Power Electronics

Snubber Circuit

缓冲电路

Please read Chapter 27 in the textbook

Forget the dog, beware of the inductor...

Protection of Switching Devices and Circuits

Switching devices and circuit components may fail due to the following reasons:

1. Overheating – thermal failure
2. Overcurrent
3. Overvoltage – usually happens during turn-off
4. Excessive ***di/dt***
5. Excessive ***dv/dt***
6. Switching loss – excessive switching loss is a major contributing factor of overheating.

Power electronic circuits and their switching devices and components can be protected from overcurrent by placing fuses at suitable locations. Heat sinks, fins and fans are used to take the excess heat away from switching devices and other components.

Snubber circuits are required to limit ***di/dt, dv/dt*** and overvoltage during turn-on and turnoff.

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

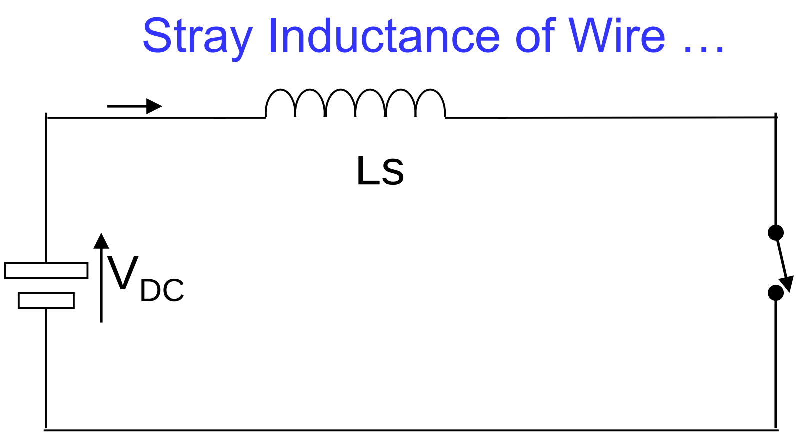
$$i_c = C\frac{dv}{dt}$$

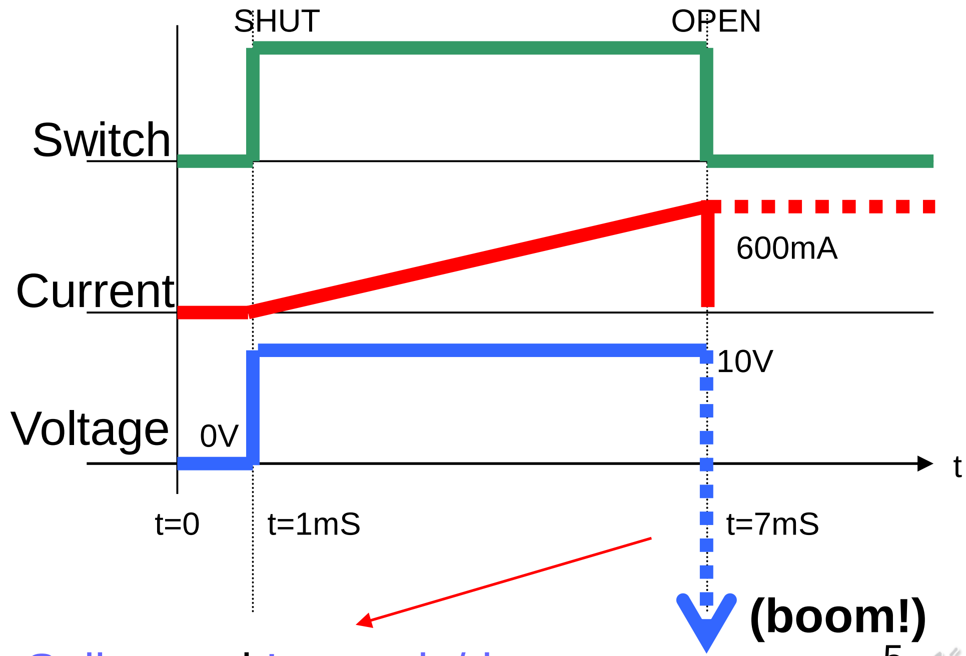
1. Unpolarized series **R-C** snubbers:
   - Used to **protect diodes and thyristors**
2. Polarized **R-C** snubbers:
   - Used as **turn-off** snubbers to shape the turn-off switching trajectory of controlled switches
   - Used as **overvoltage** snubbers to clamp voltages applied to controlled switches to safe values; Limit **dv/dt** during device turn-off
3. Polarized **L-R** snubbers $V_L = L\frac{di}{dt}$
   - Used as **turn-on** snubbers to shape the turn-on switching trajectory of controlled switches;
   - Limit **di/dt** during device turn-on

Passive Snubber Circuits.

Snubber circuits are small networks of passive components (resistors, capacitors, inductors and diodes) that are used in power switching circuits to control the effect of circuit reactances. They are an essential part of any electronic power switching circuit.

A snubber circuit is designed to absorb or redirect reactive energy in a circuit as the circuit's operation changes. To do this, they take advantage of the transient behaviour of small inductors and capacitors. In an earlier lecture the problem of interrupting the current flowing in an inductor was discussed. This is the type of problem snubbers deal with.





Sudden Switch Off will result in Voltage Spike, and Large dv/dt

Snubbers are used extensively to prevent "ringing" when a circuit is **switched on or off.** Typical applications therefore include circuit damping, controlling the rate of change of voltage or current (dI/dt and dV/dt), and clamping voltage overshoot. By doing this, the snubber decreases the electrical stress on the switch, increases reliability and decreases circuit power dissipation.

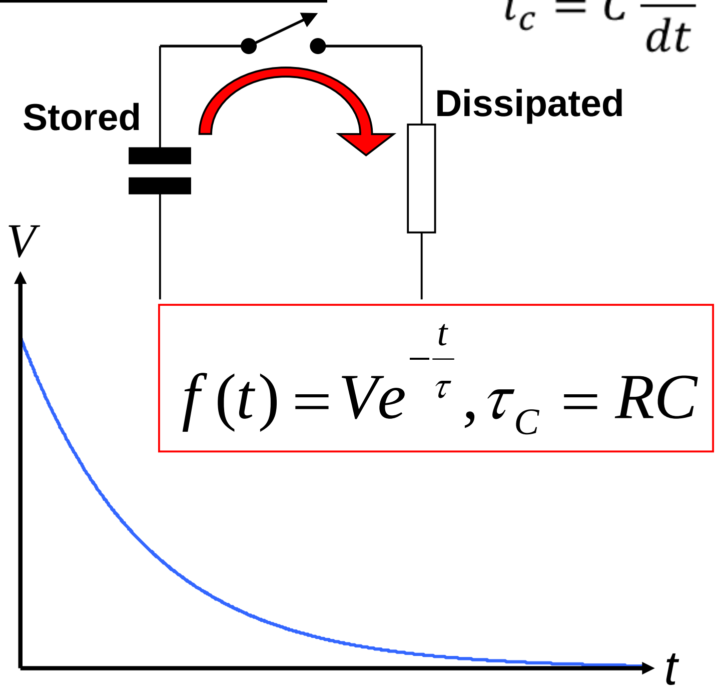
Snubbers may also be "active" (i.e., contain switching or gain elements), but these will not be considered in this course. In any case, active snubbers invariably still need passive snubbers for their reliable operation.

Table summarising instantaneous change capability of snubber components.

