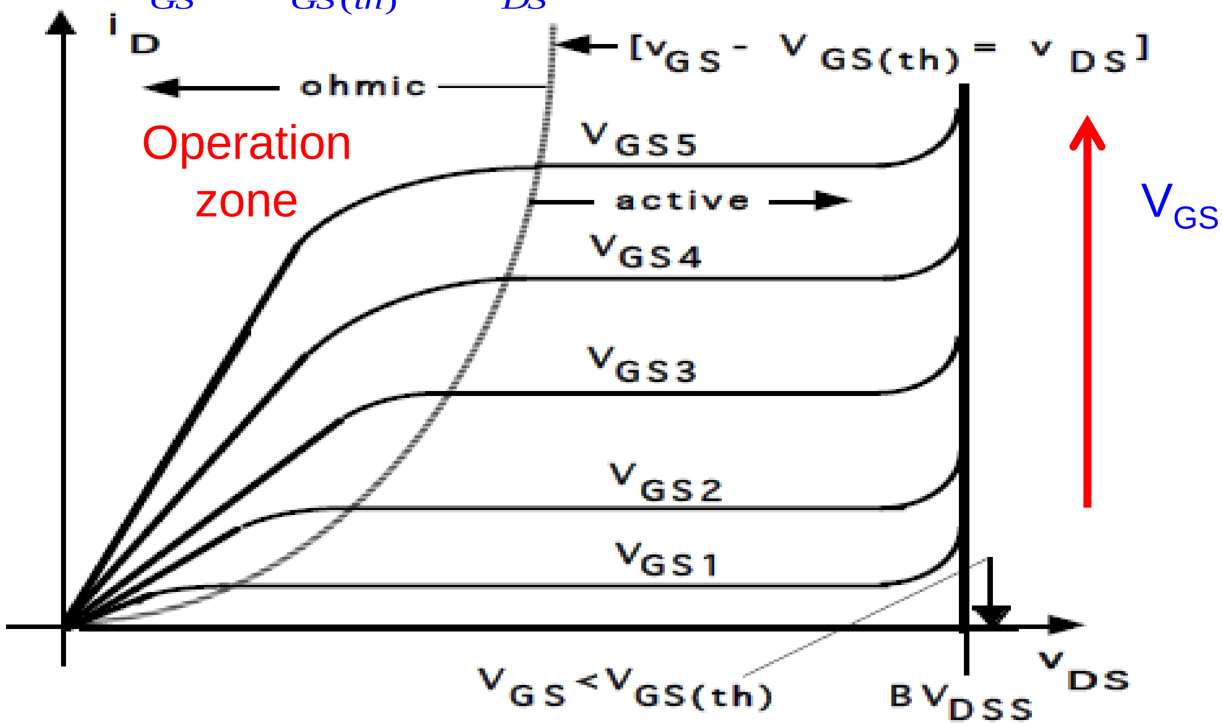
金属氧化物半导体场效应管





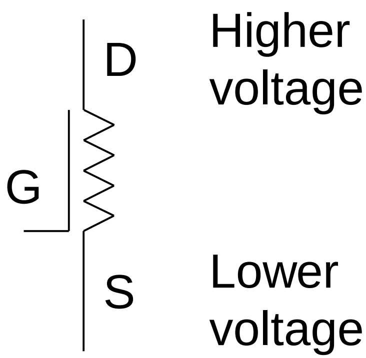
P-channel MOSFET

$$V_{GS} - V_{GS(th)} > V_{DS}$$

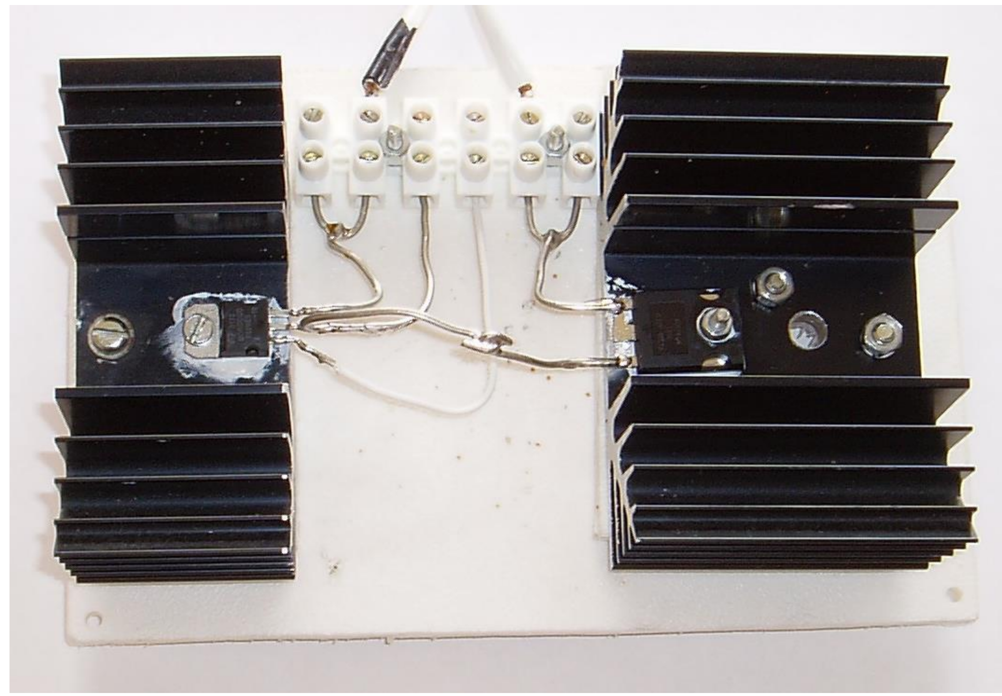


Voltage Controlled (Fully-Controllable) Device

MOSFETs can be (and often are) used for linear amplification. However, for the purposes of this course we will use them simply as **switches**. In operation, a few volts (say 5V) applied to the gate will allow a current to flow between the drain and the source. Unlike SCRs, MOSFETs can be turned on and off easily – removing the gate signal causes the MOSFET to stop conducting. **When on, the device appears as a low resistance between the drain and source**. Hence power dissipation 功率损耗 varies as I^2.



Model – “Resistor”



The fast switching speed allows MOSFETs to be used at operating frequencies of 100’s of KHz to a few MHz. As the MOSFET gets hot the resistance rises. This allows parallel operation because current is balanced amongst available devices automatically. There can be a significant capacitance between Drain & Source.

Characteristics of MOSFET

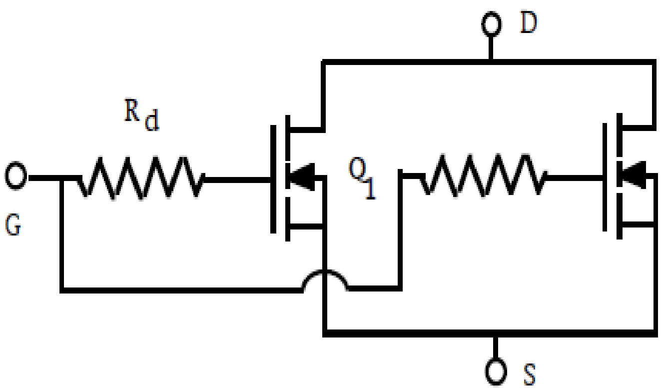
On-State Conduction Losses (Ohmic zone)

