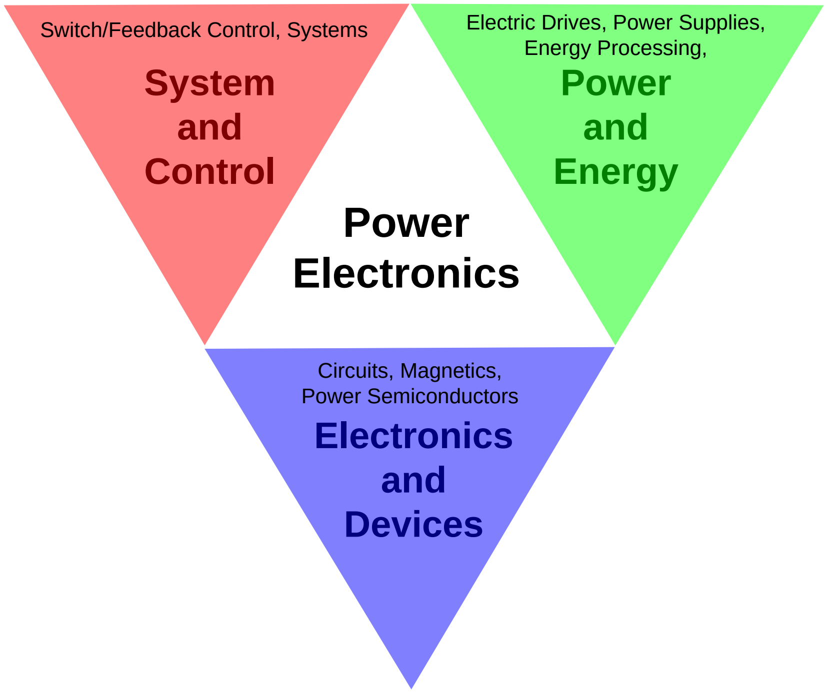
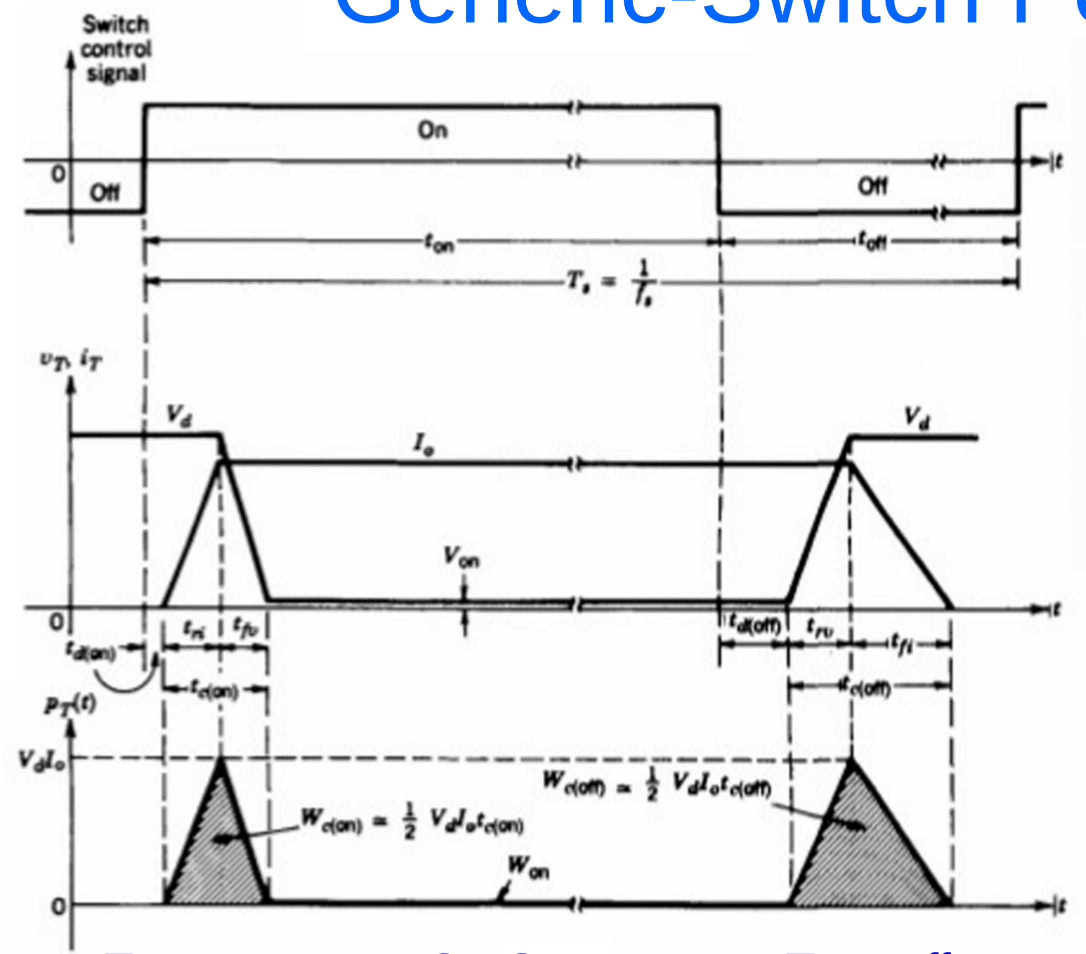
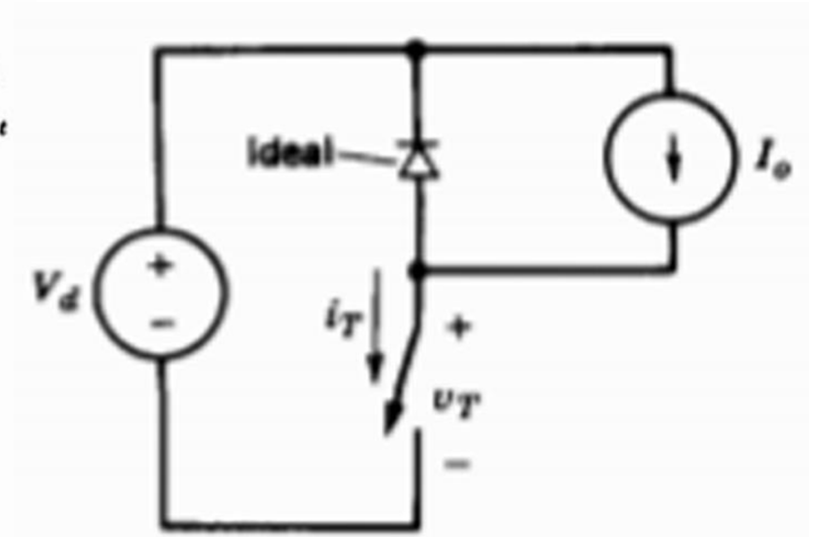
Power Electronics

Week 1 and week 5 lectures review



Generic-Switch Power Loss





Turn-on On-State Turn-off

Total Power Loss:

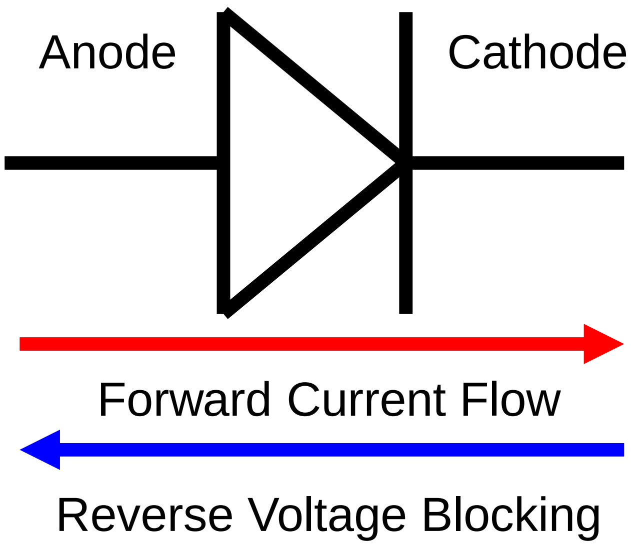
$$P_s = \frac{1}{2} V_d I_o f_s \left(t_{c(on)} + t_{c(off)} \right) + P_{on} = V_{on} I_o \frac{t_{on}}{T_s} = V_{on} I_o f_s t_{on}$$

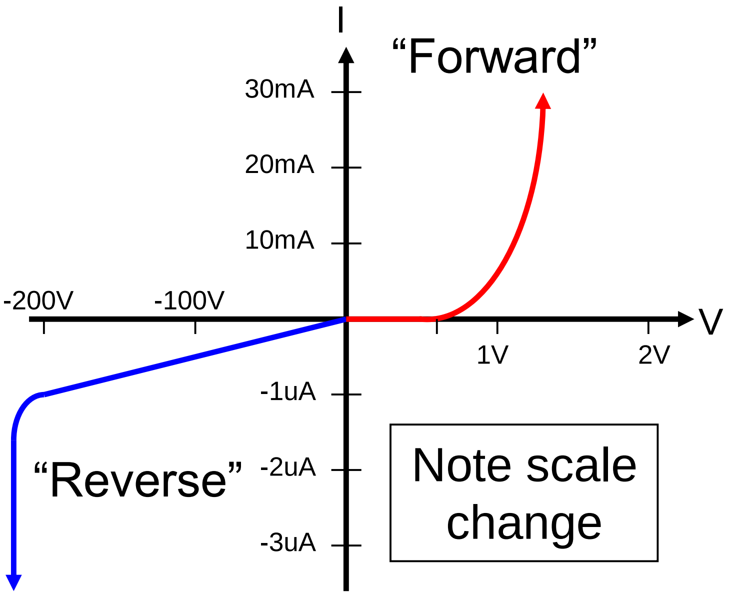
Switching Power Loss Conduction Power Loss

$t_{c(on)}, t_{c(off)} \rightarrow 0 \Rightarrow$ faster switching capability; $V_{on} \rightarrow 0 \Rightarrow$ higher efficiency