Instant change?	**Inductor**	**Capacitor**	**Resistor**	**Diode**
Voltage	Yes	No **(So use for dV/dt)**	Yes	Yes (nearly)
Current	No **(So use for dI/dt)**	Yes	Yes	Yes (nearly)

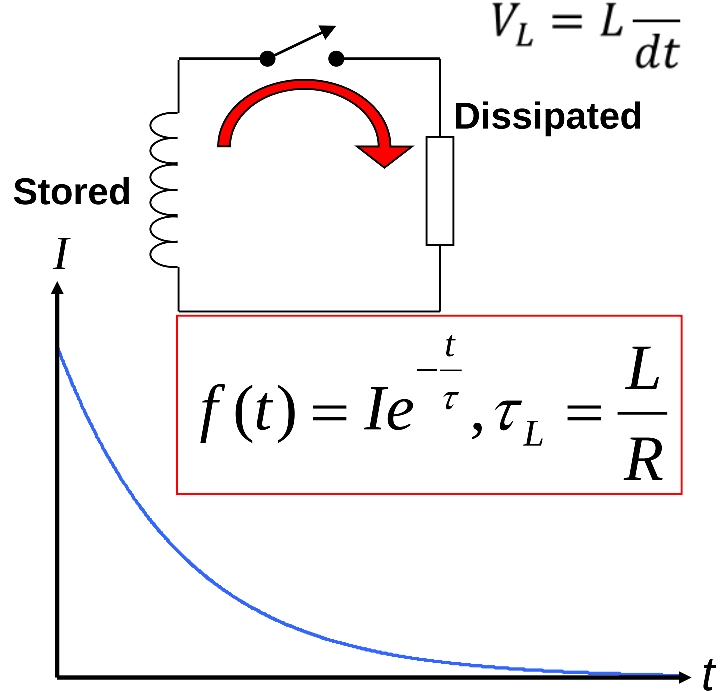
Time constants.

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



$$f(t) = Ve^{-\frac{t}{\tau}}, \tau_C = RC$$

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



$$f(t) = Ie^{-\frac{t}{\tau}}, \tau_L = \frac{L}{R}$$

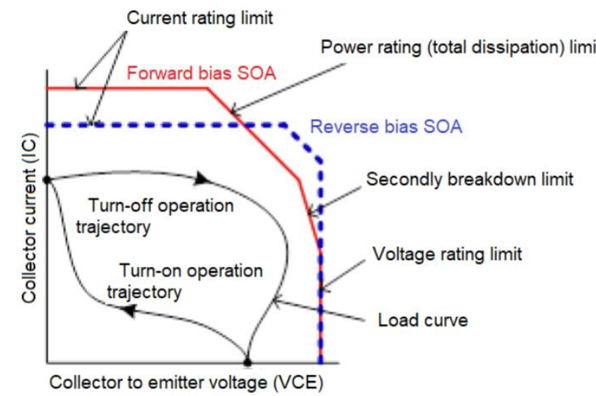
Snubber circuits can be classified into two broad headings:

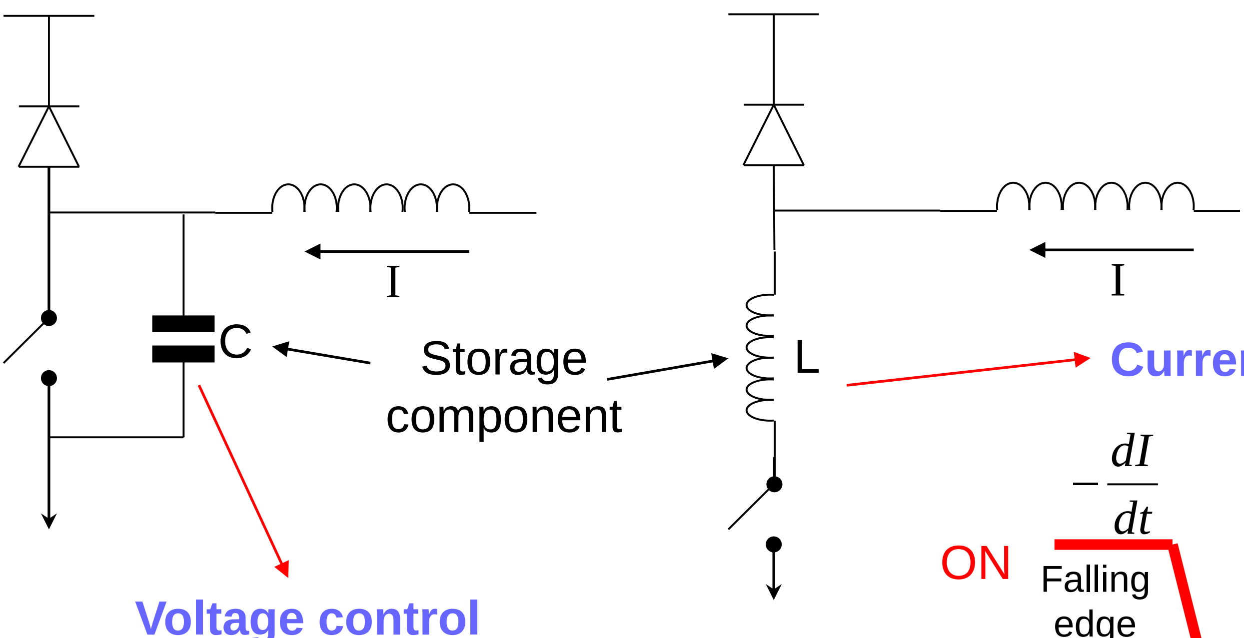
1. Circuits to control voltage
2. Circuits to control current.

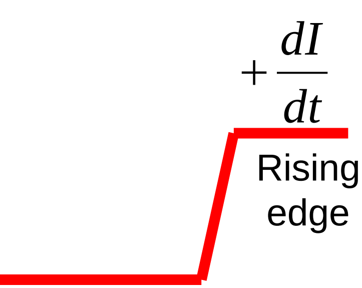
Snubber circuits are used to protect the transistors by improving their switching trajectory. There are three basic types of snubbers:

1. Turn-off snubbers
2. Turn-on snubbers
3. Overvoltage snubbers

For example, a capacitor placed in parallel with other circuit elements will control the rate of change of voltage (dV/dt) across them. An inductor placed in series with circuit elements will control the rate of change of current flow (dI/dt) through them.







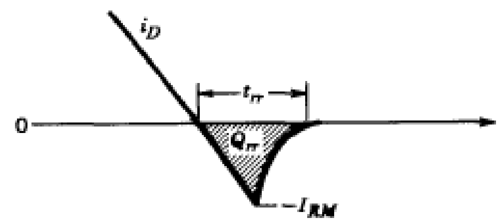
Within these broad headings there are further classifications according to whether energy is stored in the snubber or if it is dissipated, how stored energy is returned to the circuit, and whether energy moves in or out of the snubber on one or both edges of the switching event. The following table summarises some applications of snubber use.

Rate of change control

V ● Reduce power dissipation and voltage stress at turn-off.

I ● Reduce power dissipation and current stress at turn-on.

I ● Reduce diode reverse recovery current.



Damping (of natural frequency)

V ● Reduce overshoot and ringing at turn-off

I ● Reduce overshoot and ringing at turn-on.

V & I ● Reduce Electromagnetic Interference (EMI).

Clamping

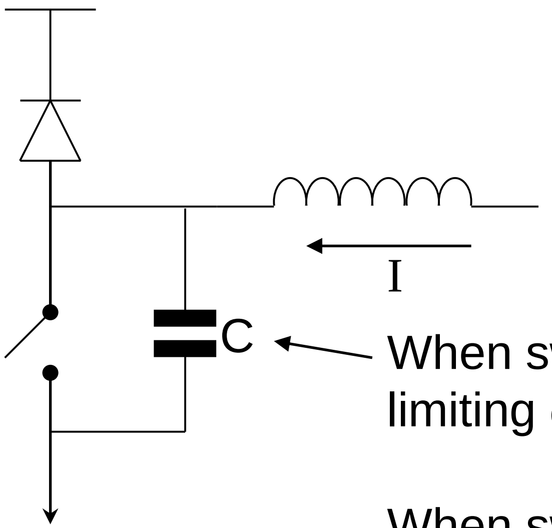
V ● Reduce peak switch voltage.