$$\boxed{p_{on} = I_d^2 r_{DS(on)}}$$

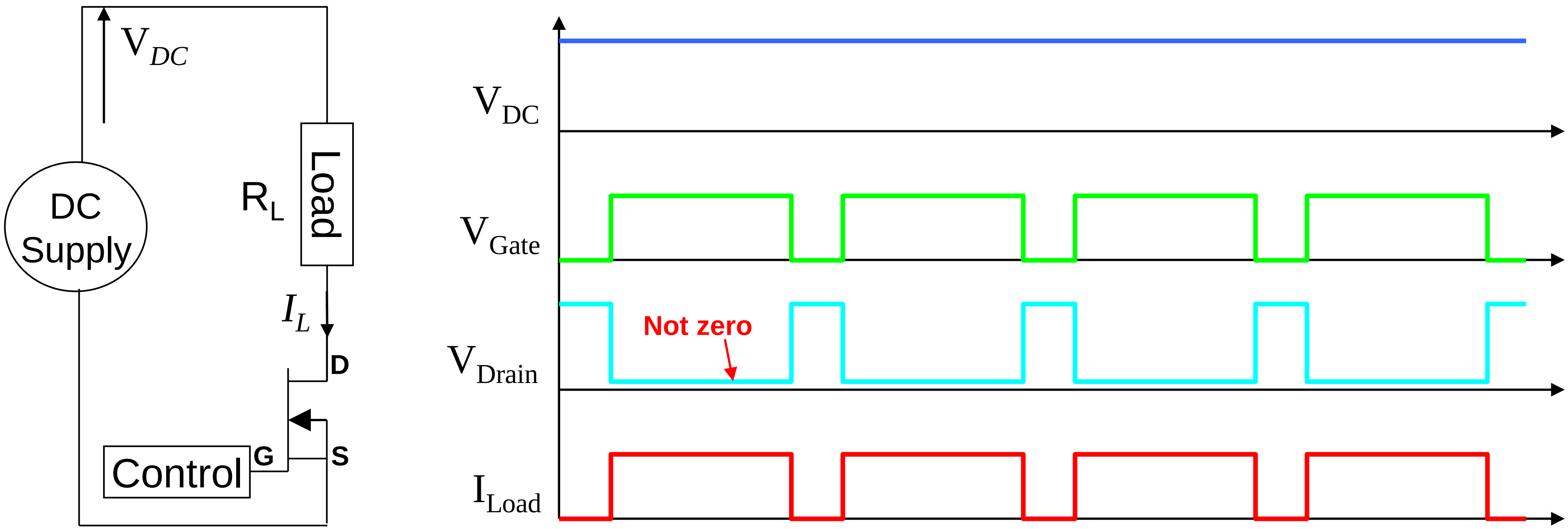
Good for synchronous rectification in low voltage applications.

$r_{DS(on)}$ is an approximated constant resistance

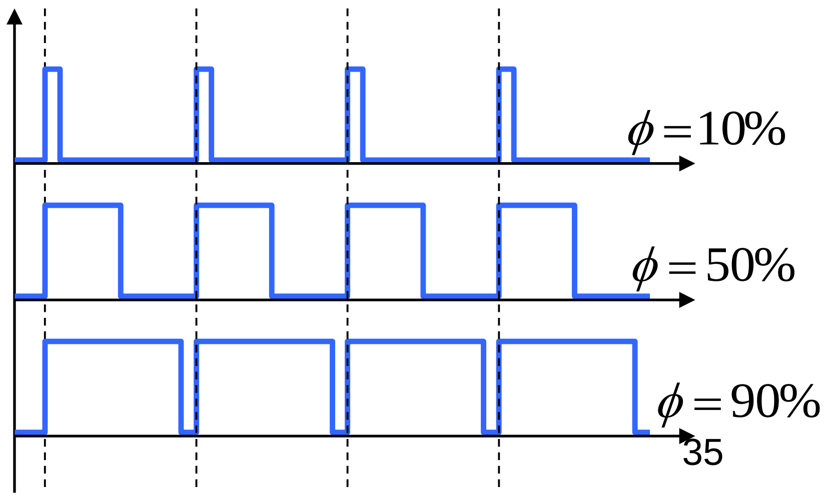
- Large V_{GS} minimizes accumulation layer resistance and channel resistance
- Positive temperature coefficient: $r_{DS(on)}$ increases as temperature increases. leads to thermal stabilization effect.
- MOSFETs can be easily paralleled due to positive temperature coefficient of $r_{DS(on)}$.



The ease with which MOSFETs can be turned on and off makes them particularly useful in DC applications.



By changing the width of the gate pulse in relation to the operating frequency we can vary the width of the current pulses in the load. This is called ***Pulse Width Modulation.***



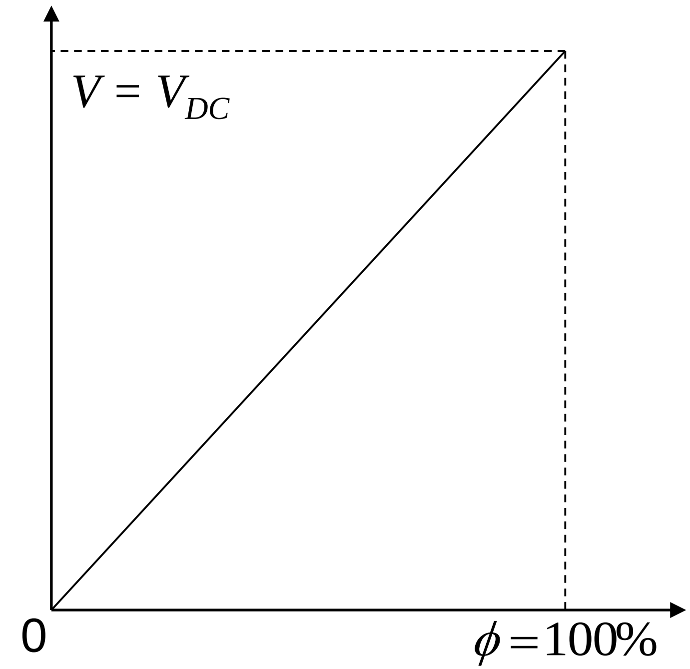
$$\text{Definition : Duty Cycle } \phi = \frac{\text{On time}}{\text{Period}}$$

We can calculate the **mean DC load voltage** as a function of the duty cycle:

$$V_{AVE} = \frac{1}{T}\int_0^T v(t)dt$$

$$= \frac{1}{T}\left[\int_0^{T_{ON}} V_{DC}dt + \int_{T_{ON}}^{T} 0dt\right]$$

$$= \frac{V_{DC}.T_{ON}}{T} = \phi.V_{DC}$$



If we plot this relationship we have a straight line. In other words, The average DC voltage is simply the supply voltage V_{DC} x the duty cycle ϕ.

Example

A heater for use with a 12V DC supply is to be designed. The heat output of the product is to be continually variable using PWM control. At 25% of the maximum setting the power output is 40W. What is the heater element resistance? (Assume a perfect switch and that there are no other power losses in the system.)

Method 1. At 25%, P = 40W therefore at 100% P = 160W.
Power = V^2 / R => R = V^2 / P = 144/160. So the resistance = 0.9Ω.

Method 2. At 25%, the mean current is P/V = 40/12 = 3.333A.

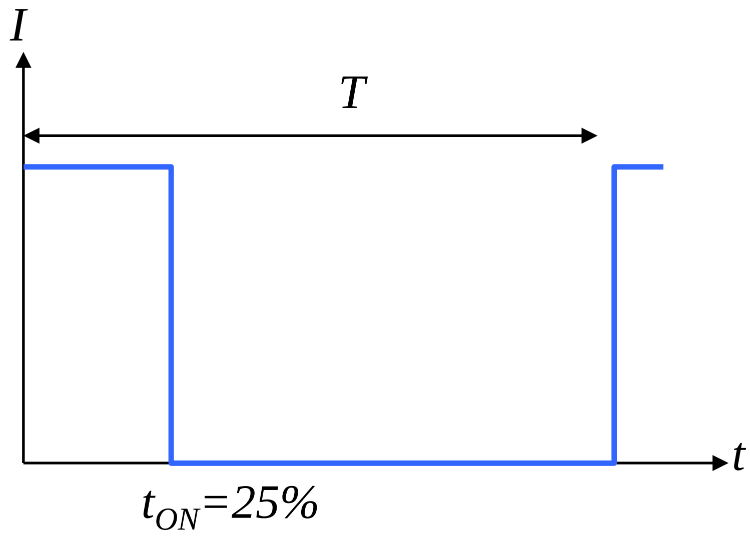
$$I_{AVE} = \frac{1}{T}\int_0^T i(t)dt. \quad \text{Pick T = 1 second to make it easy:}$$

$$I_{AVE} = \int_0^1 i(t)dt \qquad = \int_0^{0.25} i(t)dt + \int_{0.25}^1 i(t)dt$$

$$=> I_{AVE} = I_{MAX}.t\Big|_{t=0}^{t=0.25}$$

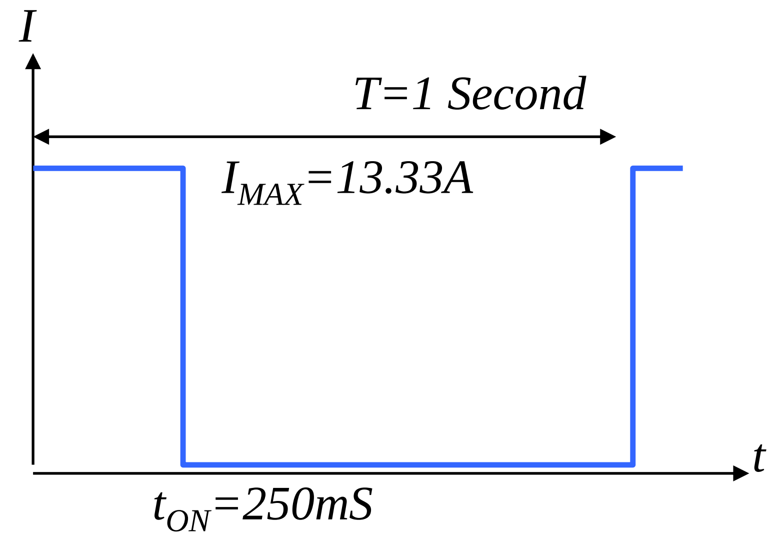
$$=> I_{MAX} = 4 \times I_{AVE} = 13.3\dot{3}A$$

$$R = \frac{V}{I} = \frac{12}{13.33} = 0.9\Omega$$



Proof of RMS being the heating value

At 25%, the RMS value of the waveform is:



$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i(t)^2\,dt}$$

$$= \sqrt{\int_0^{0.25} I_{MAX}^2\,dt + \int_{0.25}^{1} 0.dt}$$

$$= \sqrt{I^2{}_{MAX}.t\Big|_0^{0.25}}$$

$$= \sqrt{0.25 I_{MAX}^2} = \sqrt{\frac{178}{4}} = 6.6\dot{6}A$$

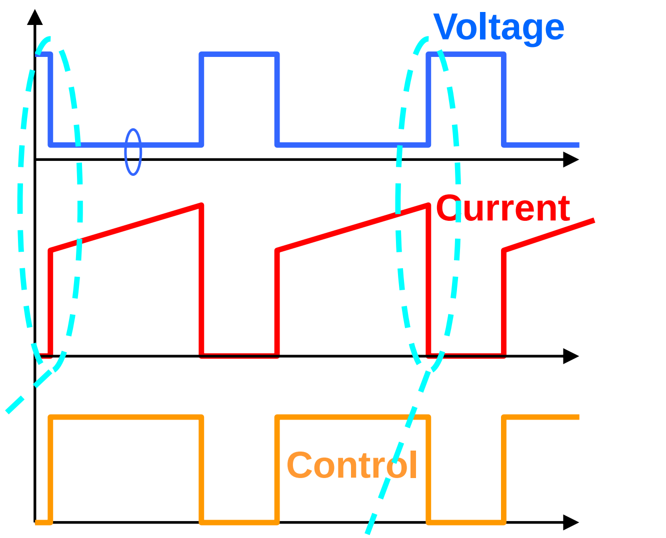
We also know $\mathrm{P = I^2R,\ R = 0.9\Omega,\ P = 40W.}$

$$\Rightarrow \mathrm{I}^2 = \frac{\mathrm{P}}{\mathrm{R}} = \frac{40}{9} = 44.\dot{4}$$

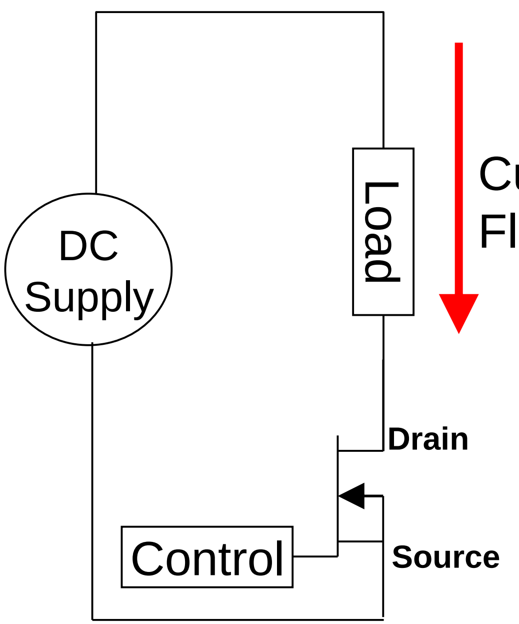
$$\Rightarrow \mathrm{I_{RMS}} = 6.6\dot{6}\ \mathrm{Amps}$$

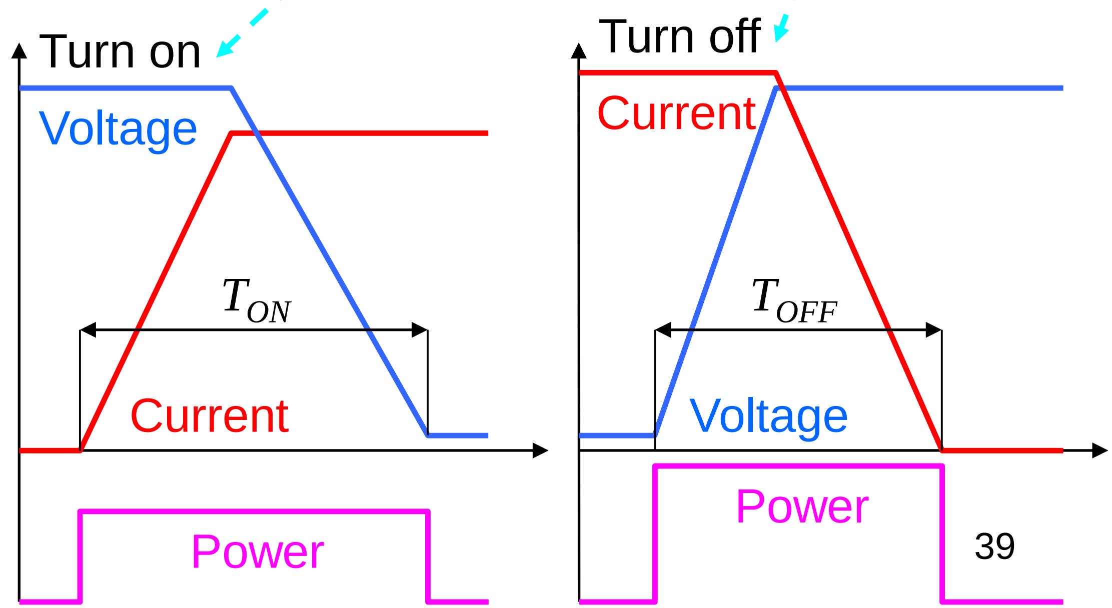
The MOSFET switching loss needs to be carefully considered: there are two switching edges for each cycle of the periodic waveform.

At switch-on, V_{DS} falls to a low value determined by I_{ON} and the equivalent resistance $R_{DS\ ON}$.



When driving inductive loads, the current through the switch will not usually be a constant value during the cycle.





Power dissipation in MOSFETs

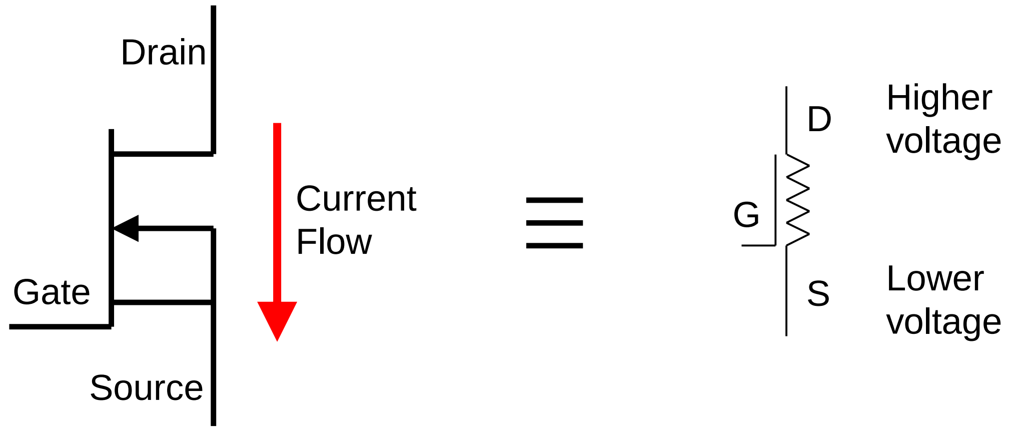
There are two main power loss mechanisms in a MOSFET:

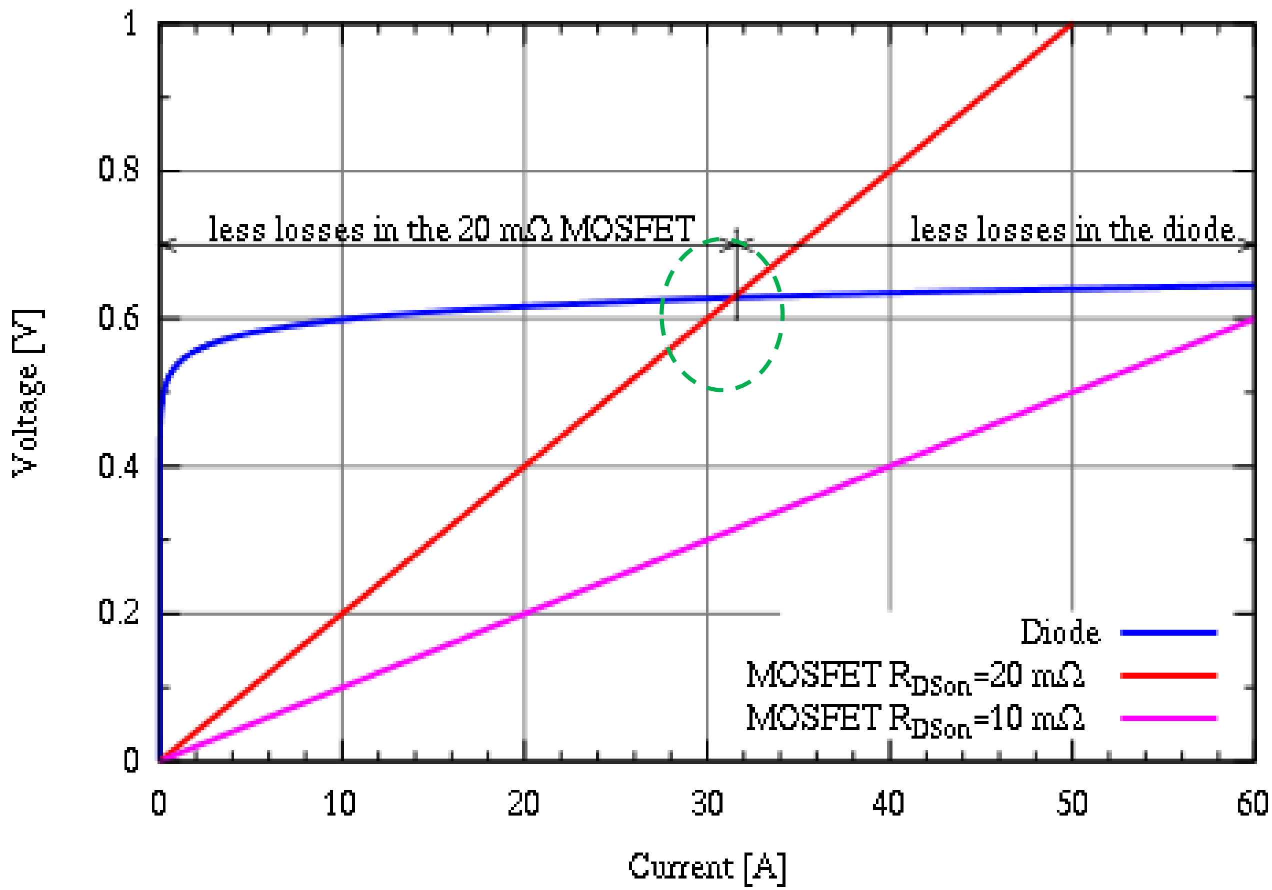
Power loss = Conduction loss + Switching loss

The conduction loss is the I^2R loss due to the load current flowing through the equivalent resistance between the drain and source. This depends directly on the duty cycle the switch is operating at.

Calculate the RMS load current to include the duty cycle. (See example in a few pages time.)

$$P_{Conduction} = I^2_{Load\,RMS} R_{DS\,ON}$$

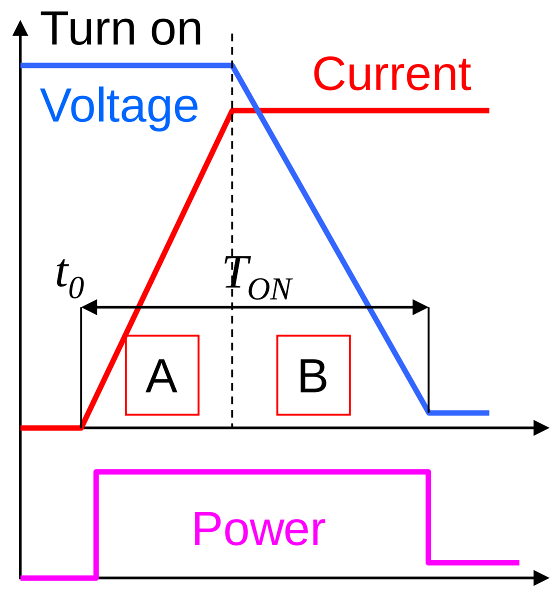




MOSFET is not suitable for high power applications !!!

- In the low current flow range, the voltage drop across the MOSFET is less than the almost constant voltage drop across diode/GTR/SCR, the conduction power loss of MOSFET is less than that of Diode/SCR/….
- Voltage and Current ratings are only up to 1kV and several hundred Amperes.

During turn-on, at switching event t_0 the current through the FET starts to rise towards the “on” value. During this period (A) the voltage across the FET ($V_{DS\ (Off)}$) is essentially constant. Once the current reaches the “on” value, the voltage across the switch then starts to fall (B) to the conduction value, determined by $R_{DS\ ON}$. When this value is reached the FET is in the “on” state. The time for this sequence of events to happen, T_{ON}, is specified in the device’s data sheet. A typical value is 25nS.



During ‘A’, V_{DS} is constant at $V_{DS\ (Off)}$ and I_{Ave} = ½ I_{ON} => $E_A = ½ I_{ON} V_{DS\ (Off)} T_A$.

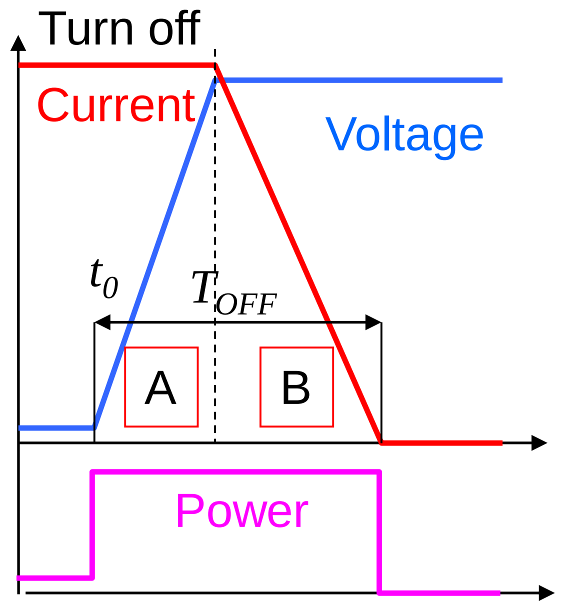
During ‘B’ I_{ON} is constant and $V_{DS\ AVE}$ = ½$V_{DS\ (Off)}$ => $E_B = ½ I_{ON} V_{DS\ (Off)} T_B$.

The energy during the switching event is thus $E_A + E_B = ½ I_{ON} V_{DS\ (Off)} T_{ON}$.

The total power per second for switch-on is given by:

$$\boxed{\text{Total "on" power} = \frac{1}{2}\left(F_{SW}.T_{ON}.I_{ON}.V_{DS(Off)}\right)}$$

During turn-off, at switching event t_0 the voltage across the FET starts to rise towards the “off” value $V_{DS\ (Off)}$. During this period (A) the current through the FET (I_{OFF}) is essentially constant at the value just before the turn-off event started. <u>Note this is unlikely to be the same as</u> I_{ON}. Once the voltage reaches the “off” value, the current through the switch then starts to fall (B) to zero. When this value is reached the FET is in the “off” state. The time for this sequence of events to happen, T_{OFF}, is specified in the device’s data sheet. A typical value is 30nS.



During ‘A’ I_{OFF} is constant and $V_{DS\ AVE} = ½V_{DS\ (Off)}$ => $E_A = ½I_{OFF}V_{DS\ (Off)}T_A$.

During ‘B’, V_{DS} is constant at $V_{DS\ (Off)}$ and $I_{Ave} = ½\ I_{OFF}$ => $E_B = ½I_{OFF}V_{DS\ (Off)}T_B$.

The energy during the switching event is thus $E_A + E_B = ½I_{OFF}\ V_{DS\ (Off)}T_{OFF}$.

The total power per second for switch-off is given by:

$$\boxed{\text{Total "off" power} = \frac{1}{2}\left(F_{SW}.T_{OFF}.I_{OFF}.V_{DS(Off)}\right)}$$

The total switching loss for the MOSFET is the sum of the ON and OFF losses:

$$\boxed{P_{Switching} = \left(\frac{F_{SW} \cdot V_{DS(Off)}}{2}\right)\left(T_{ON}.I_{ON} + T_{OFF}.I_{OFF}\right)}$$

We can now calculate the total power loss in the MOSFET due to the conduction and switching losses.