Diodes

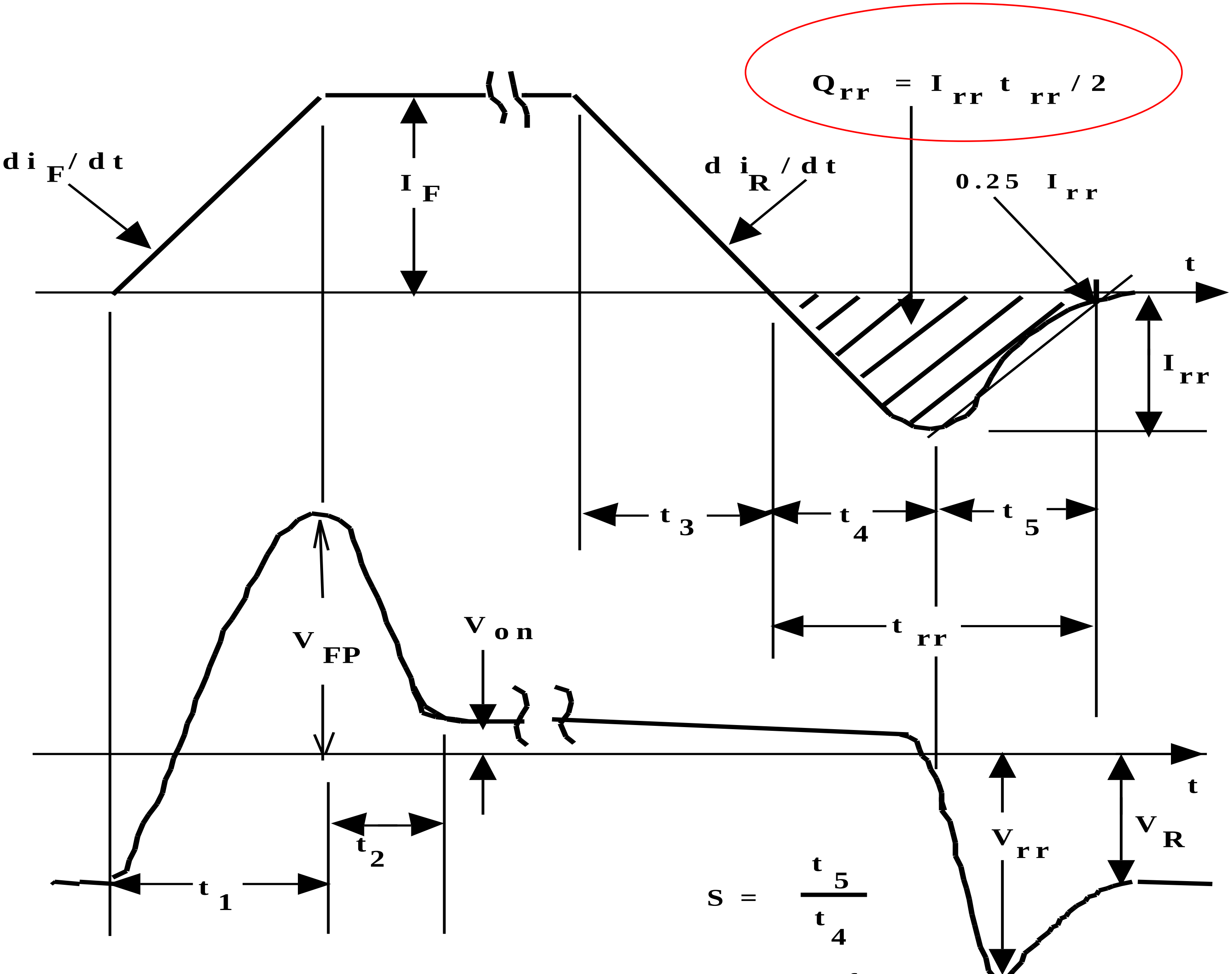
All the circuit elements we have considered so far have been linear – doubling the applied signal (voltage, say) doubles the response (a current, say). The diode is a non-linear semiconductor device with the V-I curve as shown in the diagram.





The diode's arrow indicates the normal current flow. In operation, the diode behaves like a voltage-sensitive switch. When the anode is more positive than the cathode current flows (quadrant 1 of diagram). When the anode is negative with respect to the cathode, current flow is blocked (quadrant 3 of diagram). This selective process of passage / blocking of current is called *rectification*.

Reverse Recovery Charge Q_{rr}



$$S = \frac{t_5}{t_4}$$

Recovery factor

Example:

A diode in a power supply circuit is operated with a forward current I_F = 10A and a forward voltage drop V_F at this current of 1.1V. The power supply circuit is switching at a frequency of 31.5KHz and the duty cycle is 50%. The steady-state reverse voltage across the diode is -50V and the reverse recovery charge Q_{rr} is 2.5uC.

What power does the diode dissipate?

$$P_{Total} = P_{Conduction} + P_{Switching}$$

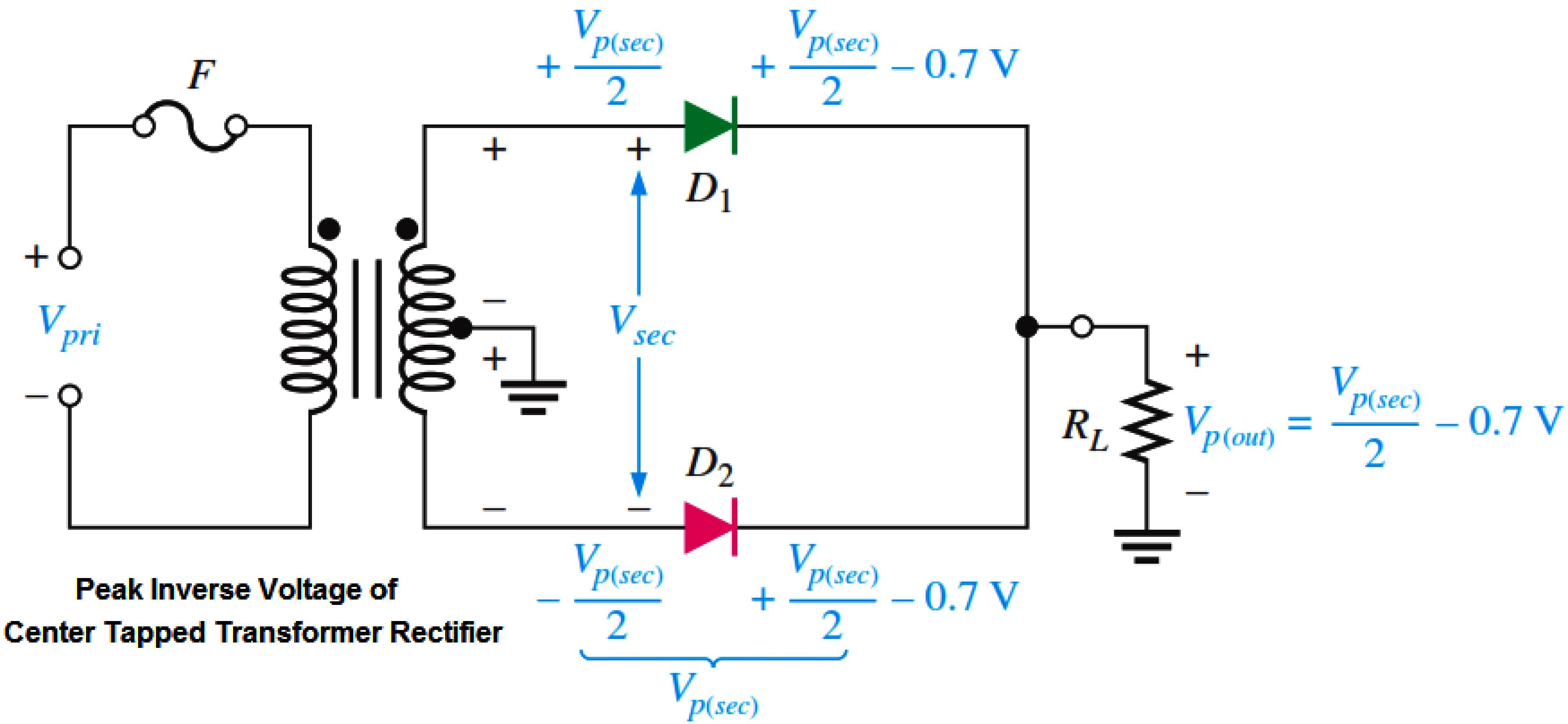
Conduction loss = $V_F \times I_F \times 0.5$ = 1.1V x 10A x 50% = 5.5W.

Switching loss = $Q_{rr} \times V_R \times F_{SW}$ = 2.5×10^{-6}C x 50V x 31500 = 3.9W

$\Rightarrow$Total power loss = 5.5W + 3.9W = <u>9.4W</u>

Important:
Switching losses vary directly with switching frequency.
Conduction losses vary directly with 'on' time (and current, obviously).

Centre-Tapped Full-wave Rectifier



Peak Inverse Voltage of Center Tapped Transformer Rectifier

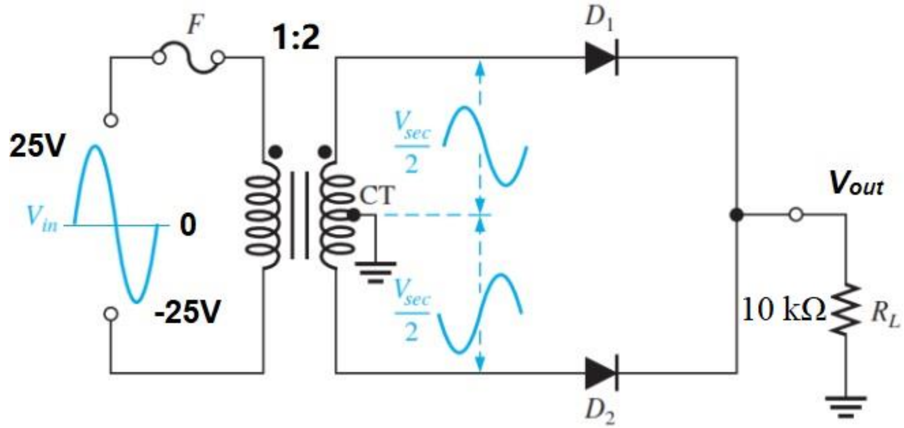
$$\text{PIV} = \left(\frac{V_{p(sec)}}{2} - 0.7\text{ V}\right) - \left(-\frac{V_{p(sec)}}{2}\right) = \frac{V_{p(sec)}}{2} + \frac{V_{p(sec)}}{2} - 0.7\text{ V}$$

$$= V_{p(sec)} - 0.7\text{ V}$$

Since $V_{p(out)} = V_{p(sec)}/2 - 0.7\text{ V}$,

$$V_{p(sec)} = 2V_{p(out)} + 1.4\text{ V}$$

$$\mathbf{PIV = 2V_{p(out)} + 0.7\ V}$$

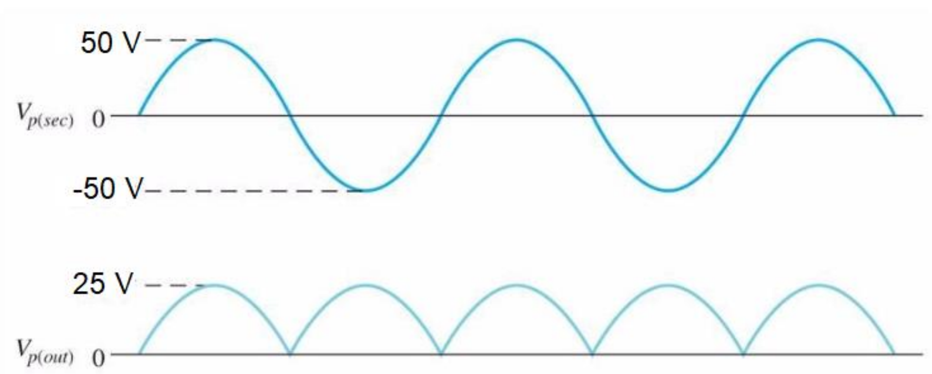


For ideal diodes, a 25 V peak sine wave is applied to the primary winding.

(1) Show the voltage waveforms V_{out} across the load R_L.