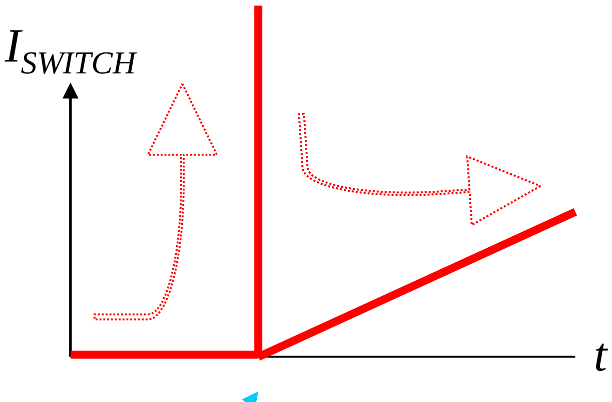
We will only consider simple **RC voltage** and **RL current** snubbers, and **diode clamps**.

There are two key points to note about snubber circuit design:

1. There is always **a degree of experimentation** needed to tune a snubber's operation. It is impossible to precisely design the circuit (although the desired function can be predicted).

2. The final circuit will probably be a **compromise**. A capacitive snubber that controls a voltage spike at turn-off may cause a current spike at turn-on. Similarly, controlling a current spike on one edge may cause a voltage spike on the other.





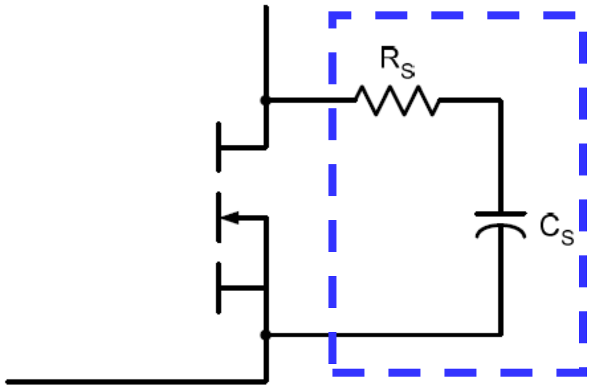
When switch opens, capacitor charges up, limiting dV/dt. (**Desired**)

When switch closes, capacitor is shorted, causing current spike. (**Undesired**)

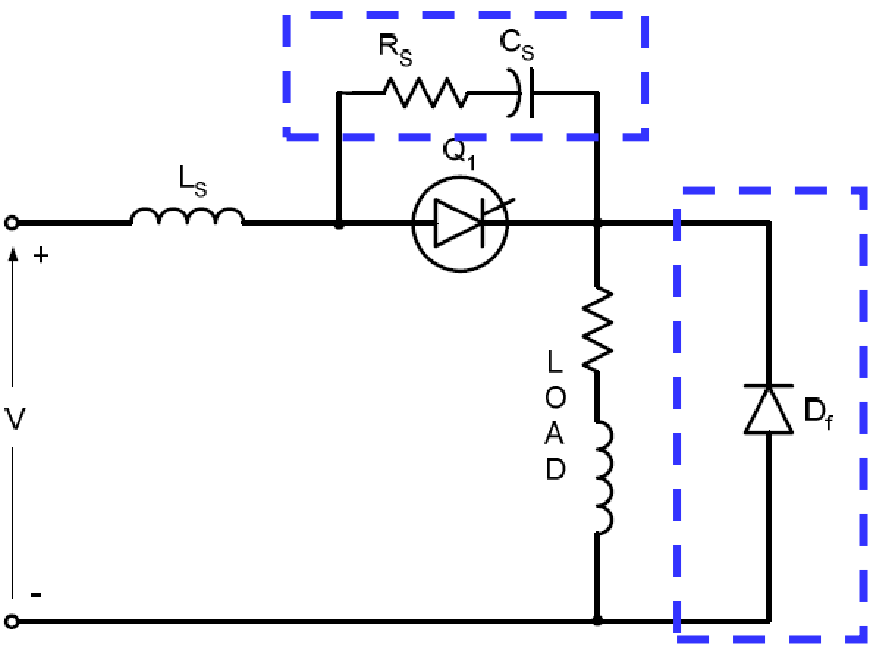
$$i_c = C\frac{dv}{dt}$$

Some Snubber Circuit Examples

Unpolarized **R-C** snubber



Unpolarized **R-C** snubber



Freewheeling/Clamping **Diode**

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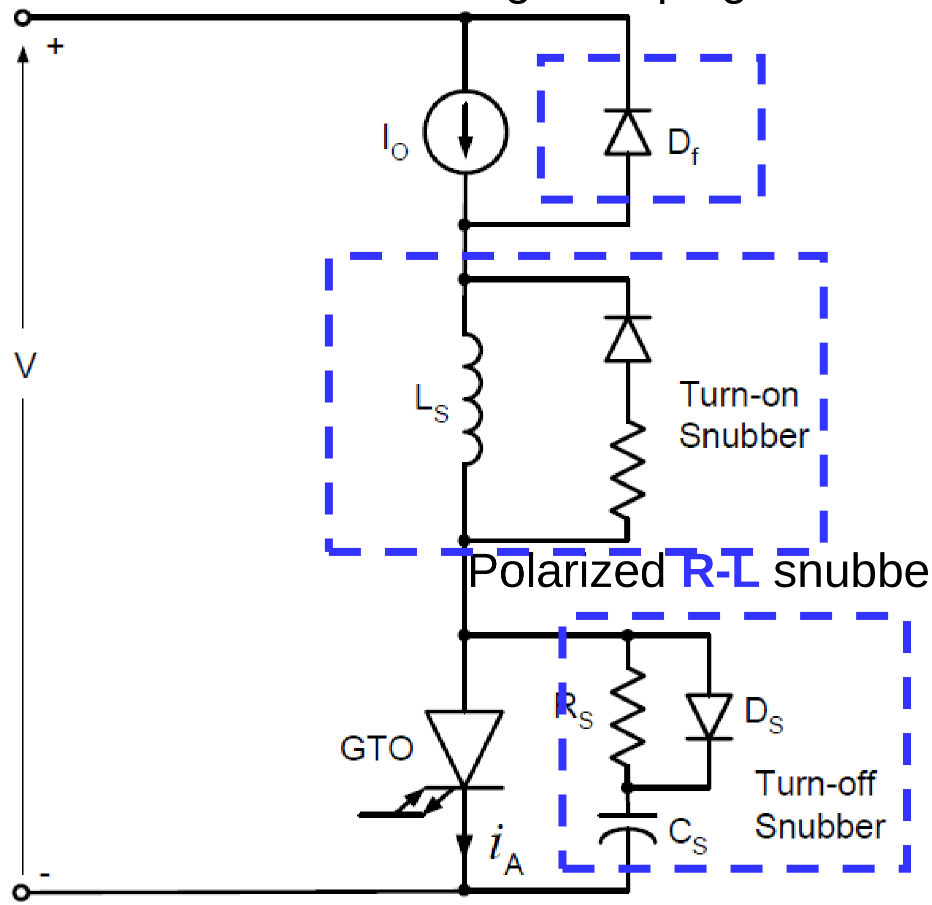


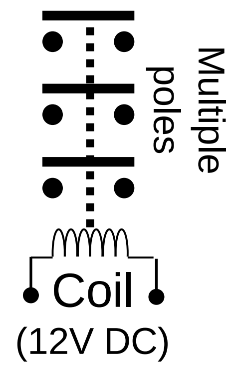
Polarized **R-C** snubber

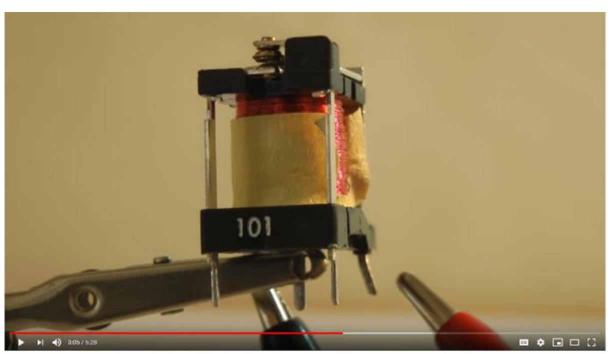
Diode clamps (freewheeling).(二极管钳位电路/续流电路)

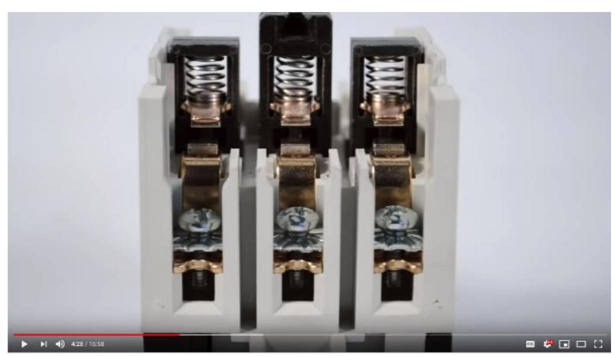
A relay（继电器） is an electromechanical device used to switch large currents and / or high voltages. A good example is the relay used to connect a car’s starter motor to the battery. The device is operated by using the magnetic field generated by a solenoid(电磁铁) to draw the main electrical contacts together.