Remember $\boxed{P_{Conduction} = I_{Load\,RMS}^{2} R_{DS\,ON}}$

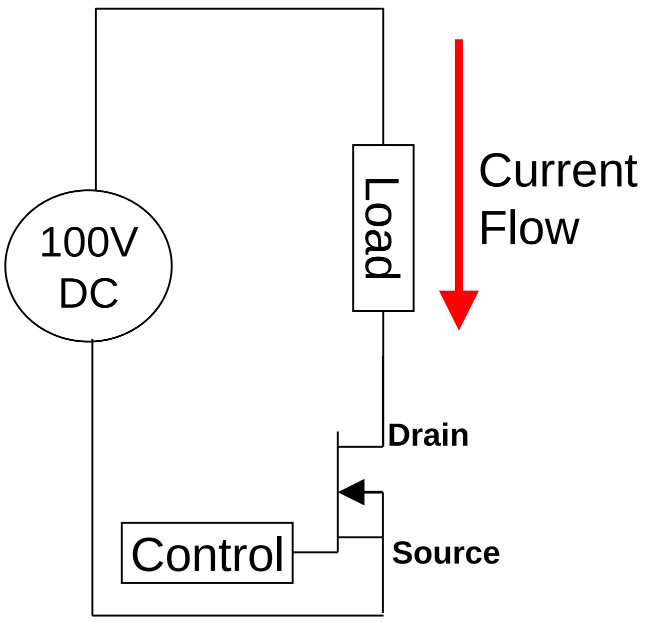
$$\boxed{P_{Total} = I_{Load\,RMS}^{2} R_{DS\,ON} + \left(\frac{F_{SW} \cdot V_{DS(Off)}}{2}\right)\left(T_{ON}.I_{ON} + T_{OFF}.I_{OFF}\right)}$$

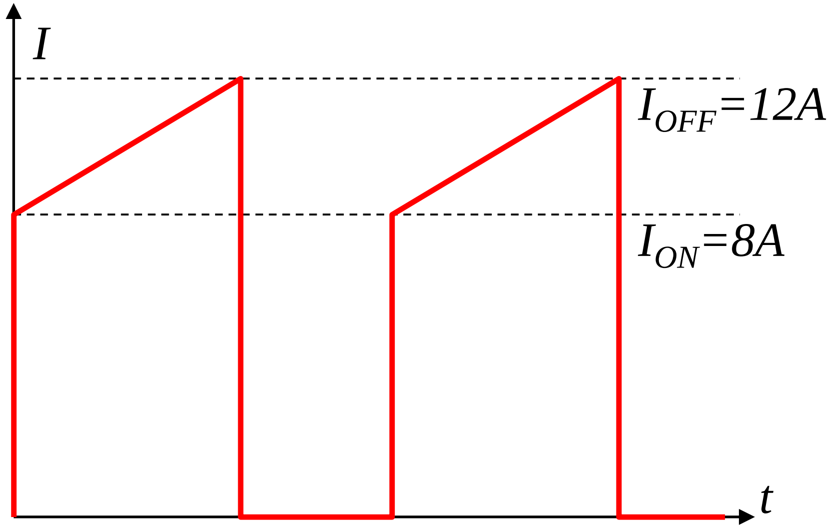
From data sheet

Example

Using the following data, determine the power loss in the MOSFET.

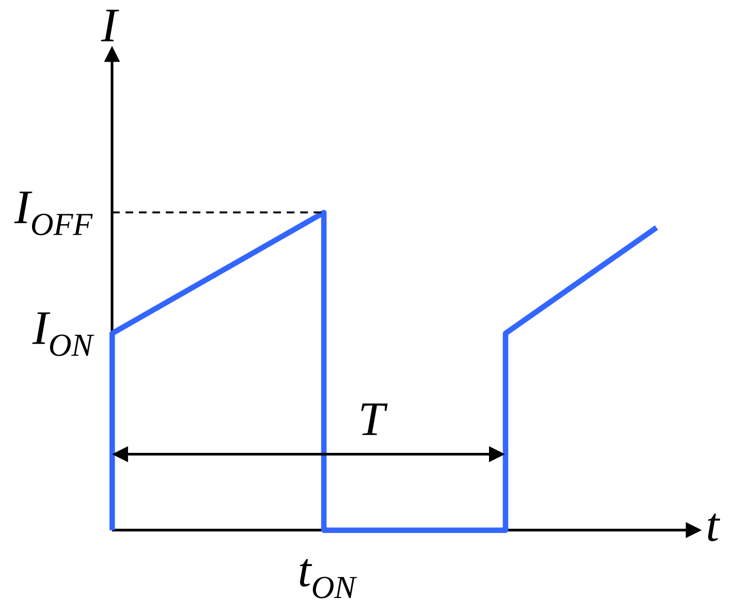
I_{ON}	8A
I_{OFF}	12A
PWM Duty	60%
PWM Freq	50KHz
Supply	100V DC
R_{ON}	50mΩ
T_{ON}	25nS
T_{OFF}	30nS





PWM period = 20μS
On time = 12μS
Off time = 8μS

Step 1 - Calculation of RMS current for the conduction loss.



Current function $: i(t) = I_{ON} + \frac{(I_{OFF} - I_{ON})t}{t_{ON}}; 0 < t \le t_{ON}$

$$(i(t))^2 = I_{ON}^2 + \frac{2I_{ON}(I_{OFF} - I_{ON})t}{t_{ON}} + \frac{(I_{OFF} - I_{ON})^2 t^2}{t_{ON}^2}$$

$$I_{RMS}^2 = \frac{1}{T}\int_0^{t_{ON}} \left[I_{ON}^2 + \frac{2I_{ON}(I_{OFF} - I_{ON})t}{t_{ON}} + \frac{(I_{OFF} - I_{ON})^2 t^2}{t_{ON}^2} \right] dt$$

$$= \frac{1}{T}\left[I_{ON}^2 .t + \frac{I_{ON}(I_{OFF} - I_{ON})t^2}{t_{ON}} + \frac{1}{3}\cdot\frac{(I_{OFF} - I_{ON})^2 t^3}{t_{ON}^2} \right]_0^{t_{ON}}$$

$$= \frac{t_{ON}}{T}\left[I_{ON}^2 + I_{OFF}.I_{ON} + \frac{1}{3}\cdot\left(I^2{}_{OFF} - 2I_{OFF}.I_{ON} + I^2{}_{ON} \right) \right]$$

$$= \frac{\phi}{3}\left[I^2{}_{OFF} + I_{OFF}.I_{ON} + I^2{}_{ON} \right]$$

For I_{ON} = 8A, I_{OFF} = 12A and ϕ = 60%, I_{RMS}=7.8A

$$\boxed{P_{Conduction} = I_{Load\,RMS}^2 R_{DS\,ON}}$$

=> $P_{Conduction} = 7.8^2 \times 50m\Omega = 3.042W$

Step 2 – calculation of switching loss.

$$P_{Switching} = \left(\frac{F_{SW} . V_{DS(Off)}}{2} \right) \left(T_{ON} . I_{ON} + T_{OFF} . I_{OFF} \right)$$

$$= \left(\frac{50KHz \times 100V}{2} \right) (25nS \times 8A + 30nS \times 12A)$$