(2) What the minimum PIV rating must the diodes have?

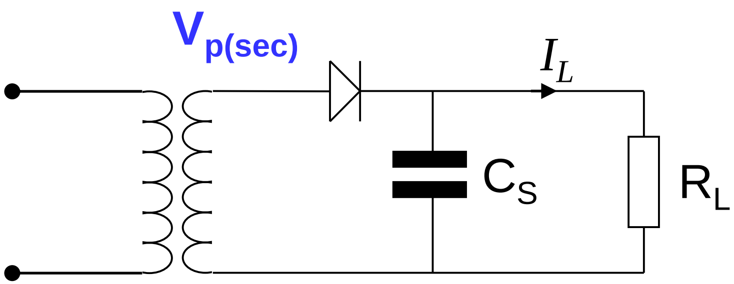
(a)

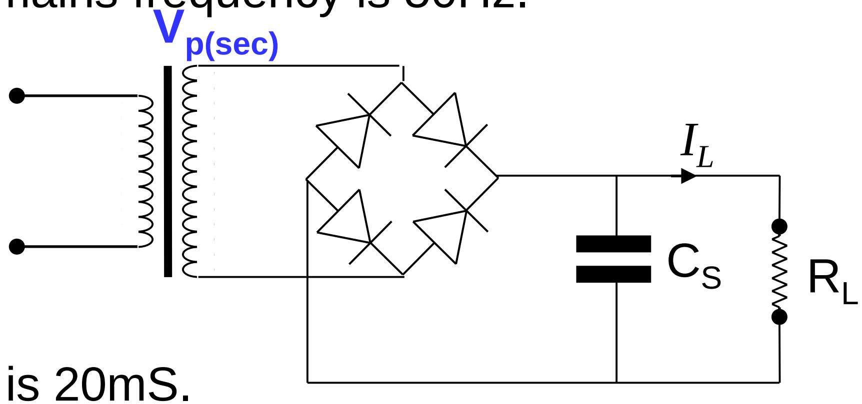


(b) $$PIV = 2V_{p(out)} = 2(25V)=50\ V$$

Example.

What is the peak to peak ripple voltage in the circuits shown for a load current of 5A and a capacitor of 15,000μF? Assume the mains frequency is 50Hz.



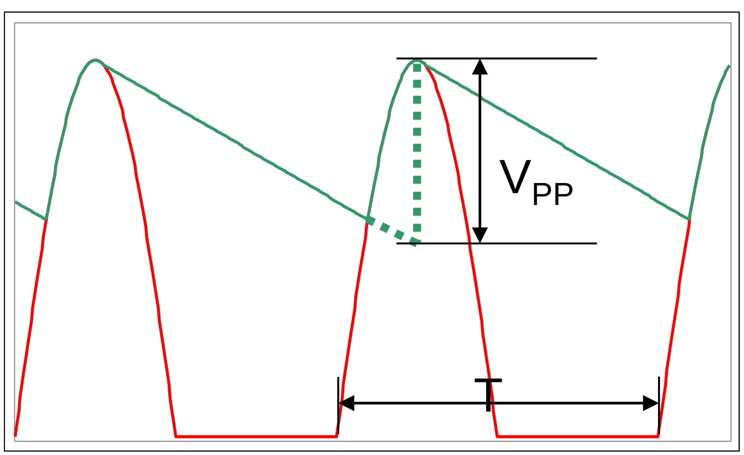


For the half-wave case, the discharge time is 20mS.

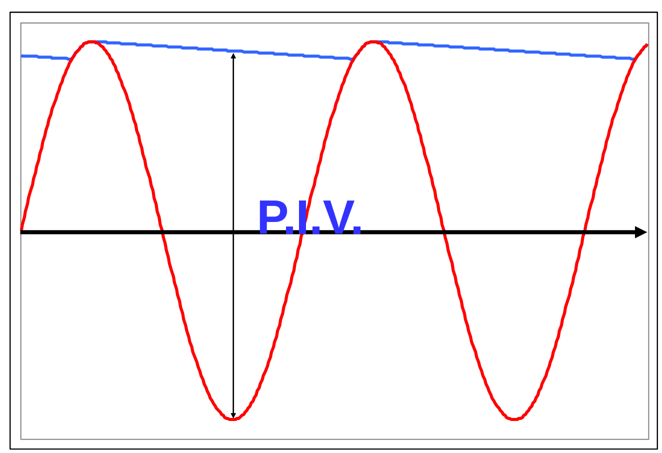
$$\frac{dV_{Load}}{dt} = \frac{I_{Load}}{C} = \frac{5}{15000 \times 10^{-6}} = 333\ Vs^{-1}$$

PIV=$V_{p(sec)}$= $V_{p(load)}$

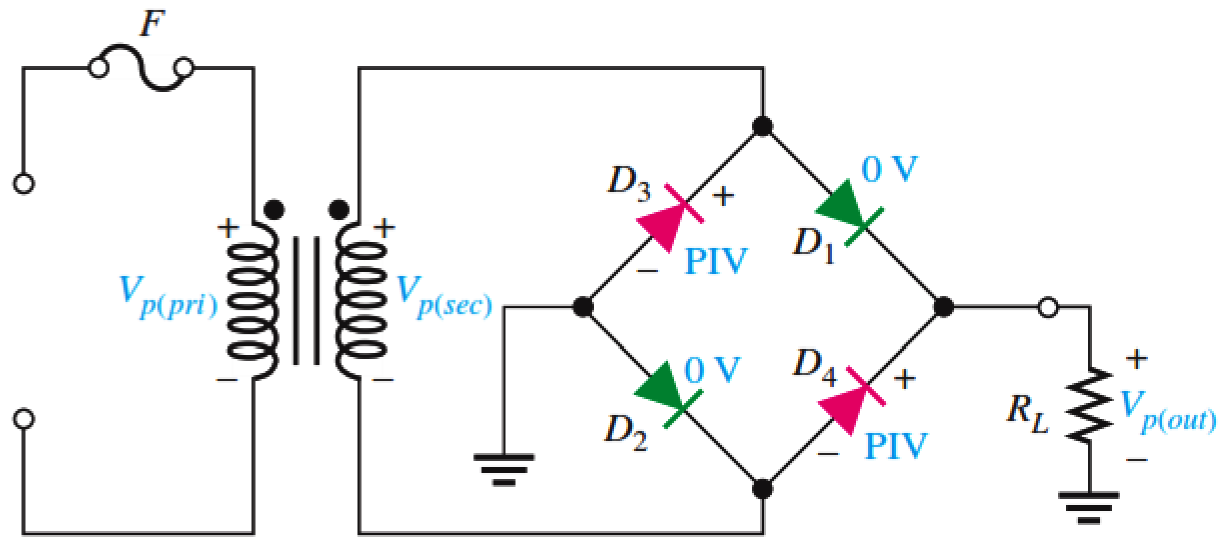
$$=> \Delta V_{PP} = \text{Discharge time} \times \frac{dV_L}{dt} = 20mS \times 333Vs^{-1} = 6.67V$$



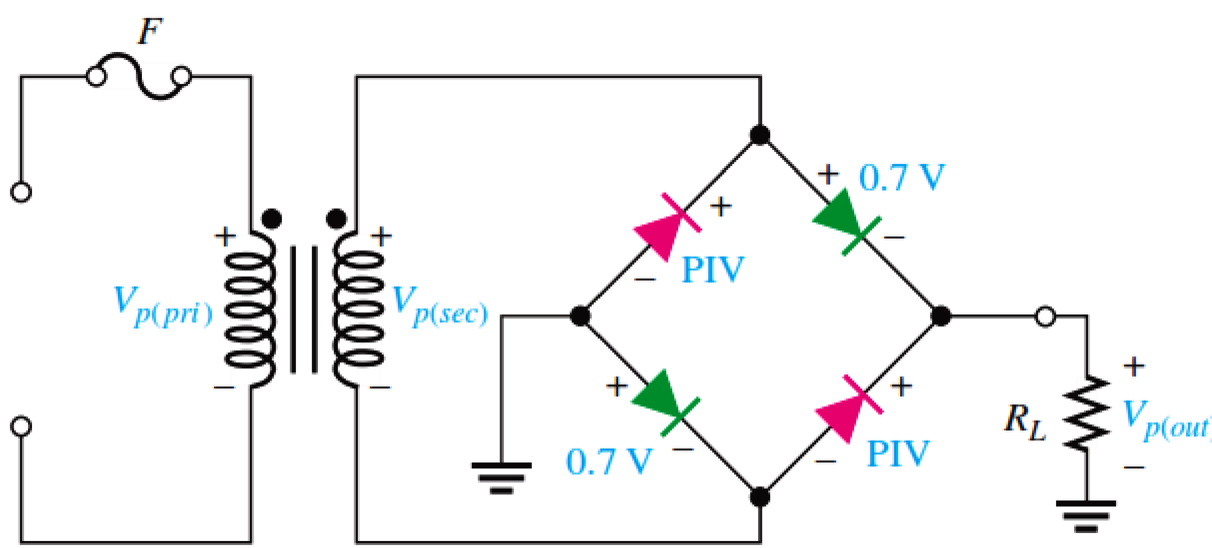
Half-wave case



Half-wave case **PIV=2$V_{p(sec)}$**



(a) For the ideal diode model (forward-biased diodes D_1 and D_2 are shown in green), PIV = $V_{p(out)}$.



(b) For the practical diode model (forward-biased diodes D_1 and D_2 are shown in green), PIV = $V_{p(out)}$ + 0.7 V.

The effect of the form factor on the capacitor ripple voltage

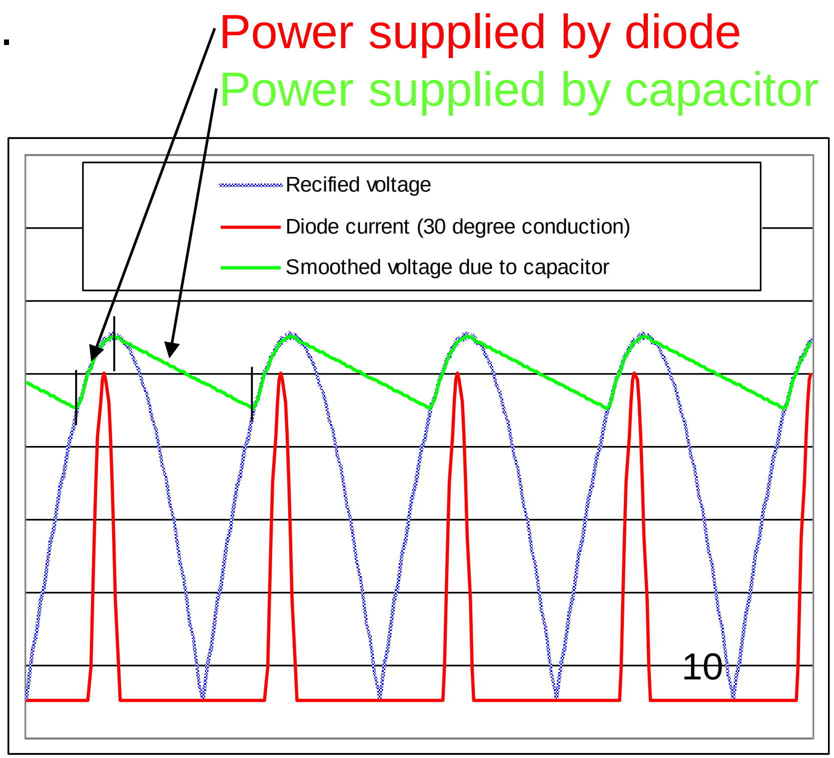
So far we have approximated the charging pulse in the capacitor to be of such a short time that it doesn't affect the voltage waveform. In reality, the charging pulse affects the waveform sufficiently to warrant its inclusion. Whilst the diode is conducting, it is supplying the load AND re-charging the capacitor. Hence the capacitor discharge period is shortened by the diode's conduction period.