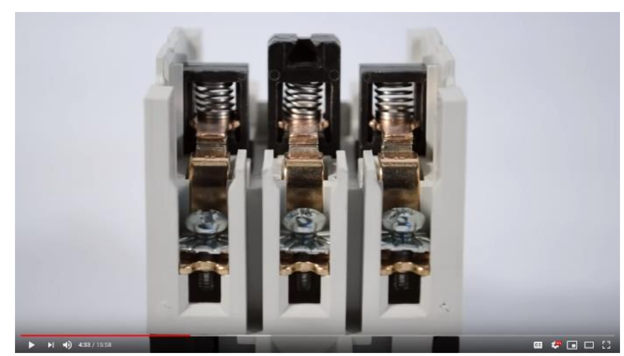
The electrical schematic is shown opposite.

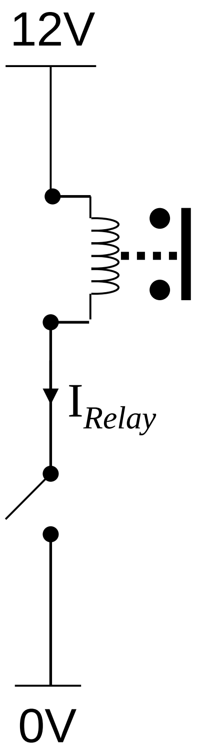
The solenoid used in the relay is a coil of wire wound around a high permeability (usually iron) core. The coil has both resistance and inductance.









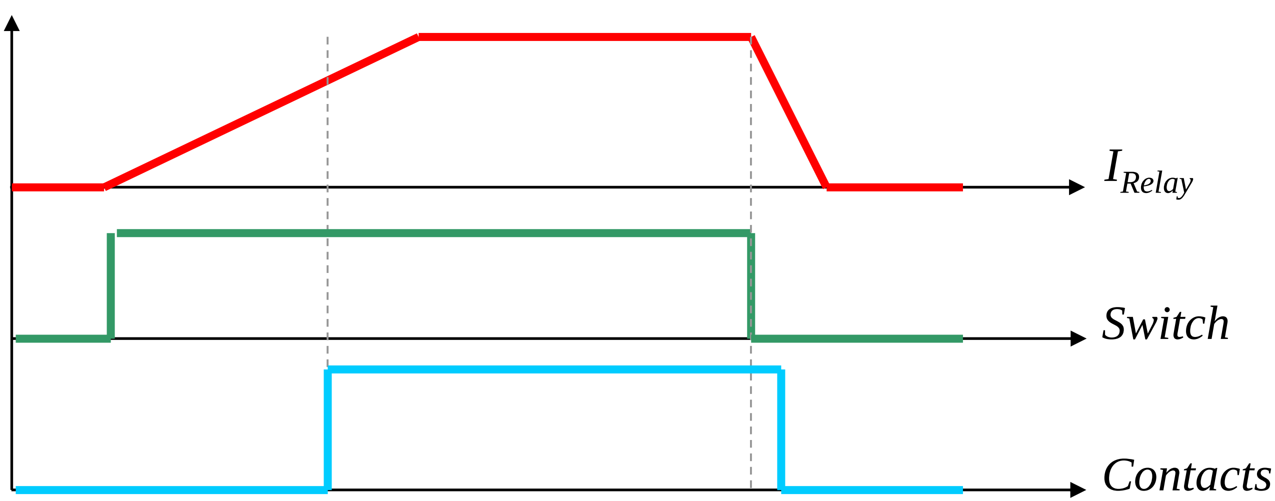


When the switch is closed, current (initially zero) starts to flow through the relay's solenoid. The current rises to the point where the magnetic field is sufficiently strong to close the relay contacts. (To ensure reliable operation, the relay usually operates at about 75% of the rated voltage.)

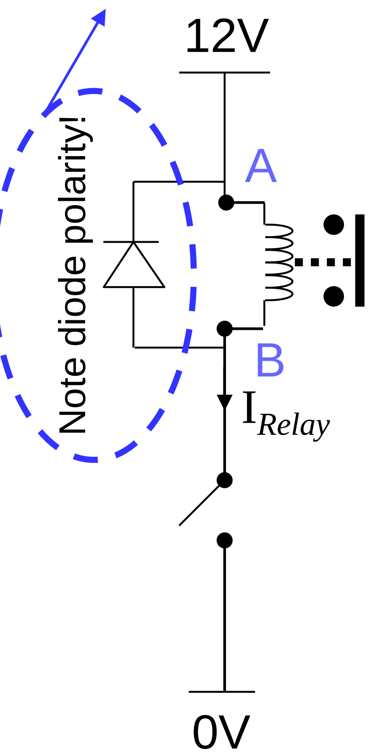
The DC current that flows through the relay's coil is limited by the coil's resistance.

At turn-off, the coil's inductance wants to keep I_{Coil} flowing, and to do this the coil voltage rises uncontrollably until a spark jumps across the mechanical switch contacts or destroys the electronic switch.

(**Typically the reverse spike is about 15X the supply voltage**.)



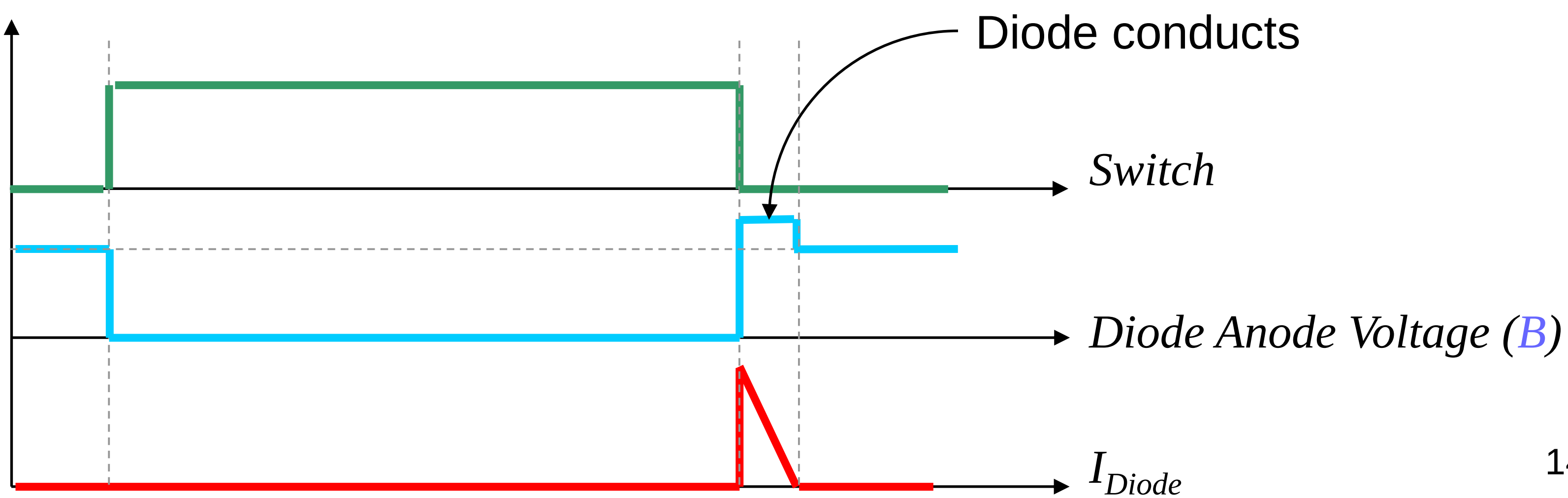
Clamp Diode



If a diode is placed in inverse parallel with the coil it is normally reverse biased and therefore does not affect circuit operation. However, when the switch is opened, the voltage a 'B' rises, as before, but the diode quickly starts to conduct and the reactive energy from the coil is dumped into the positive supply.