$$= 1.4W$$

Step 3 – calculate total power loss

Power loss = Conduction loss + Switching loss

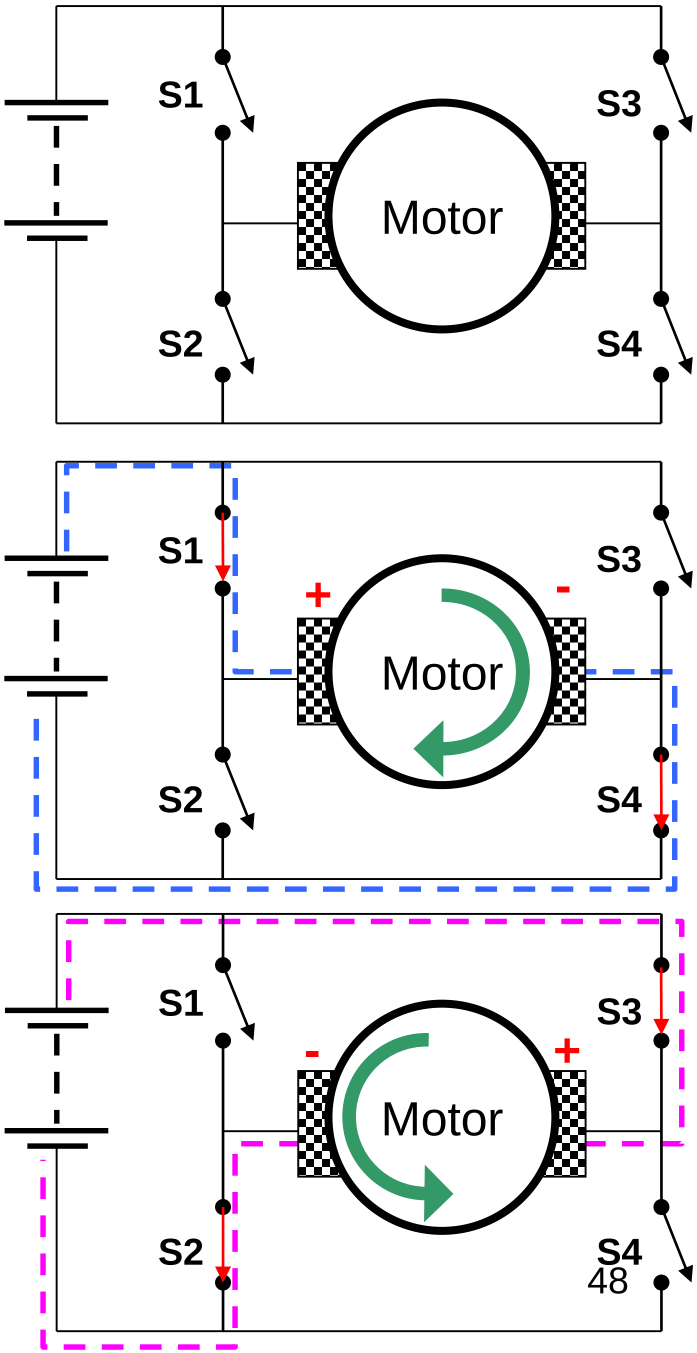
= 3.04W + 1.4W = 4.44W

The ‘H’ Bridge

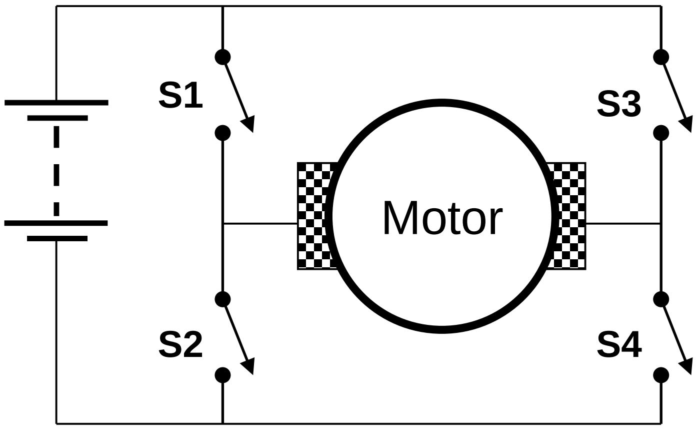
The H bridge is a useful circuit made up of a set of 4 switches. It is used to switch the direction of a motor and is often found in robotic systems, car electric window controls, and so on.

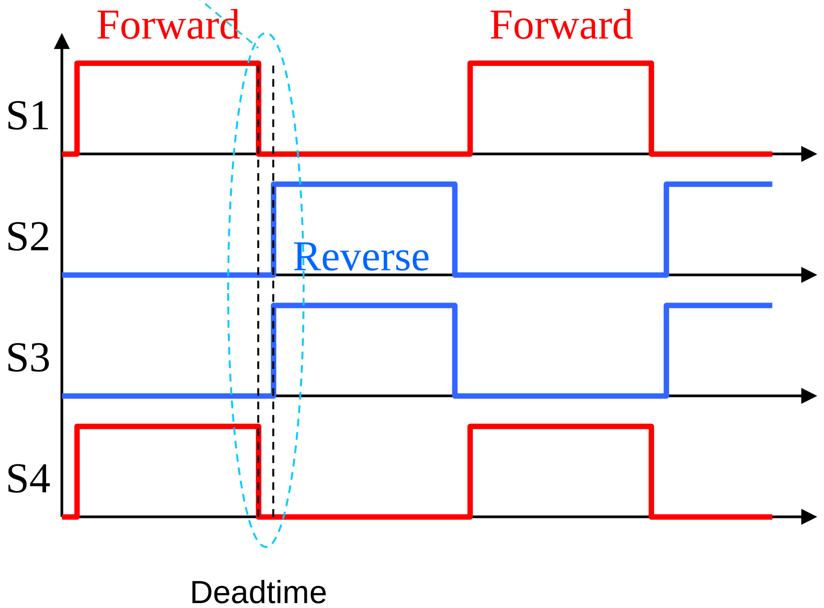
These circuits are used so often nowadays that the control circuitry for driving the gates of MOSFET switches, including the delay logic and a few other useful things are available as in integrated circuit.

In operation the switches are closed in diagonally 对角线 opposite pairs and thus each motor terminal may be connected to either side of the supply. In one configuration the motor will run clockwise and in the other it will run anticlockwise. [With all switches open the motor obviously will stop.]

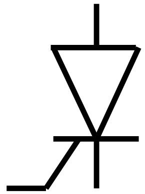
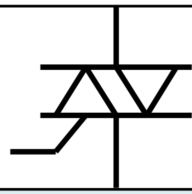
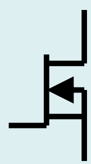
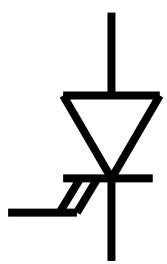


If both the high-side and low-side switches are closed simultaneously a short circuit will be imposed across the supply – a condition called "*shoot-through*"直通. This condition should be avoided at all costs. In practise a short delay is introduced during switching to prevent this.

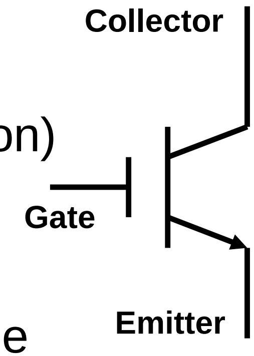




Device selection chart

Device	Symbol	Control	Power Rating	Switch speed
SCR		Partial	Very high	Slow
TRIAC & SSR		Partial	Medium	Slow
MOSFET		Full	Medium	Fast
IGBT				
GTO		Full	High	Slow

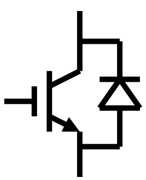
Insulated Gate Bipolar Transistor (IGBT)



IGBTs are medium to high power switches that can operate very quickly with high current and a low "on" voltage. The latest devices (3rd generation) are extremely robust and tolerant of overloads. The IGBT gate drive requirements are very similar to those of a MOSFET.

Rather conveniently the typical application reverse blocking voltage range for the IGBT starts more or less where the MOSFET starts to struggle. IGBTs are rarely used in application where the reverse voltage is less than 600V.

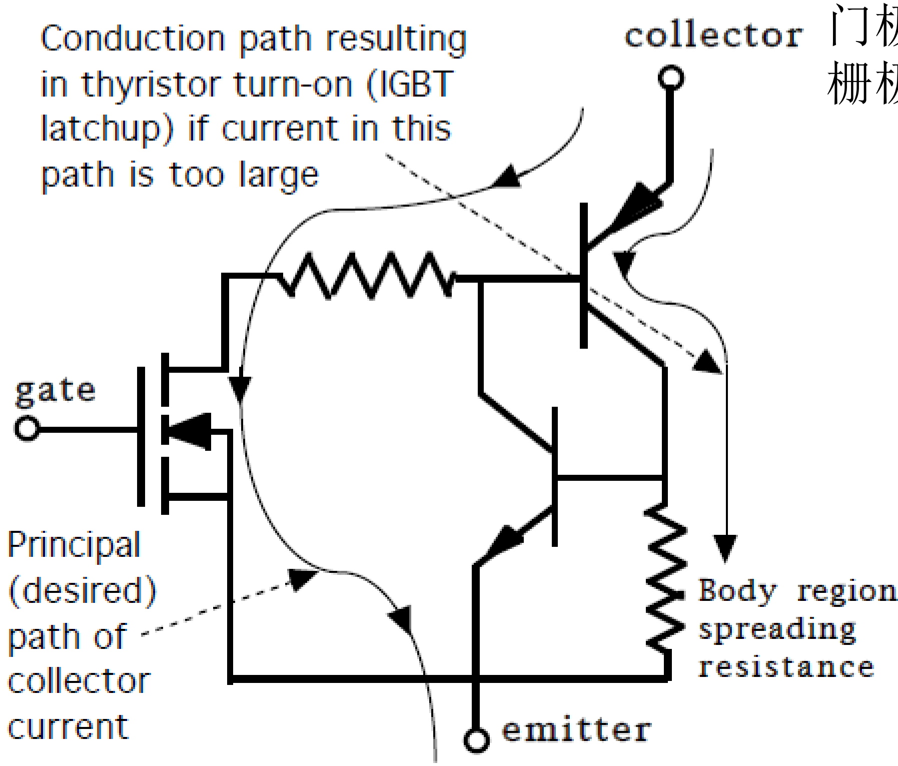
IGBTs can only conduct current in one direction. If current has to flow in the opposite direction then an external diode must be used in inverse parallel with the device. This is sometimes called a "flyback" 反激 diode or a "free-wheeling" diode 续流二极管 (from its first use in television sets).