Example. If the input to a full-wave rectifier is 12V @ 50Hz, R_{Load} is 8.5Ω and $C_{Smoothing}$ 10,000µF, what is the ripple voltage if the diode conduction angle is 30°?

f = 50Hz => full-wave rectified pulse freq is 100Hz. Period = 10ms, Conduction angle = 30° or 1.66mS, so capacitor discharge time is 8.33mS. Peak load voltage is √2 x 12V = $17V_{Peak}$. Load = 8.5Ω so load current is 2A.

$$I_L = C\frac{dV_L}{dt} \quad or \quad dV_L = \frac{I_L.dt}{C} = \frac{2A \times 8.33mS}{10mF} = 1.66V$$

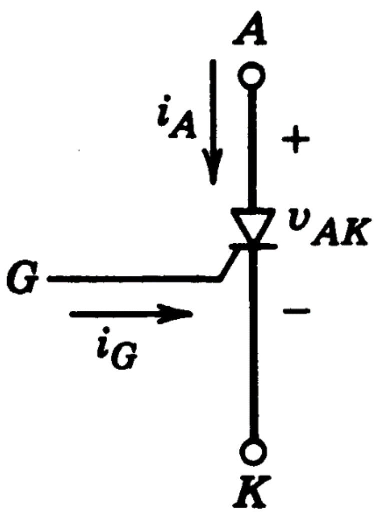
$$V_{ripple} = \frac{V_p}{R_L C} \times \Delta t$$

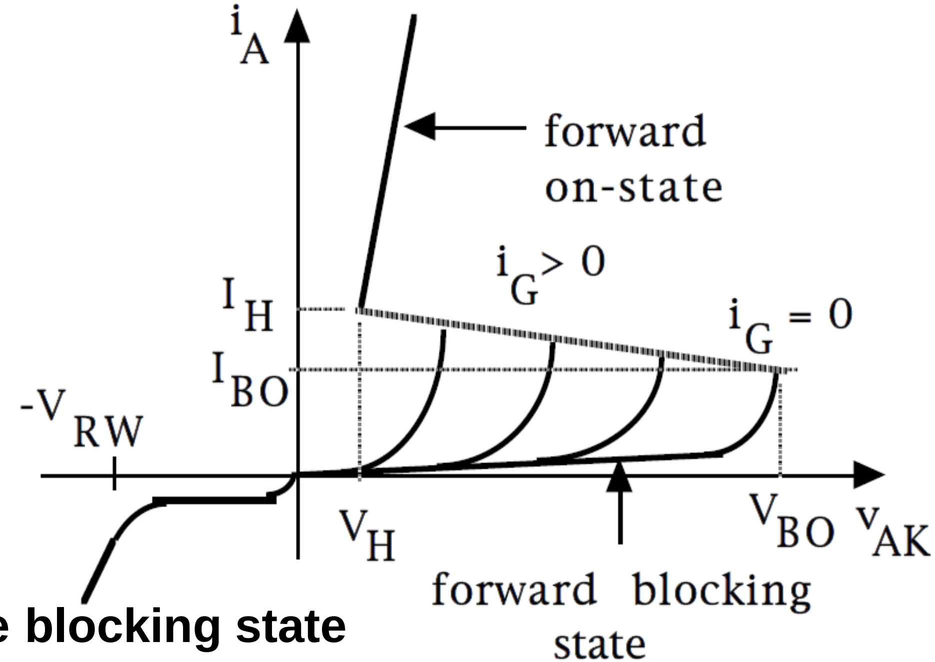


Notes.

Assume load current doesn't vary during discharge period. Approximate to a linear discharge ramp.
Peak to peak ripple is 1.66V and mean ripple is half this (0.83V) Mean output is 16.2V.
Larger cap: higher mean output voltage, reduced ripple, decreased diode conduction angle, higher diode current.

Thyristor





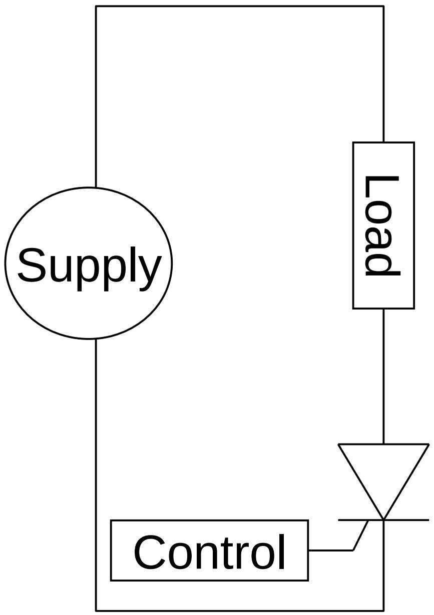
Half-Controllable Switch 半控开关

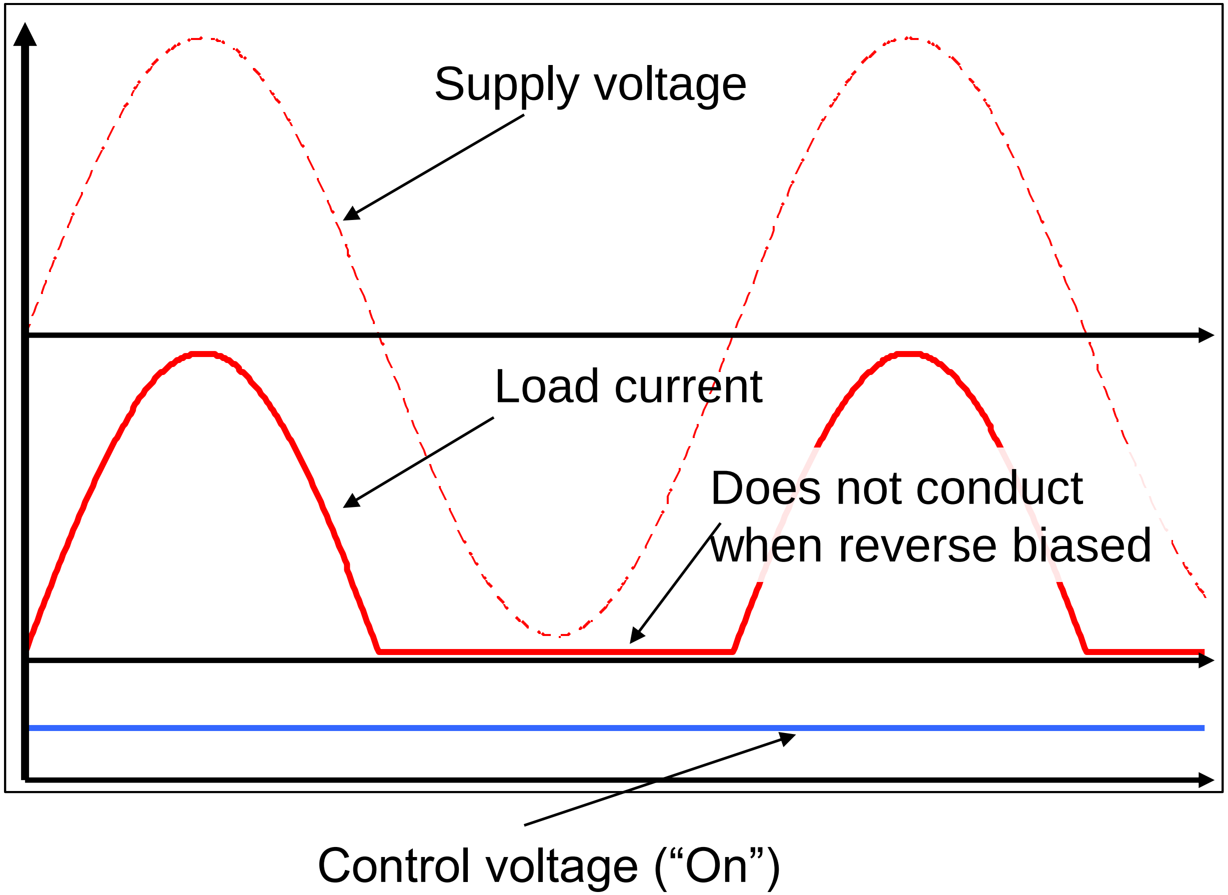
The thyristor can be turned on by applying a pulse of positive gate current i_G for a short duration when the device in its forward-blocking 前向阻断 state.

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.

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.

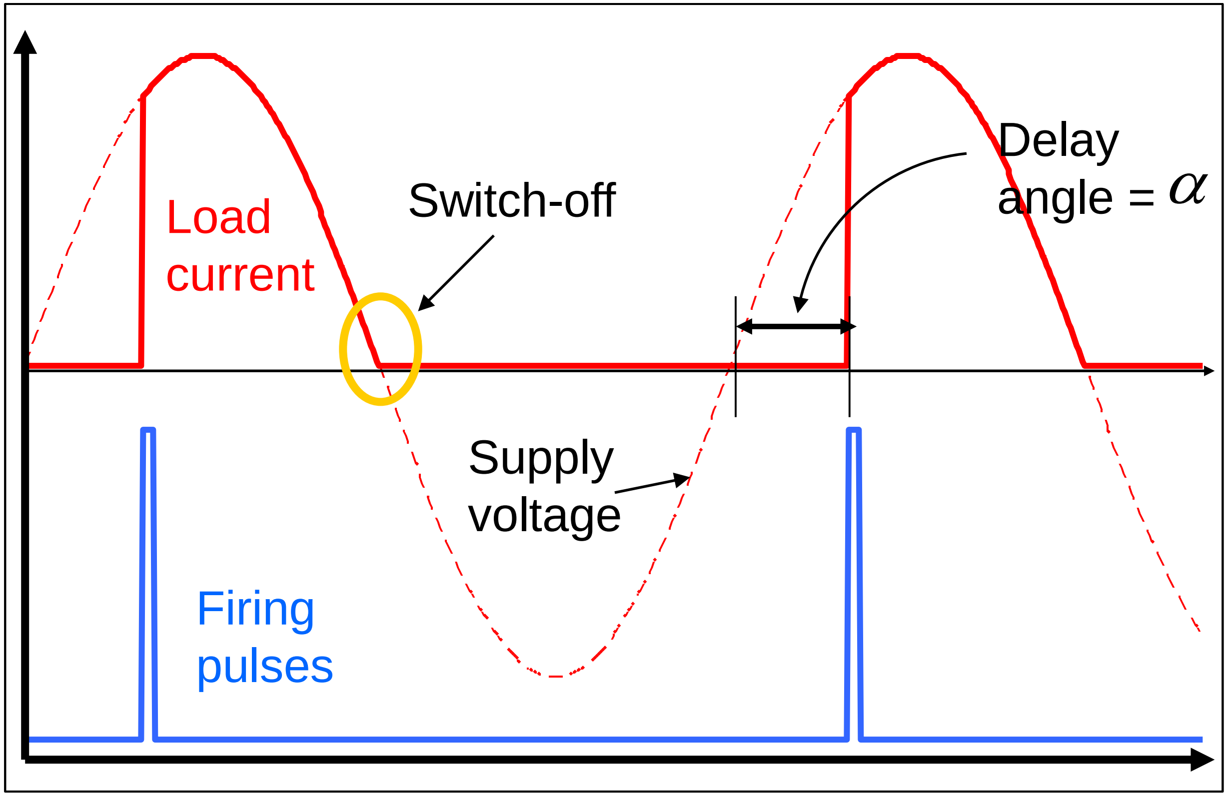




Thyristor behaving as a half-wave rectifier. The SCR turns off ("commutates"换流) automatically at the end of each positive half cycle.