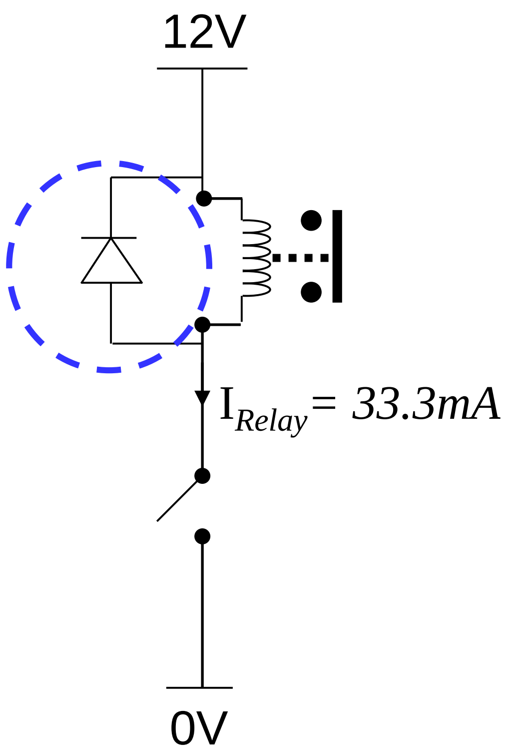
The maximum current in the diode is the same as the current that was flowing in the coil the instant before the switch was opened.

A disadvantage of this circuit is that the relay turn-off can be quite slow – the rate of change of inductor current is proportional to the voltage across it ($V = L\, dI/dt$), in this case about a volt.



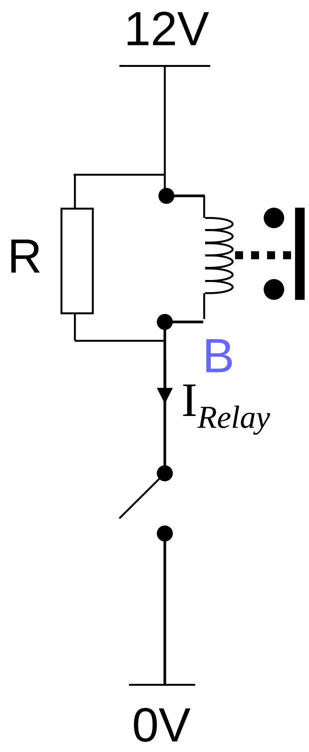
Example.

A relay has a coil rated at 12V DC and which has a resistance of 360Ω. What is the maximum current in a diode clamp placed across the relay's contacts?

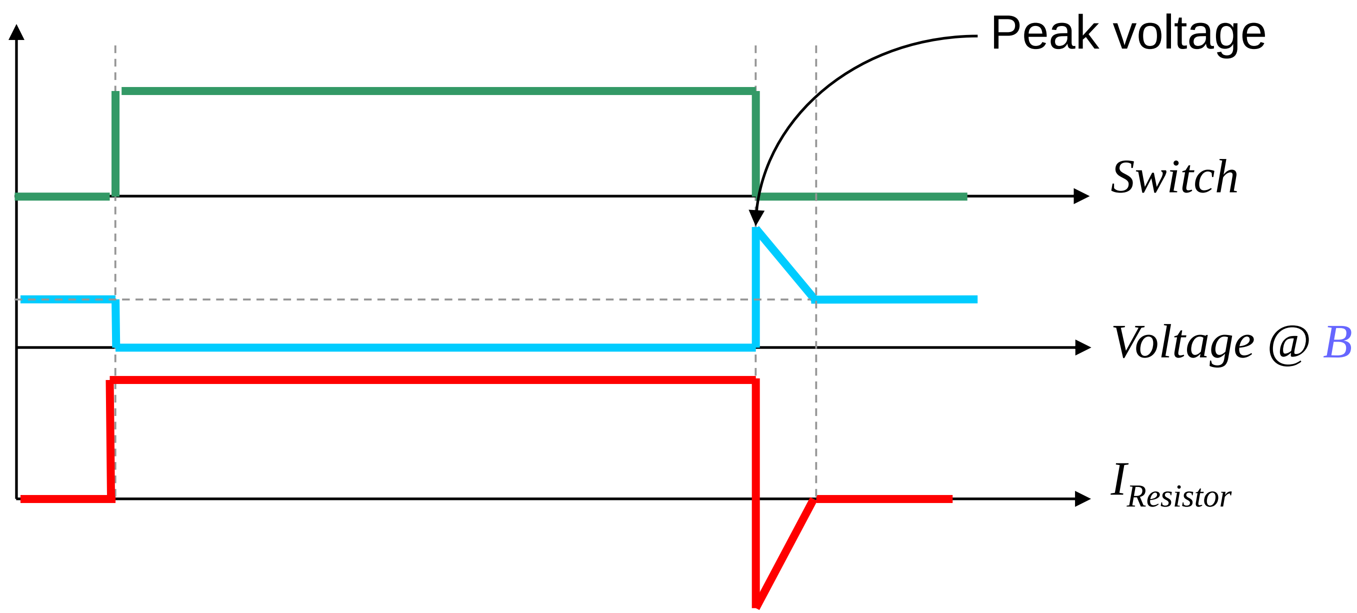


$$I_{\text{Relay}} = \frac{V}{R} = \frac{12}{360} = 33.3mA = \hat{I}_{\text{Diode}}$$

Note: Although the relay is inductive, we don't need to know anything about the value of the inductance to calculate the current in this instance.



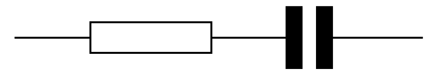
To speed up the relay release a resistor can be placed in parallel ("shunt") with the coil. However, this will dissipate power whenever the relay is energized. At turn-off the peak voltage seen at B is **$V_{Supply} + I_{Coil} \times R_{Shunt}$**.



For AC relays, a diode can't be used (it would short-circuit the relay on each negative half cycle). In these situations, a better choice is the RC snubber network.

Homework: What is a "Varistor"?

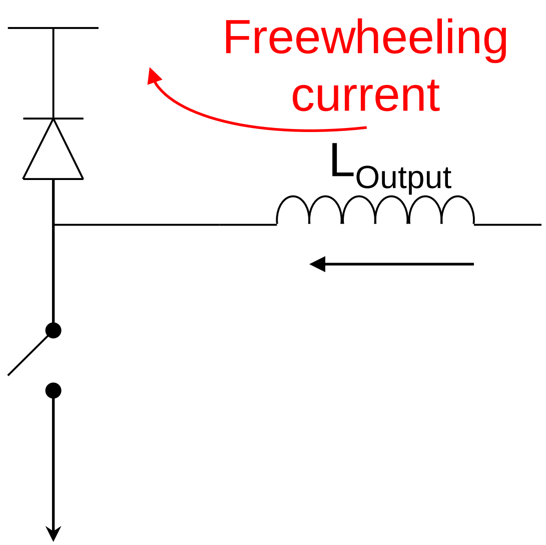
Voltage snubbers. (turn-off snubbers,电压缓冲电路 或 关断缓冲电路）