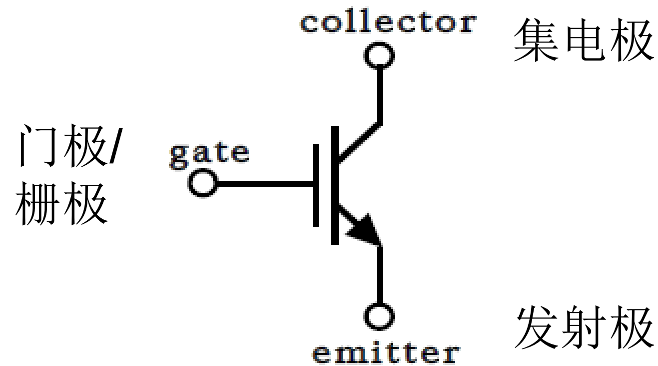
The Toyota Prius hybrid electric car uses IGBTs in its regenerative inverter drive.

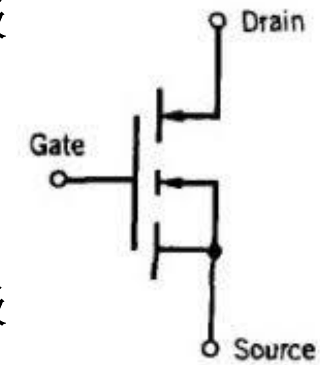
[The car has been declared a hazard to the visually impaired because it is so quiet.]

IGBT - Hybrid Switch



N-channel IGBT Equivalent Circuit

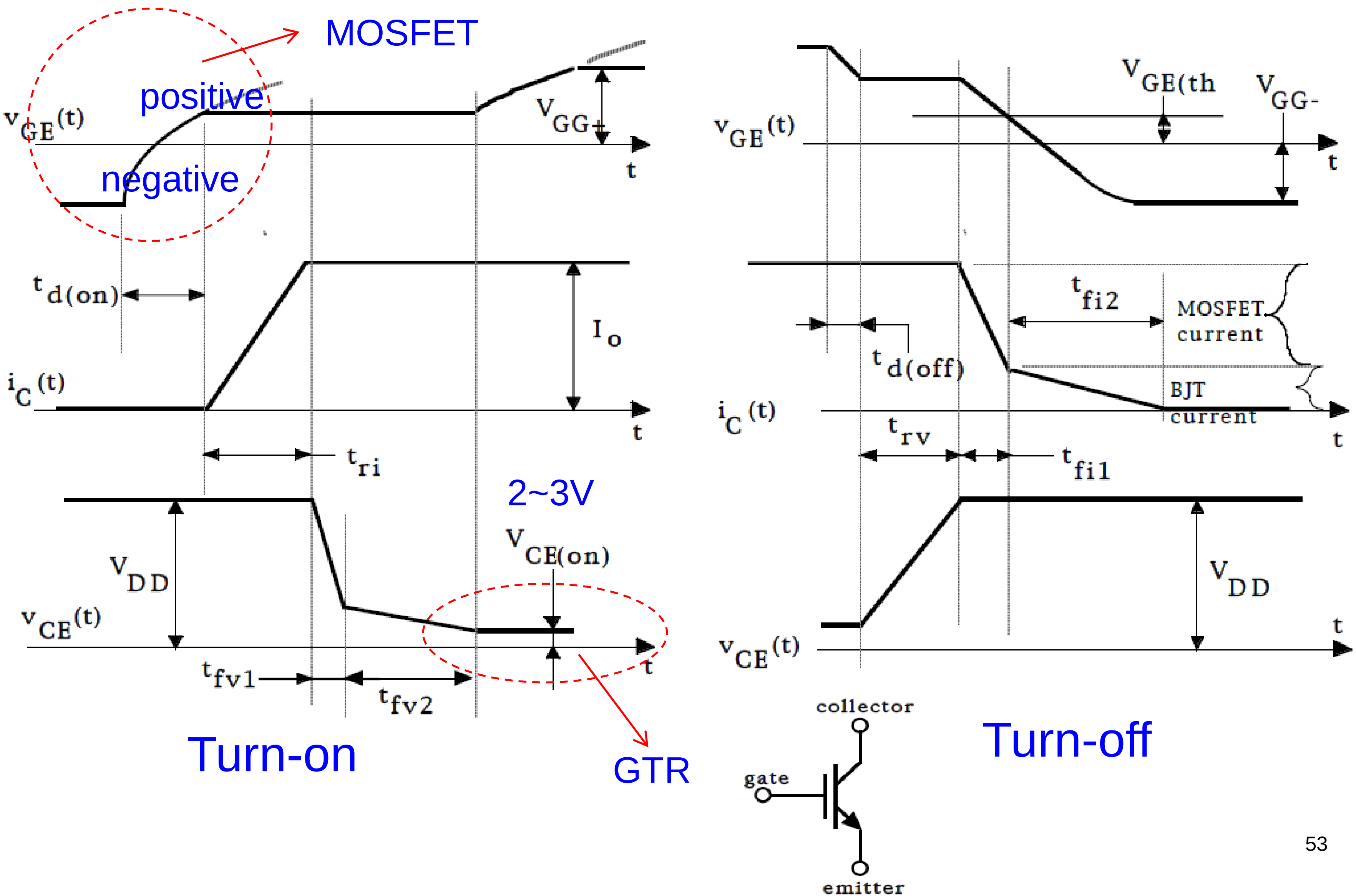




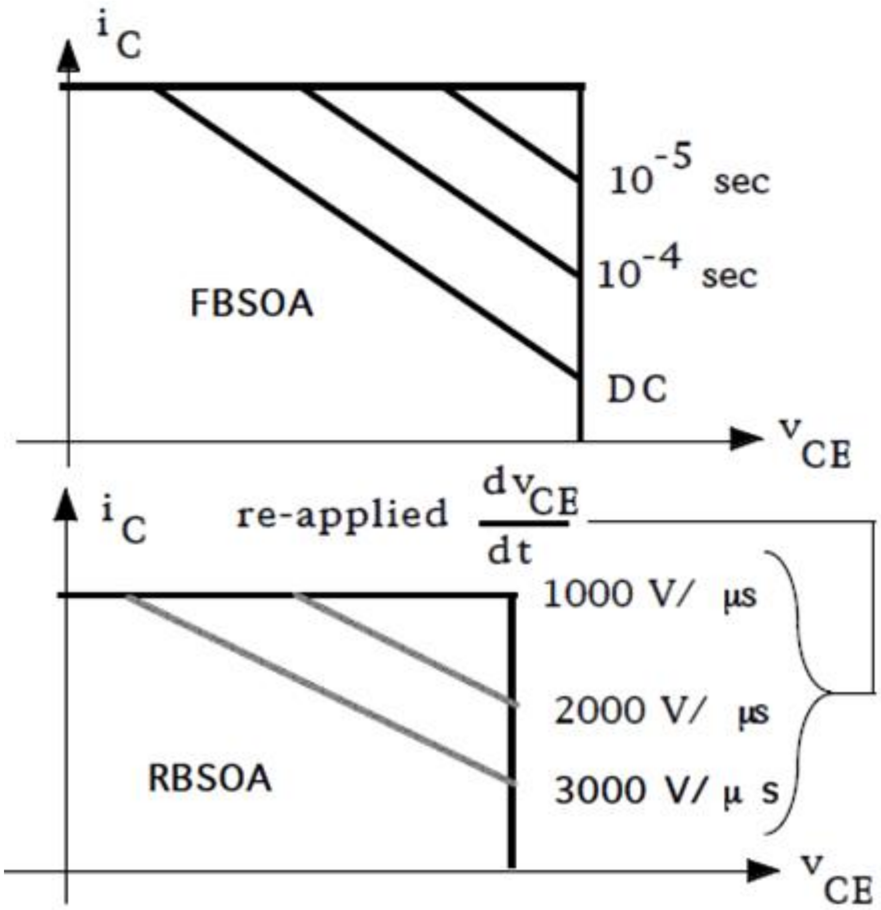
N-channel IGBT

- Gate Voltage V_{GE} Controlled Device like MOSFET
- Turn-on V_{CE} like GTR: 2~3V

Turn On/Off of IGBT



SOA for IGBT



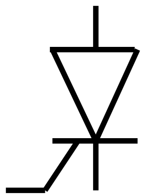
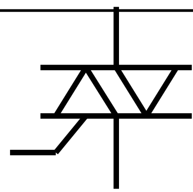
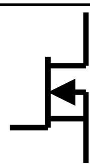
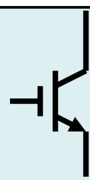
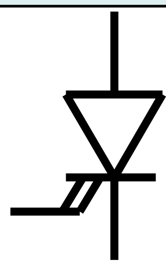
Voltage/current ratings of IGBT, MOSFET and BJT in SOA and datasheets are peak values, not average or rms value

Snubber circuits are needed to shape i-v curve for IGBT during switching transition.