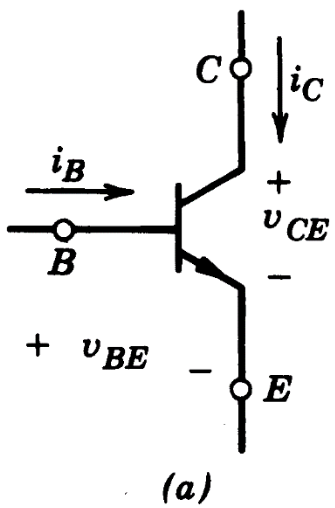
Phase control of SCRs

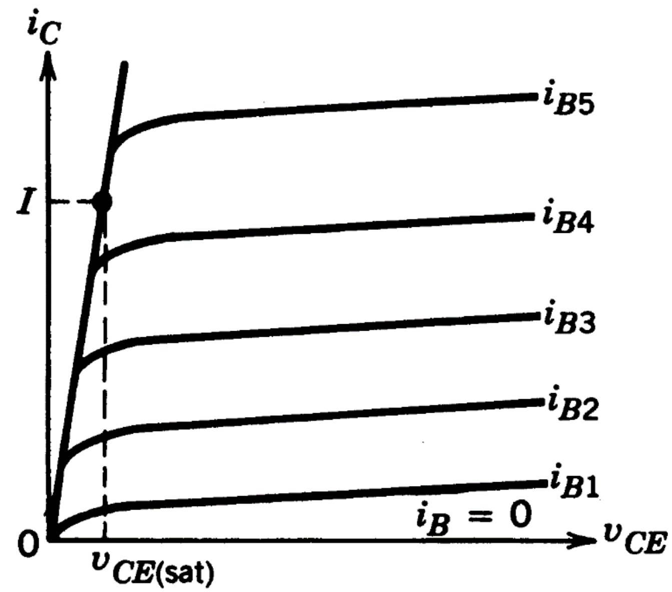
If we delay the firing pulse 触发脉冲 for the SCR relative to the zero-crossing points, we can use the SCR as a means 手段 of regulating the power applied to the load.



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

Bipolar Junction Transistor (BJT or GTR)





Now GTRs are replaced by MOSFETs, IGBTs

On-State Voltage: 1~2V

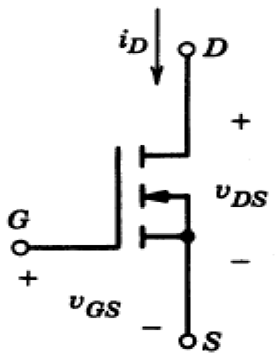
Limited Voltage/Current Rating: 1400V/several hundred A

Limited Switching Frequency: several kHz

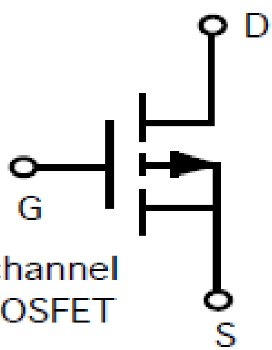
Complex current controlled drive circuit.

Metal Oxide Semiconductor Field-Effect Transistor (MOSFET)

金属氧化物半导体场效应管

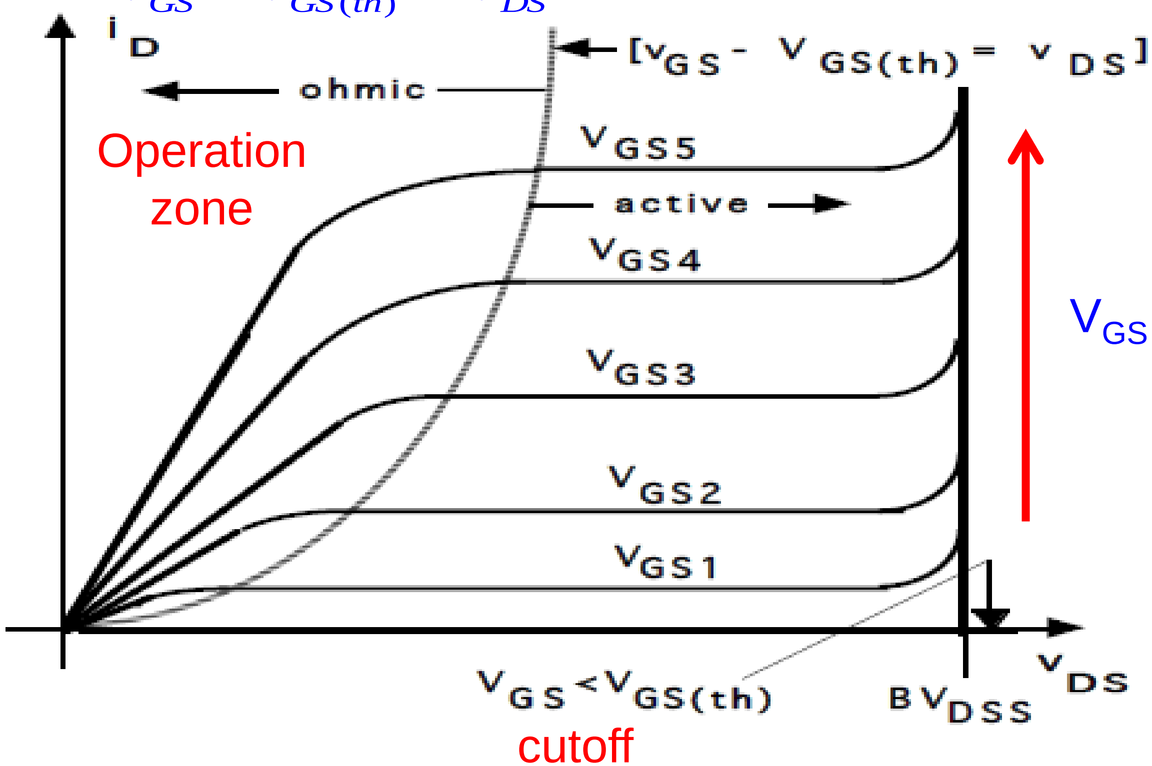


N-channel



P-channel MOSFET

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



Voltage Controlled (Fully-Controllable) Device

Characteristics of MOSFET

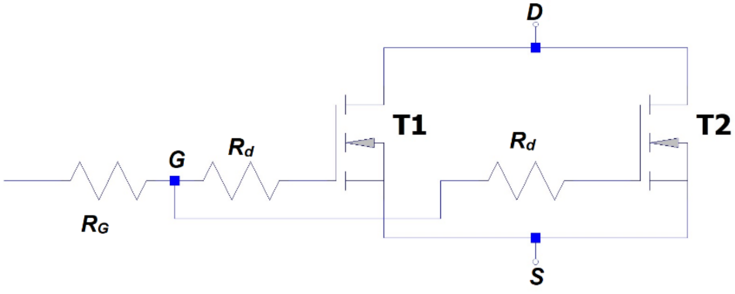
On-State Conduction Losses (Ohmic zone)

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

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 $r_{DS(on)}$.

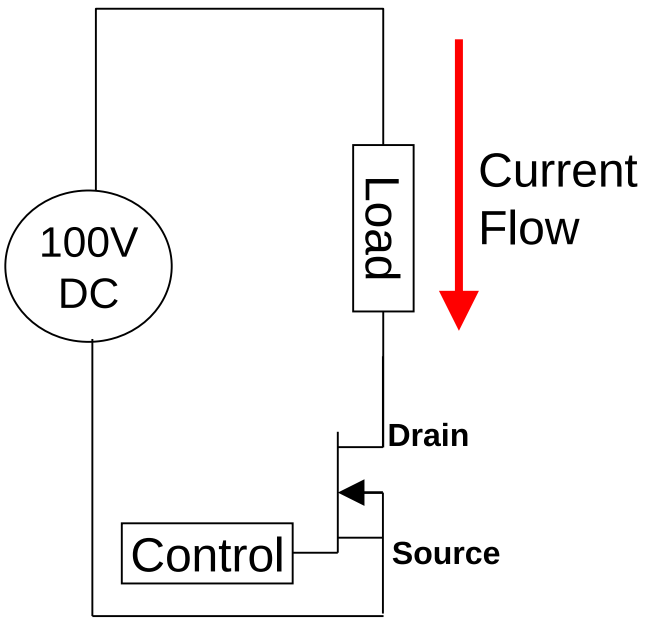


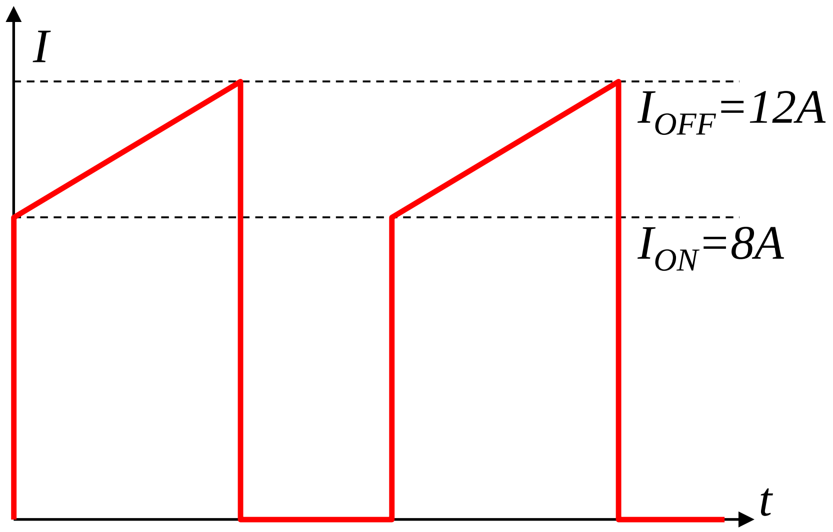
MOSFETs can be paralleled very easily, because of the positive temperature coefficient of their on-state resistance. For the same junction temperature, if $R_{DS(on)}$ of T_2 exceeds that of T_1, then during the on state, T_1 will have a higher current and thus higher power loss compared to T_2, since the same voltage appears across both transistors. Therefore, the junction temperature of T_1 will increase along with its on-state resistance. This will cause its share of current to decrease and, hence, there is a thermal stabilization effect