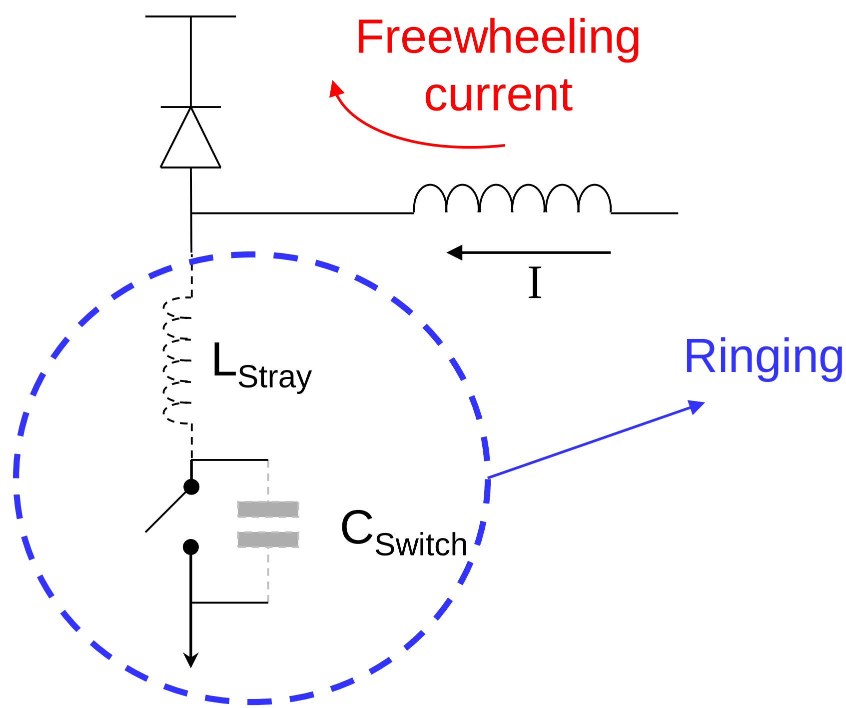
The simple resistor-capacitor (RC 阻容) snubber is probably the most widely used of all snubber circuits.

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).

Ideal circuit

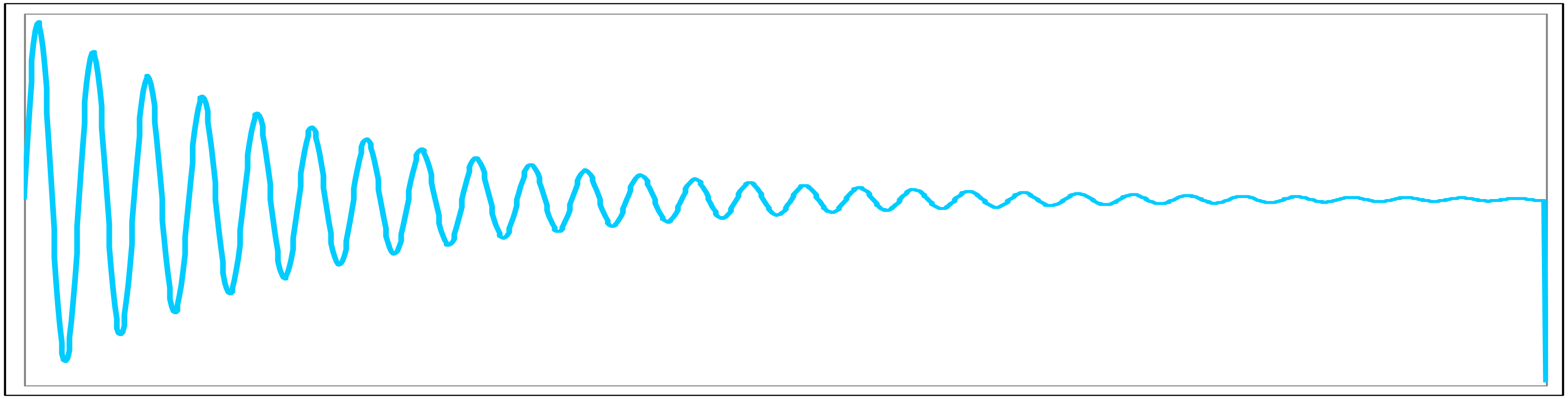


Actual circuit



In the ideal circuit (from a switched mode power supply; later lecture) the switch connects the output inductor L_{Output} to the negative supply voltage. Real electronic switches have a "**stray**" (杂散) capacitance between their terminals, and circuit board tracks introduce **stray** inductance between components. At switch-off, this capacitance rings with the inductance at the undamped resonant frequency $\boxed{f_o = \frac{1}{2\pi\sqrt{LC}}}$

In these "**parasitic**" (寄生) circuits there is usually very low resistance to dissipate the power in the oscillations and they can last for a considerable number of cycles.



The **RC snubber** will, if properly designed, damp (阻尼 或 衰减) the ringing and limit the overshoot at switching. *Optimum performance is obtained when the snubber capacitance is 3X the parasitic capacitance and the resistor value equals the characteristic impedance of the <u>un-modified</u> resonant circuit.*

The characteristic impedance is given by $\boxed{Z_O = \sqrt{\frac{L}{C}}}$

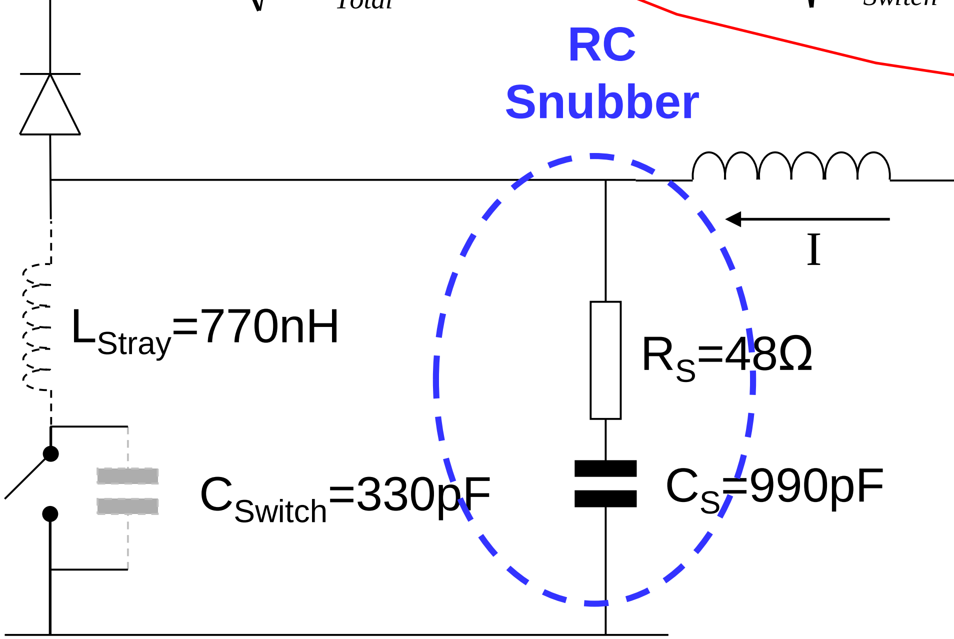
Example.

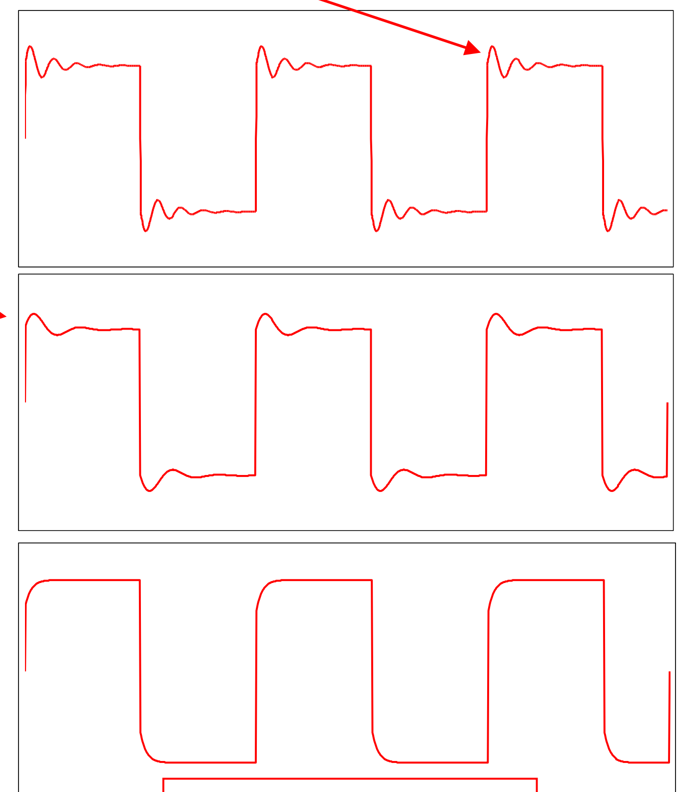
The switch in an SMPS has an output capacitance of 330pF and the stray inductance due to circuit board layout is 770nH. What is the undamped ringing frequency? An RC snubber is to be used to reduce the power dissipation in the switch and to control the ringing. What are the optimum values for R & C?

$$Undamped\ f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{330\times10^{-12}\times770\times10^{-9}}} \approx 10MHz$$

$$C_{Snubber} = 3\times C_{Switch} = 990pF \quad => C_{Total} = 1320pF$$

$$f_{New} = \frac{1}{2\pi\sqrt{LC_{Total}}} \approx 5MHz. \quad R_{Snubber} = \sqrt{\frac{L_{Stray}}{C_{Switch}}} \approx 48\Omega$$





Damped response.