1 Forward Biased Safe operating area(FBSOA)-during turn on
2. Reverse Biased Safe Operating Area(RBSOA)-during turn off

*Too large a value of *dV_{CE}/dt* is during turn-off will cause latchup the IGBT

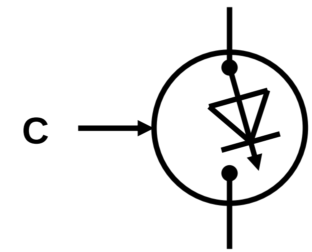
Device selection chart

Device	Symbol	Control	Power Rating	Commutation	Supply Type	Switch speed
SCR		Partial	Very high	Natural	AC	Slow
TRIAC & SSR		Partial	Medium	Natural	AC	Slow
MOSFET		Full	Medium	Self	DC	Fast
IGBT		Full	High	Self	DC	Medium
GTO		Full	High	Self	AC/DC	Slow

Commutation 换流

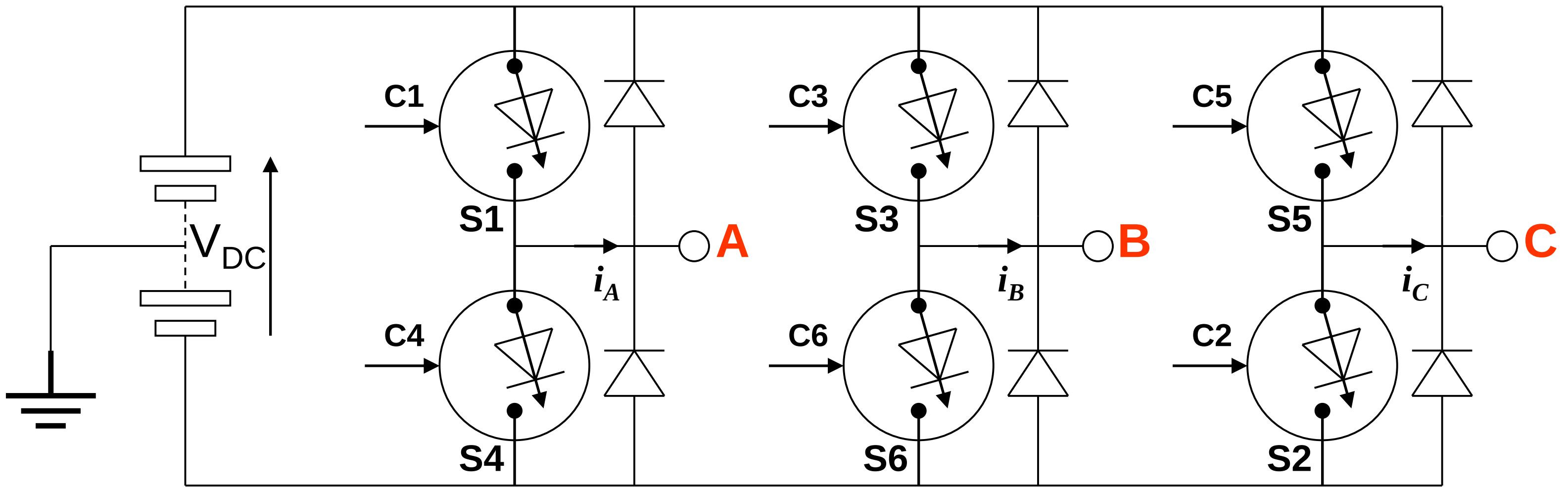
Often we want to specify in circuit schematics the operation of the device, rather than the device itself. A good example is the *self-commutated* 自换流 semiconductor switch. Devices which are fully controlled by their control input (MOSFET, IGBT, GTO, etc.) fall into this category. SCRs and TRIACs are *naturally commutated* 自然换流– cannot be switched off under gate control – and therefore are not self-commutated.

The symbol for a self-commutated switch is:
The control signal (voltage or current drive) is connected at 'C'. The diode shows the direction in which the current can flow.

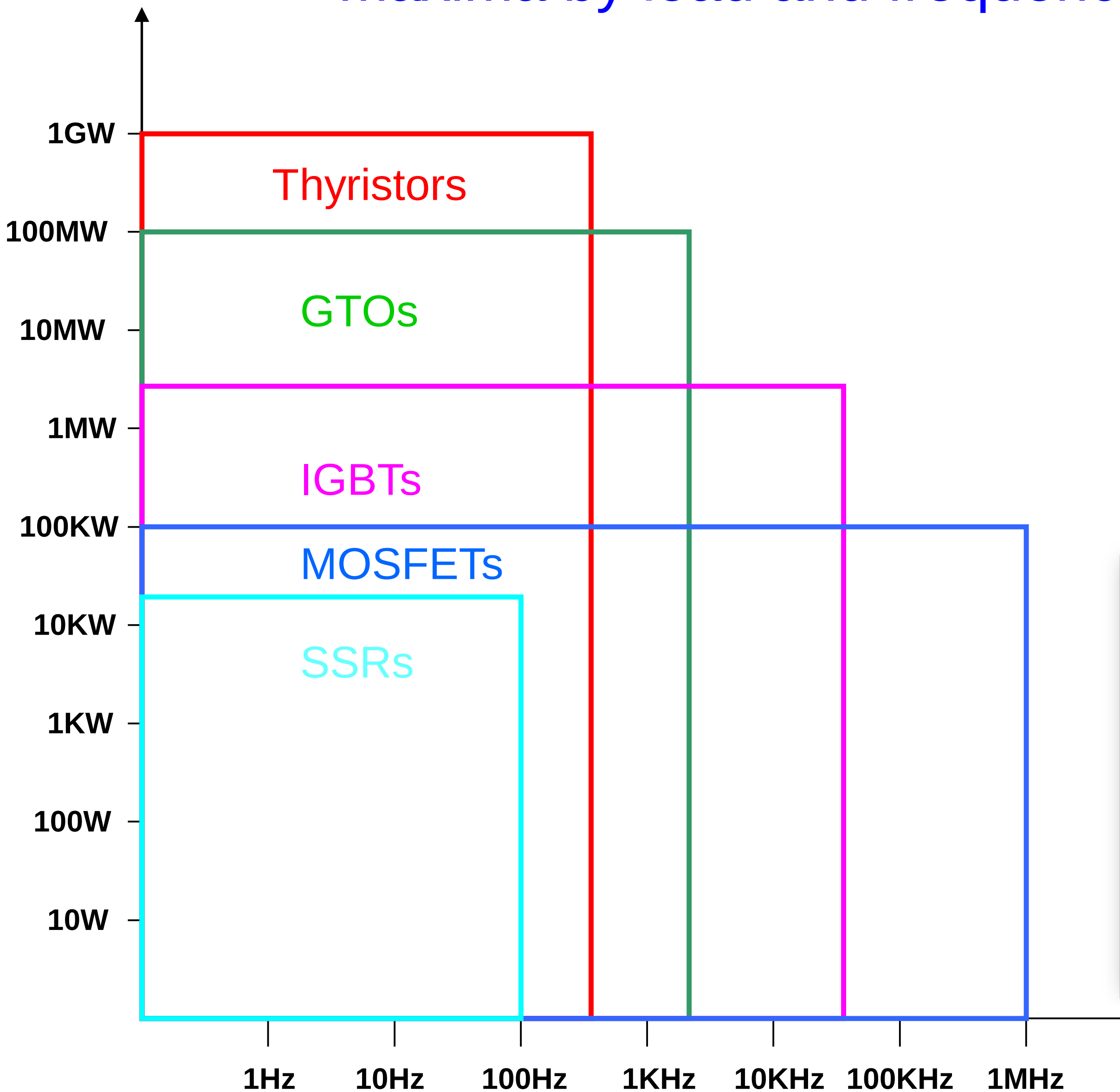


Self-commutated switches are suitable for use with DC supplies since they can be turned off independently of the polarity of the source voltage, load voltage or the nature of the load (reactive or resistive).

Three-phase inverters



Electronics power switching
– maxima by load and frequency ratings



IGBT Comparison Table

Device Characteristic	Power Bipolar	Power MOSFET	IGBT
Voltage Rating	High <1kV	High <1kV	Very High >1kV
Current Rating	High <500A	Low <200A	High >500A
Input Drive	Current, h_{FE} 20-200	Voltage, V_{GS} 3-10V	Voltage, V_{GE} 4-8V
Input Impedance	Low	High	High
Output Impedance	Low	Medium	Low
Switching Speed	Slow (uS)	Fast (nS)	Medium
Cost	Low	Medium	High