Example

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

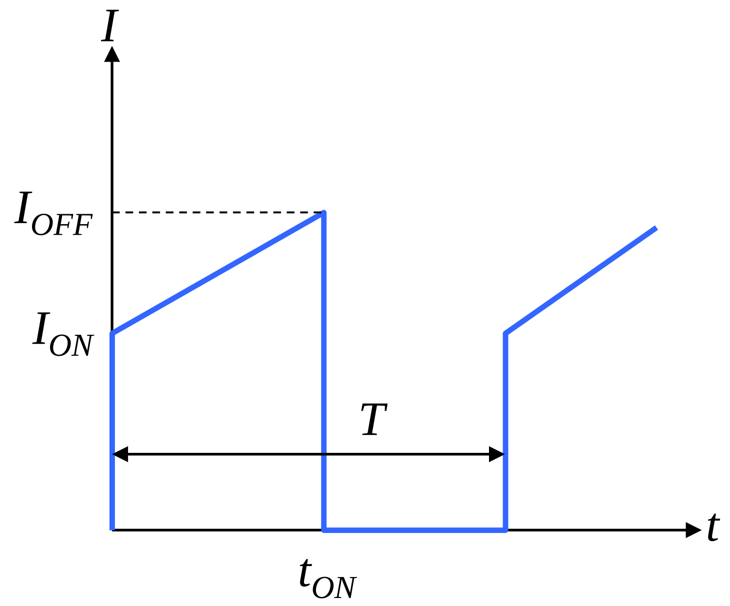
I_{ON}	8A
I_{OFF}	12A
PWM Duty	60%
PWM Freq	50KHz
Supply	100V DC
R_{ON}	50mΩ
T_{ON}	25nS
T_{OFF}	30nS





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

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



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

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

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

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

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

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

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

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

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

Step 2 – calculation of switching loss.

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

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

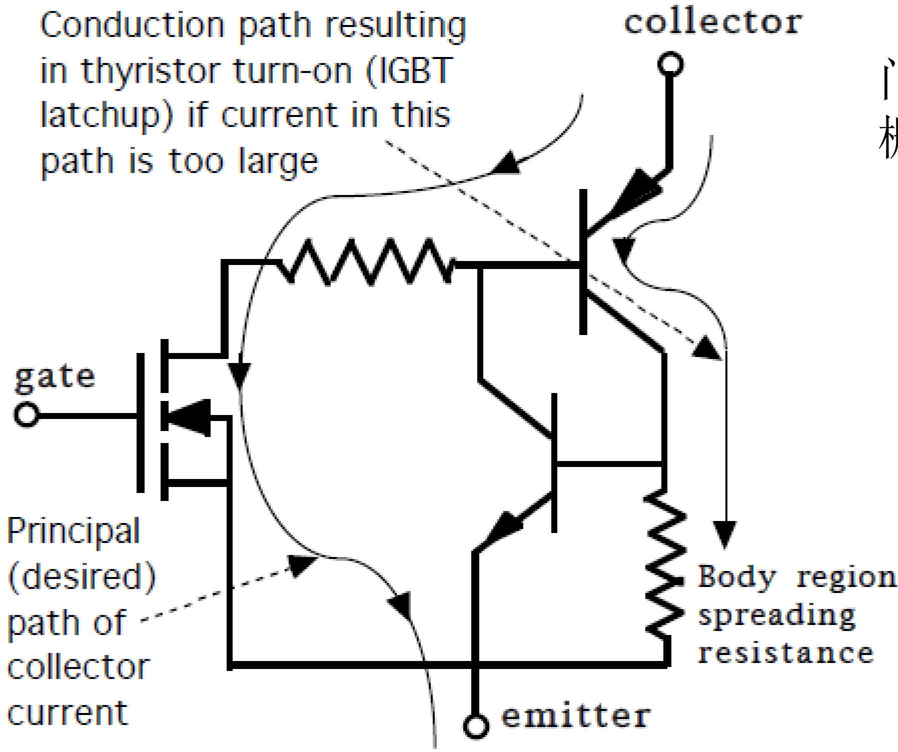
$$= 1.4W$$

Step 3 – calculate total power loss

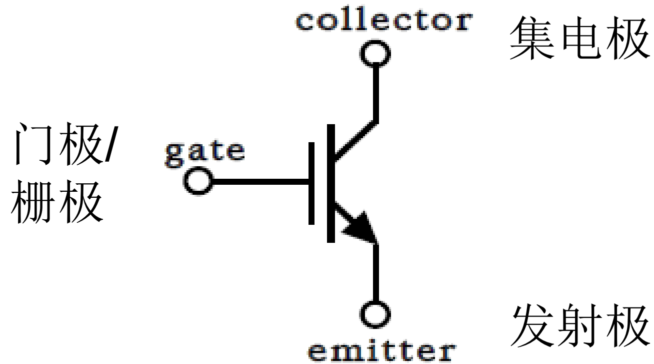
$$\boxed{\text{Power loss} = \text{Conduction loss} + \text{Switching loss}}$$

= 3.04W + 1.4W = 4.44W

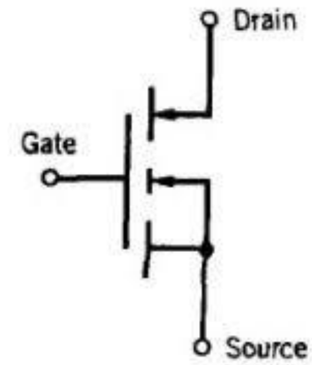
IGBT - Hybrid Switch

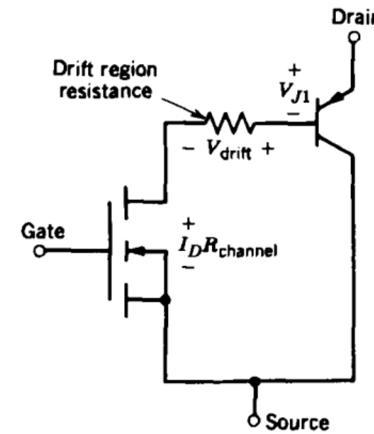


N-channel IGBT Equivalent Circuit



N-channel IGBT

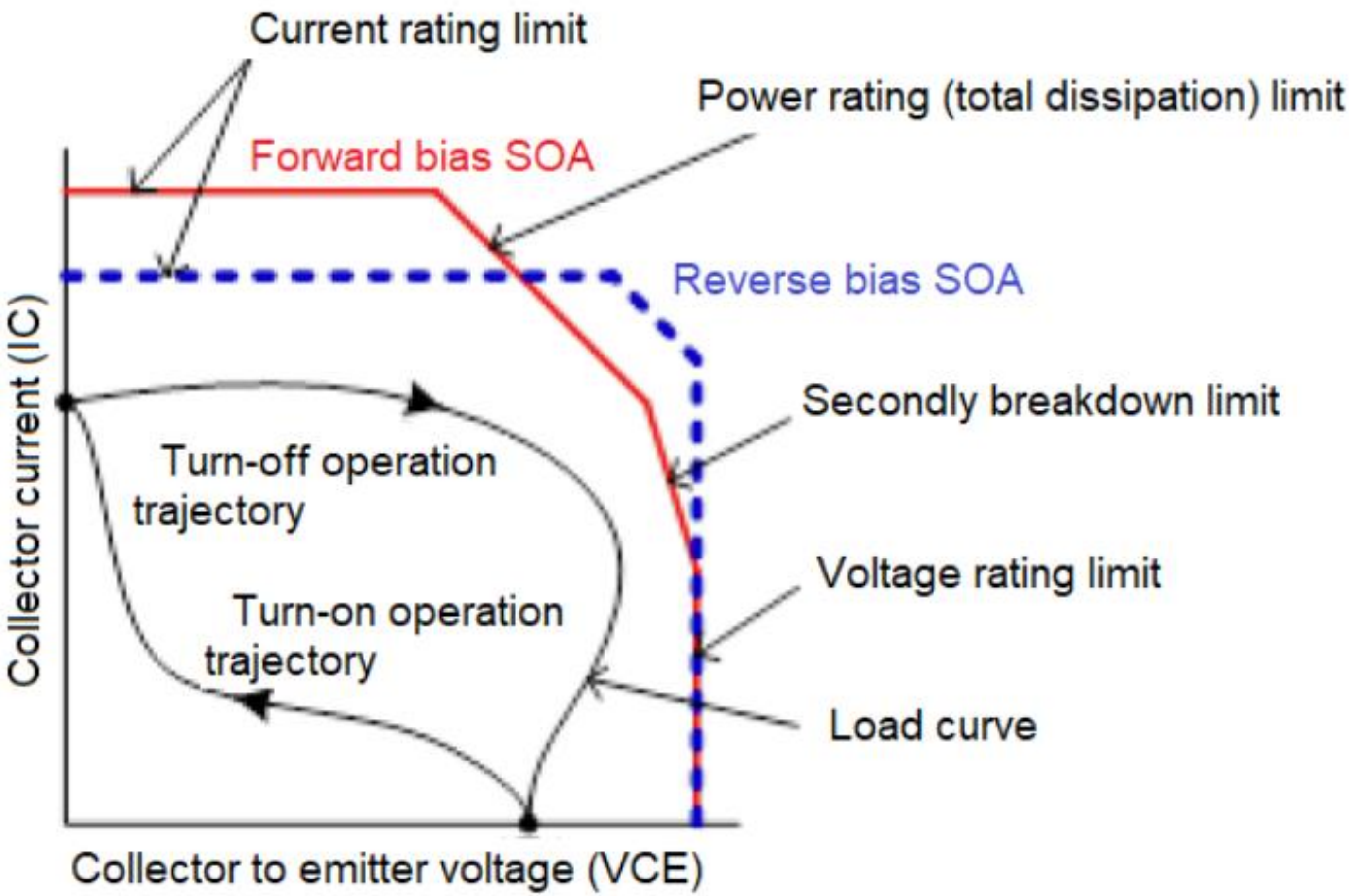




$$V_{DS(on)} = V_{J1} + V_{drift} + I_D R_{channel}$$

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

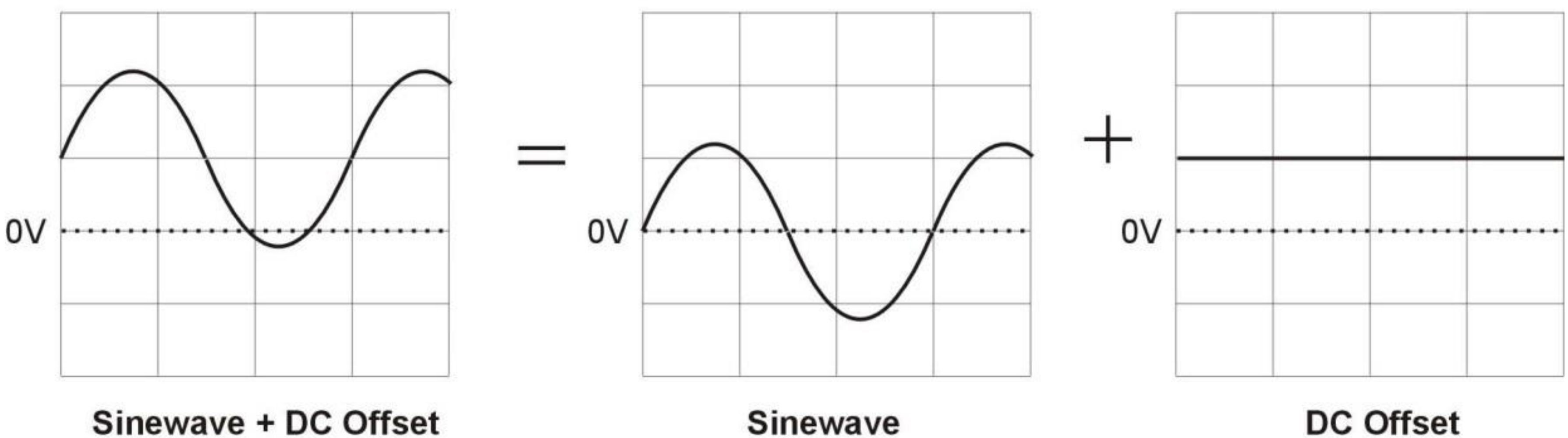
Safe Operating Area(SOA)