Example (contd)

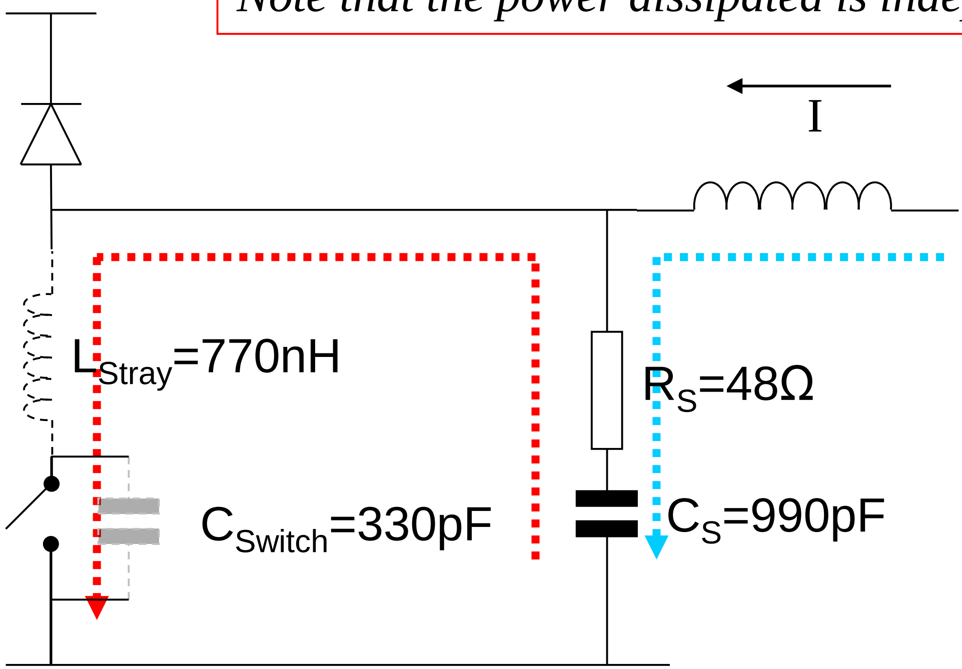
If the switching frequency is 100KHz and the maximum voltage across the snubber capacitor is 100V, estimate the power that is dissipated in the snubber resistor.

Energy in a capacitor is $E = \frac{1}{2} C V^2$

When the switch is open, the capacitor charges to 100V via the resistor. When the switch closes, the capacitor is discharged via the resistor. Hence the energy dissipated per cycle is CV^2 and the energy dissipated per second is $f\,CV^2$ W.

$$P = f\ CV^2 = 10^5 \times 990\,pF \times 100^2 = 0.99W$$

Note that the power dissipated is independent of the resistor value!



Caveat: This works for

$\tau_{Osc} << T_{Switch}$

τ=RC =>τ_{Osc} = 47.5nS

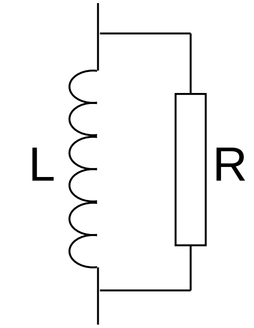
T_{Switch} = $1/F$ = 10μS, so OK.

Note that the current from the snubber flows through the switch when the switch is closed, increasing I_{Switch}.

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

The main purpose of a current snubber is as a means of controlling the rate of rise of current in a switch. Recalling that the current through an inductor cannot change instantaneously, this means that when the switch closes, the current through it must be zero. The voltage across the inductor can rise instantaneously, and it is this voltage that will cause current to start to flow through the inductor (from $V=L\ dI/dt$).

Simple RL snubber.



The parallel RL snubber is the dual of the series RC circuit just discussed. It is not used very often because the value of R tends to be too large to damp circuit ringing. If R is reduced to be effective on ringing, the power dissipation tends to be very high.

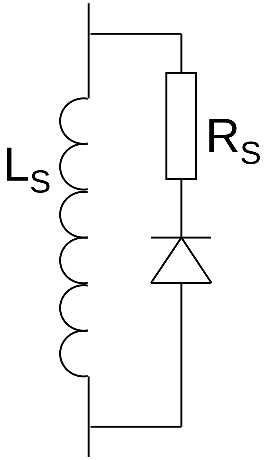
[Ferrite beads(铁氧体磁珠) are simple RL circuits . However, their power dissipation is poor and generally they aren’t used in power electronic circuits. Having said that, they are extremely useful because at low frequency the inductance dominates whereas at high frequency (F > 10MHz) the resistance dominates.]

Ferrite beads are used for damping high frequency noises.

$$z_L = \omega L$$

passive low-pass filter

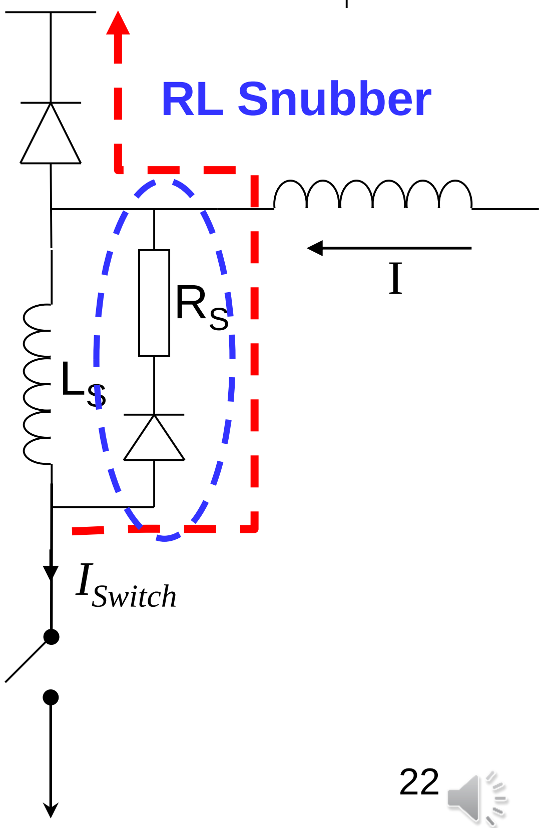
A useful variation on the simple RL snubber is to add a diode in series with the resistance. This is very similar in operation to the diode clamp discussed earlier. Because the circuit operates differently according to whether or not the diode is conducting, it is called a "**polarised snubber**".



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.

$$\boxed{V_{Peak} = \underbrace{V_{Diode}}_{=1V} + I_{Switch} R_{Snubber}}$$



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

The power dissipated in the resistor is the energy stored in the inductor X the number of times per second the inductor’s energy is dissipated. Note the current only flows in the resistor when the switch is opened.

$$P_{Resistor} = \frac{1}{2} L_{Snubber} \times I_{Switch}^2 \times f_{Switch} \qquad (\mathrm{For}\ \tau_{\mathrm{L}} << \mathrm{T}_{\mathrm{Switch}}; \tau_{\mathrm{L}} = \frac{\mathrm{L}}{\mathrm{R}})$$

Note the power dissipated is independent of the resistor value.