Question:

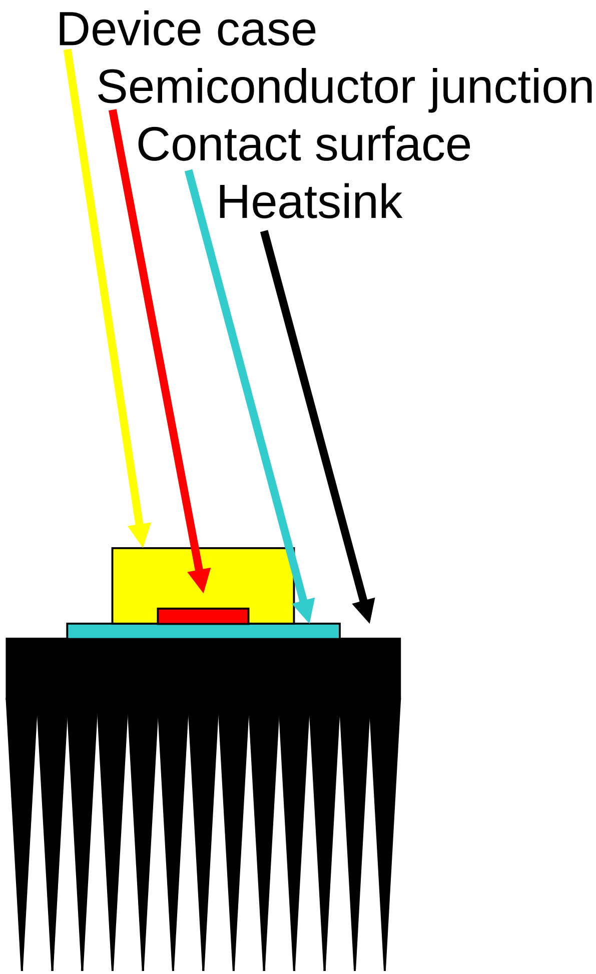
Show that the RMS value of a sinusoidal waveform with peak amplitude A volts and DC offset B volts is given by:

$$V_{RMS} = \sqrt{\frac{A^2}{2} + B^2} \qquad V_{TOTAL\,rms} = \sqrt{\left(V_{ACrms}{}^2 + V_{DCrms}{}^2\right)}$$

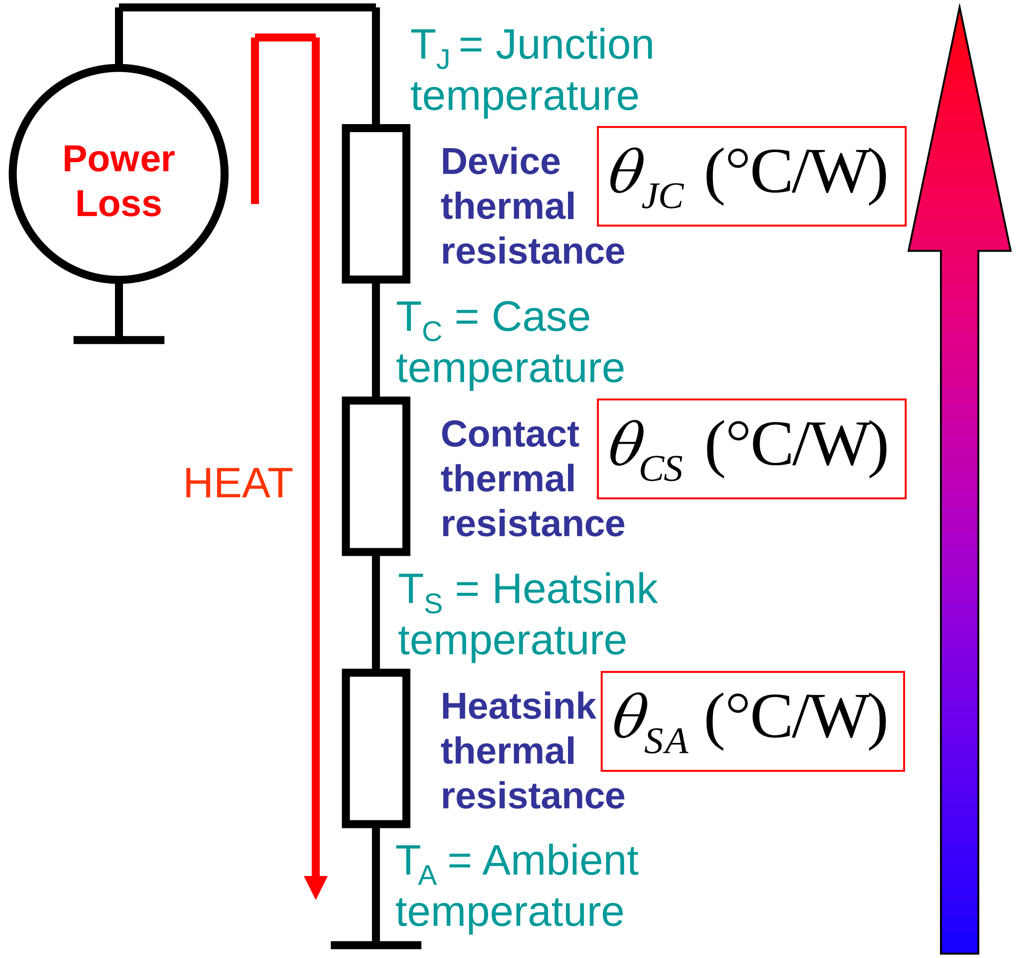


$$\mathrm{A}\sin(\omega t) + \mathrm{B} \qquad \mathrm{A}\sin(\omega t) \qquad \mathrm{B}$$

Equivalent Thermal Model



Ambient (“Free air”)



$$\Delta\,\text{Temp}\,(°\text{C}) = \text{Power}\,(\text{W}) \times \sum \theta_{XX}$$

The heatsink needs to have low thermal resistance to the surrounding cooler air.

Example 1.

Two diodes and a transistor share a single heatsink. The thermal resistances are given in the table below. What is the junction temperature for each device if the ambient temperature is 45°C and the heatsink thermal resistance is 0.75°C/W?

Each Diode	Transistor
θ_{JC}=0.33°C/W	θ_{JC}=0.2°C/W
θ_{CS}=0.15°C/W	θ_{CS}=0.1°C/W
Power = 10W	Power = 50W

First, calculate the heatsink temperature:

$T_{sink} = T_{amb} + P_{total} \times \theta_{SA} = 45 + 70W \times 0.75 = 97.5°C$

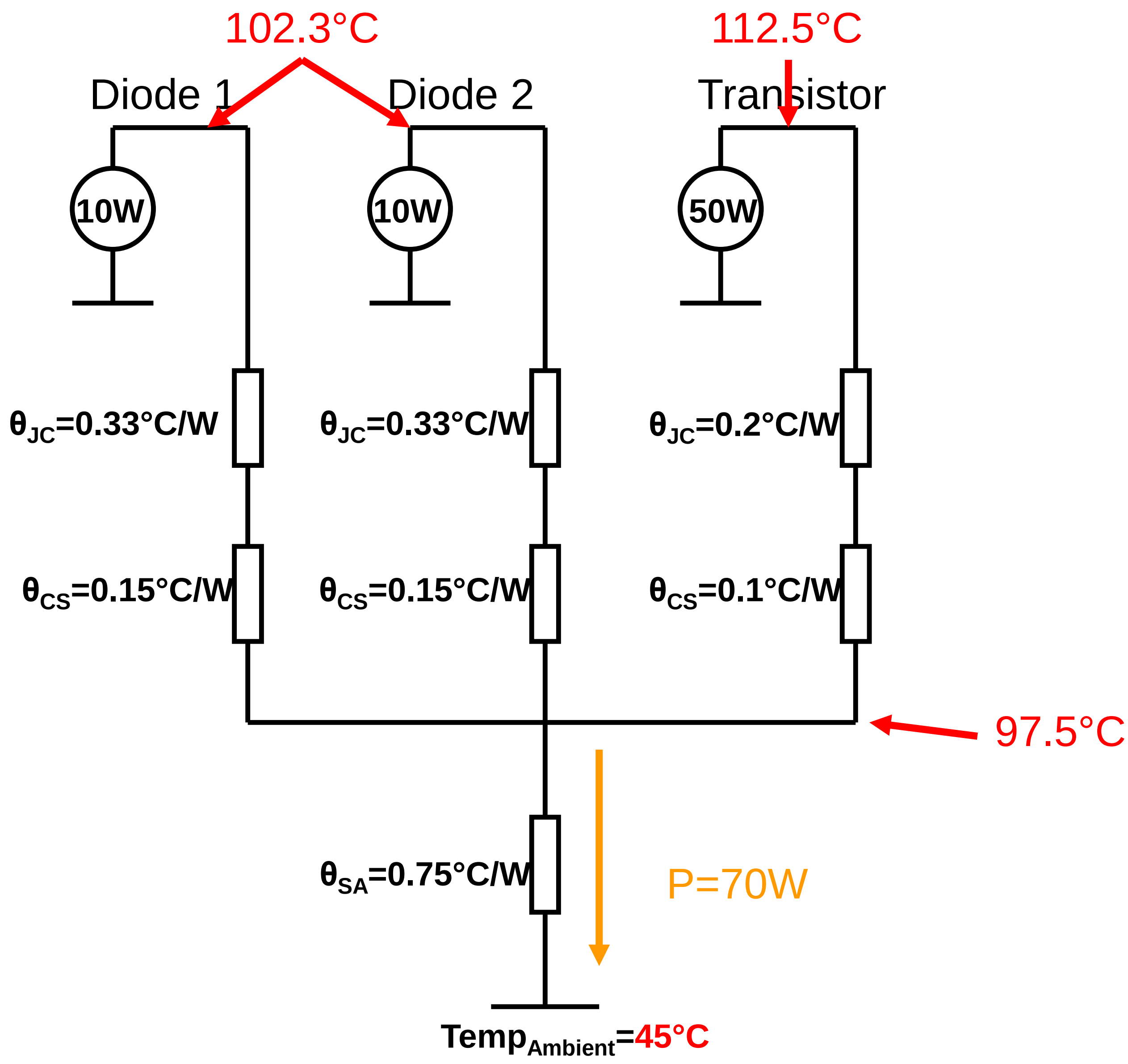
Now calculate the diode junction temperatures:

$T_{Diode} = T_{sink} + P_{diode} \times (\theta_{JC} + \theta_{CS})$
$= 97.5°C + 10 \times 0.48 = 102.3°C$

Finally, calculate the transistor junction temperature:

$T_{trans} = T_{sink} + P_{trans} \times (\theta_{JC} + \theta_{CS})$
$= 97.5°C + 50 \times 0.3 = 112.5°C$

Thermal circuit diagram for example 1.