Current rate of rise (dI/dt) is limited to V/L (from $V=LdI/dt$).

This type of snubber is very effective in increasing circuit reliability because of the way the current rise is controlled when the switch turns on.

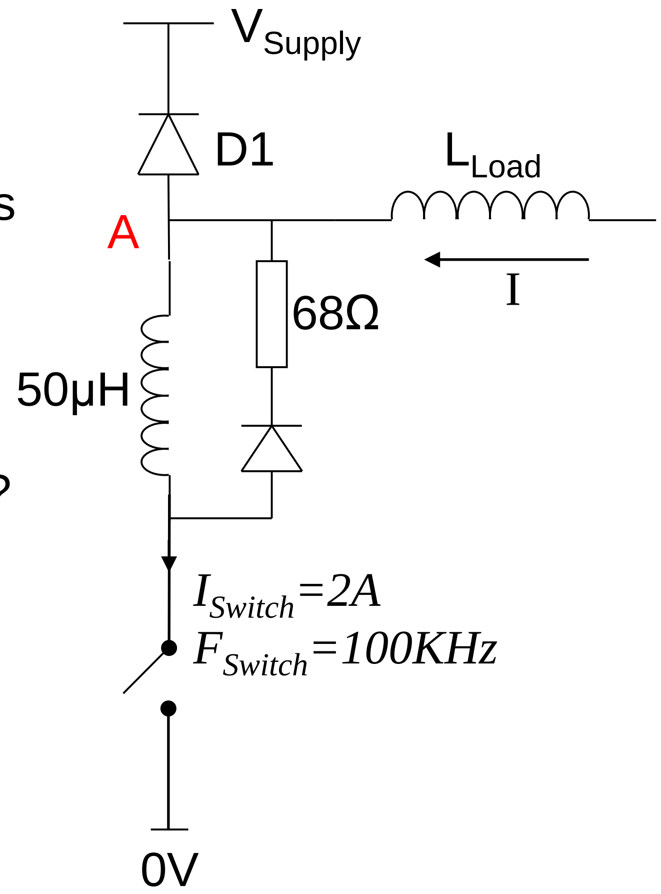
Example

In the circuit shown, the switch operates at 100KHz. The supply voltage is 200V. If the peak current in the switch is 2 amps, what power is dissipated in the resistor?

What is the rate of rise of current limited to if the voltage at A is 200V when the switch is closed?

What is the peak voltage across the inductor and switch?

[Note that when the switch opens, the voltage at A is 1 diode drop higher than V_{Supply}. Why?]



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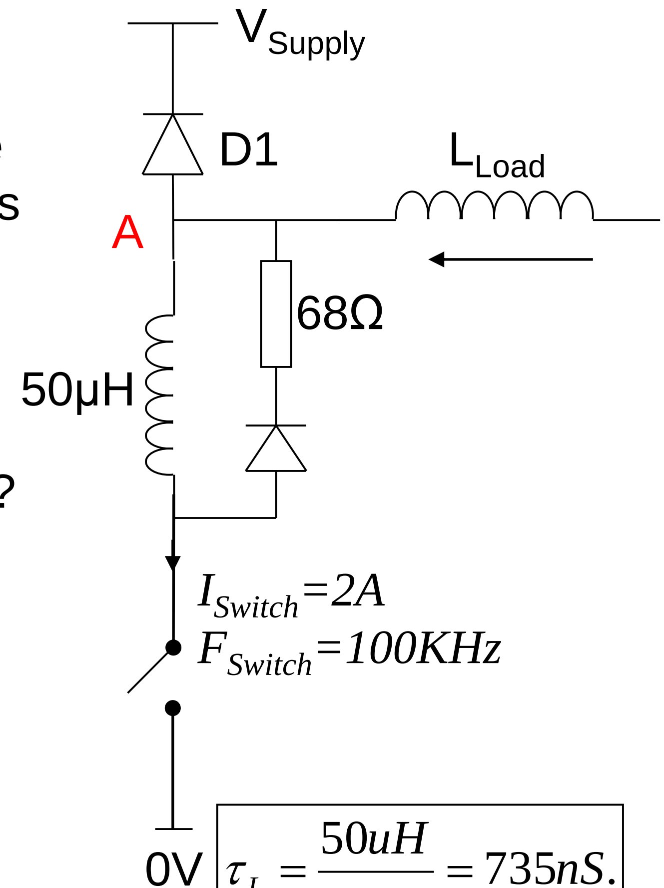


$$\tau_L = \frac{50uH}{68\Omega} = 735nS.$$

$$T_{Switch} = 10uS$$

$$\text{Inductor energy} = \frac{1}{2} L I^2 = 2 \times 50\,\mu\text{H} = 100\,\mu\text{J}$$

$$P_{Resistor} = \frac{1}{2} F_{Switch} L I^2 = 100\,\mu\text{J} \times 100\text{KHz} = 10\text{W}.$$

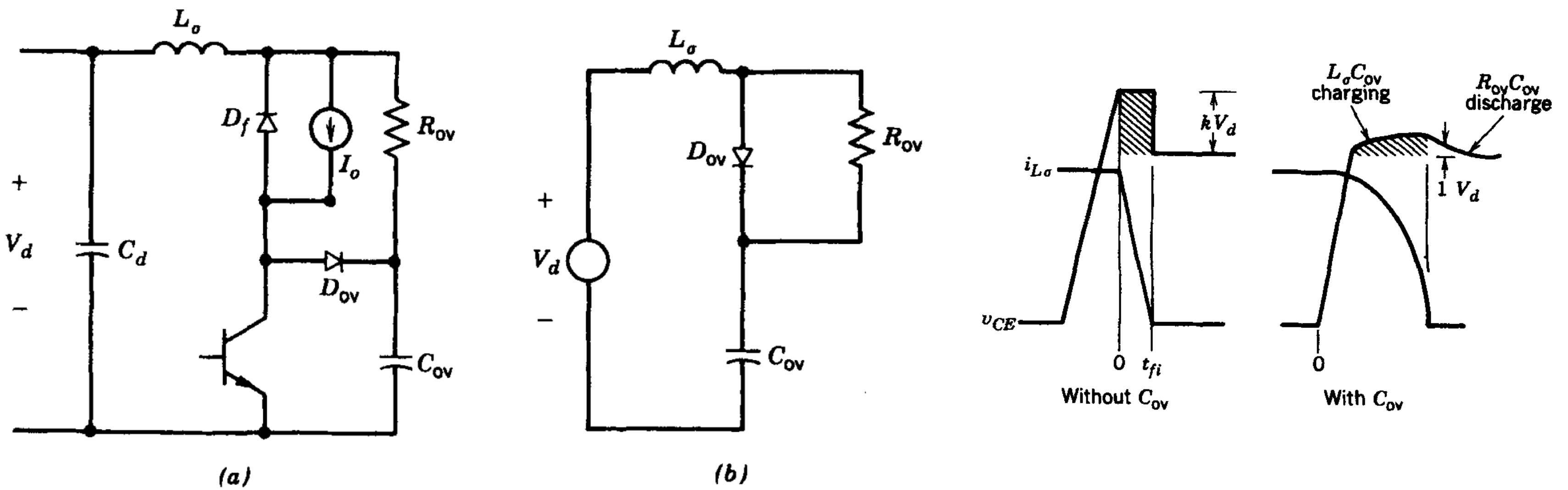
$$V = L\frac{dI}{dt} \Rightarrow \frac{dI}{dt} = \frac{V}{L} = \frac{200\text{V}}{50\,\mu\text{H}} = 4\text{A}/\mu\text{S}.$$

$$V_{Switch} = \underbrace{V_{Supply} + V_{D1}}_{\text{Voltage at A}} + (\hat{I}_{Switch} R_{Snubber} + V_{Diode}) = 200\text{V} + 1\text{V} + (2\text{A} \times 68\Omega + 1\text{V}) = 338\text{V}$$

When switch opens, current through L_{Load} drives A positive until D1 conducts.

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**.



For details, please refer to page 686 of the text book: 27-6 OVERVOLTAGE SNUBBER