Snubber Circuits for Hard-Switched Converters

Function of Snubber Ciruit

- Limiting device voltages during turn-off transients
- Limiting device currents during turn-on transients
- Limiting the rate-of-rise (di/dt) of currents through the semiconductor device at device turn-on
- Limiting the rate-of-rise (dv/dt) of voltages across the semiconductor device at device turn-off
- Shaping the switching trajectory of the device as it turns on/off

From the circuit topology perspective, there are three broad classes of snubber circuits

1. Unpolarized series **R-C** snubbers:
- Used to **protect diodes and thyristors**

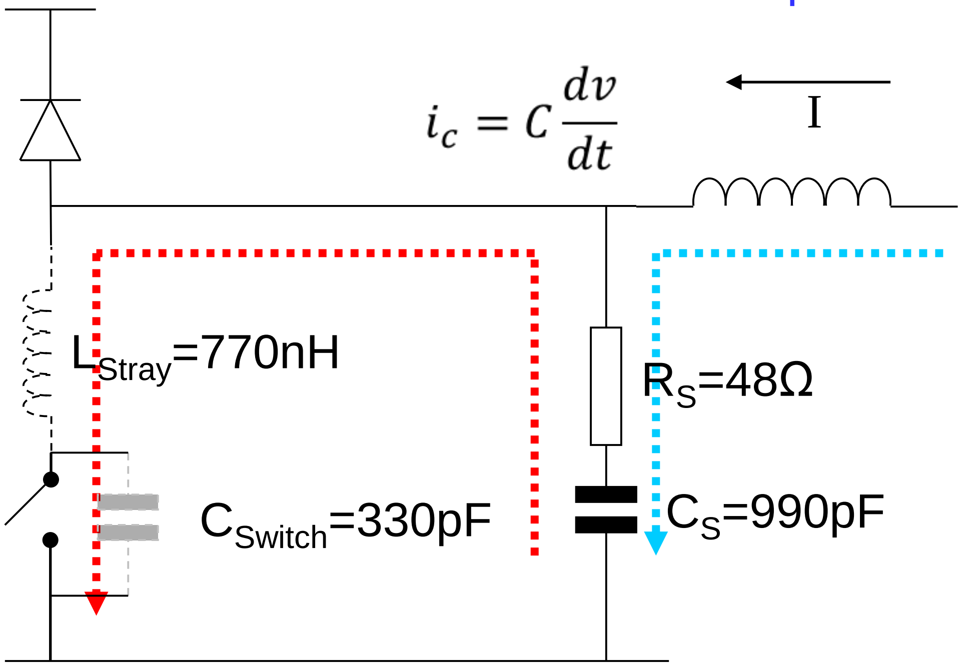
2. Polarized **R-C** snubbers:
- Used as **turn-off** snubbers to shape the turn-off switching trajectory of controlled switches
- Used as **overvoltage** snubbers to clamp voltages applied to controlled switches to safe values; Limit **dv/dt** during device turn-off

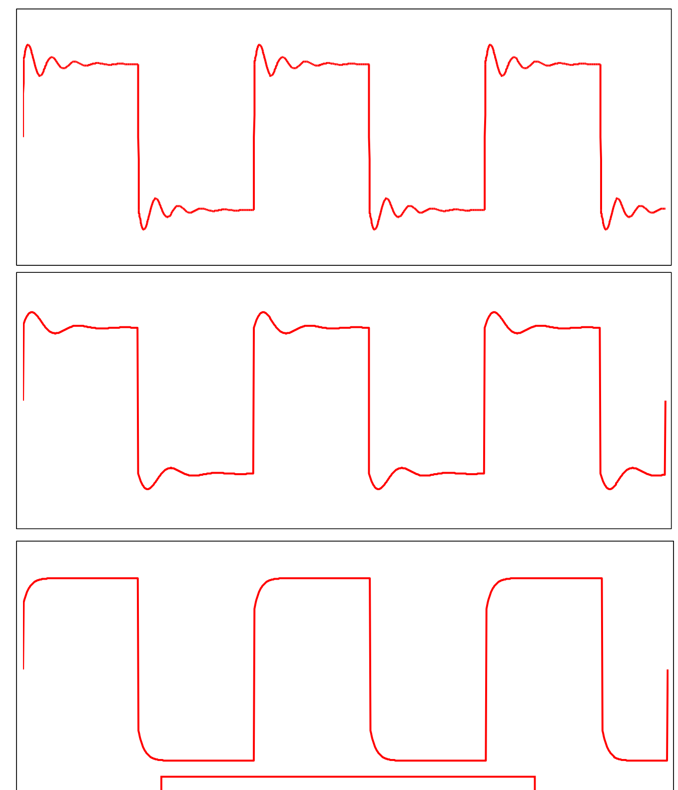
3. Polarized **L-R** snubbers
- Used as **turn-on** snubbers to shape the turn-on switching trajectory of controlled switches;
- Limit **di/dt** during device turn-on

Voltage snubbers(turn-off snubers. (电压缓冲电路 或 关断缓冲电路）

The simple resistor-capacitor (RC 阻容) snubber is probably the most widely used of all snubber circuits.

It is used on inductors, transformers, power diodes and switches. It can be used for both rate of rise control and also to damp circuit oscillations (ringing).

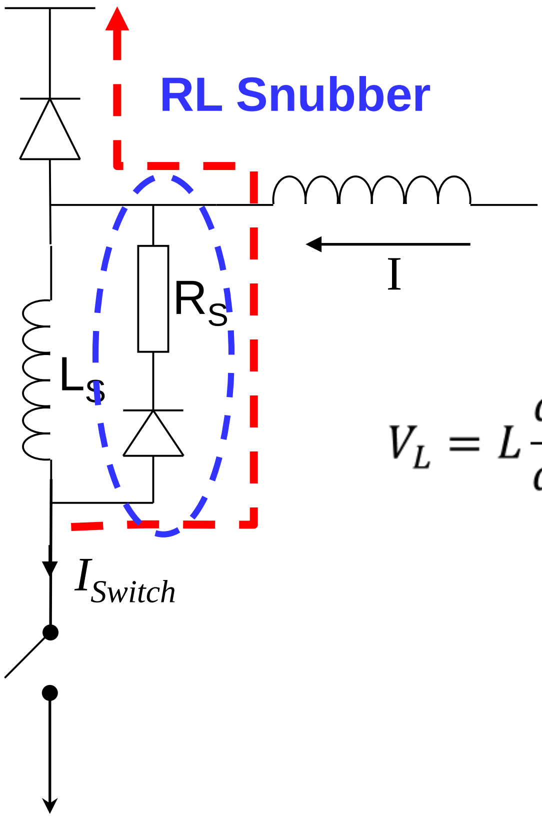




Damped response.

When the switch is open, the capacitor charges via the resistor. When the switch closes, the capacitor is discharged via the resistor

Current snubbers (turn-on snubbers). (电流缓冲电路 或 开通缓冲电路）



$$V_L = L\frac{di}{dt}$$

$$\boxed{V_{Peak} = V_{Diode} + I_{Switch}R_{Snubber}}$$

With reference to the circuit, when the switch closes, the current through it is initially zero by virtue of the inductor L_S. The value of L_S controls the rate of rise of current, dI/dt.

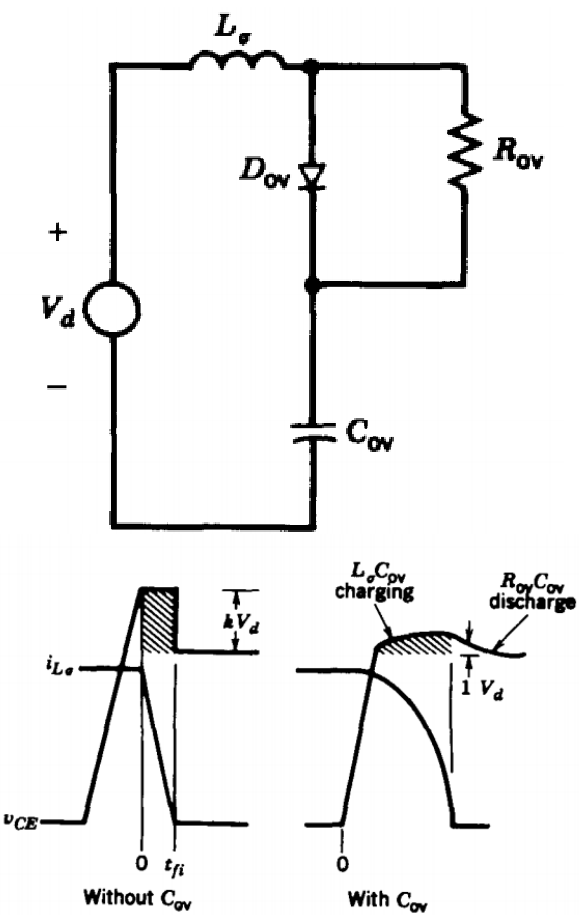
When the switch opens, the inductor initially maintains the current I_{Switch}, the diode starts to conduct and the current flows via the resistor R_S to complete the circuit. The peak voltage across the inductor is the voltage across the resistor R_S X I_{Switch}, plus the voltage drop across the diode. Unlike the diode clamp for the relay, the energy from the inductor is thus very quickly dissipated.

Note the peak voltage across the switch must include the supply voltage too.

A useful variation on the simple RL snubber is to add a diode in series with the resistance. This is very similar in operation to the diode clamp discussed earlier. Because the circuit operates differently according to whether or not the diode is conducting, it is called a "**polarised snubber**".

Overvoltage Snubber

The overvoltage at turn-off due to stray inductance can be minimized by means of the overvoltage snubber circuit. At turn-off, assuming the BJT current fall time to be small, the current through the stray inductance, $L\sigma$ is essentially I_O and the output current then free-wheels through the **free-wheeling diode**.



$$i_c = C\frac{dv}{dt}$$