EE394 Part 4

Note Title 11/5/2007

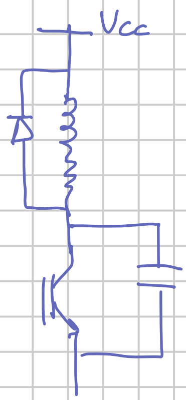
Snubbers

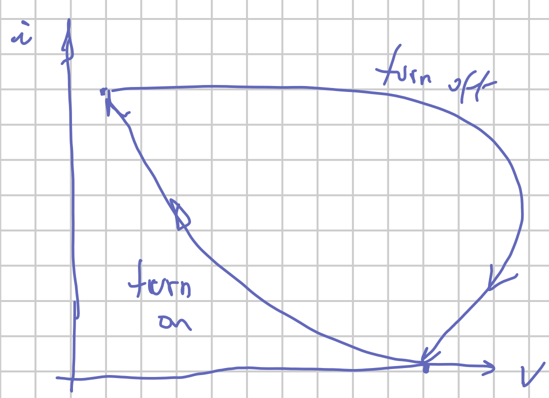
"A snubber is a circuit connected around a power semiconductor device (switch) for the purpose of altering its switching trajectory. Snubbers usually have the objective of reducing power loss in the semiconductor device."

from Krein

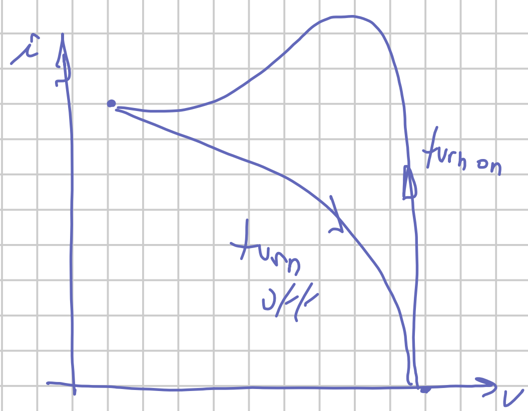
The idea is that the commutation becomes more linear

Simplest example → with inductive load a capacitor can elliminate the voltage overshoot during turn off but the "price" to pay is now a current overshoot.

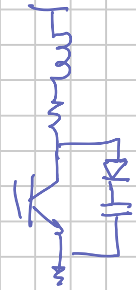




without

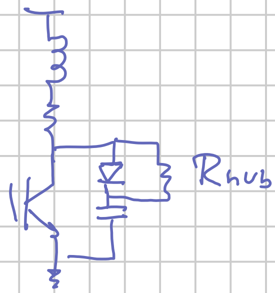


Additional issue: I can't always add the clamping diode so I can do something like this:



But this circuit doesn't work because I can't discharge the capacitor

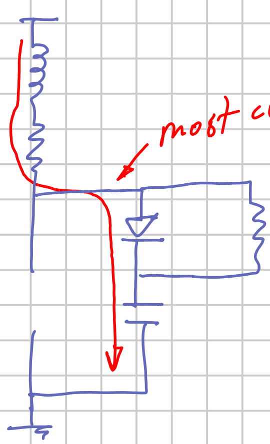
One alternative is to add a resistor to discharge the capacitor:



Lossy snubber → Switching losses are traded off for resistive losses

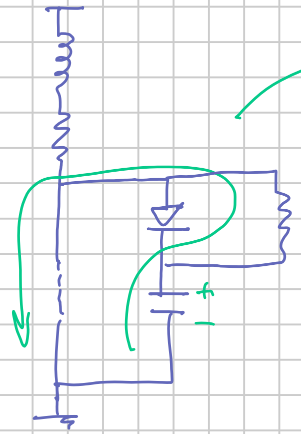
But if capacitor is sized correctly then it may be work.

turn off and Q_1 off



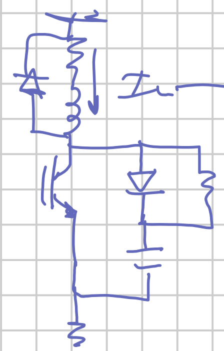
most current flows like this until the capacitor is charged and current stops to flow → so current flows mostly during turn-off (if capacitor is sized properly

oscilatory RLC circuit



During turn-on the capacitor discharges through the resistance. Hence, current overshoot is reduced (no short-circuit)

For simplicity consider a clamped RL load with real diode:



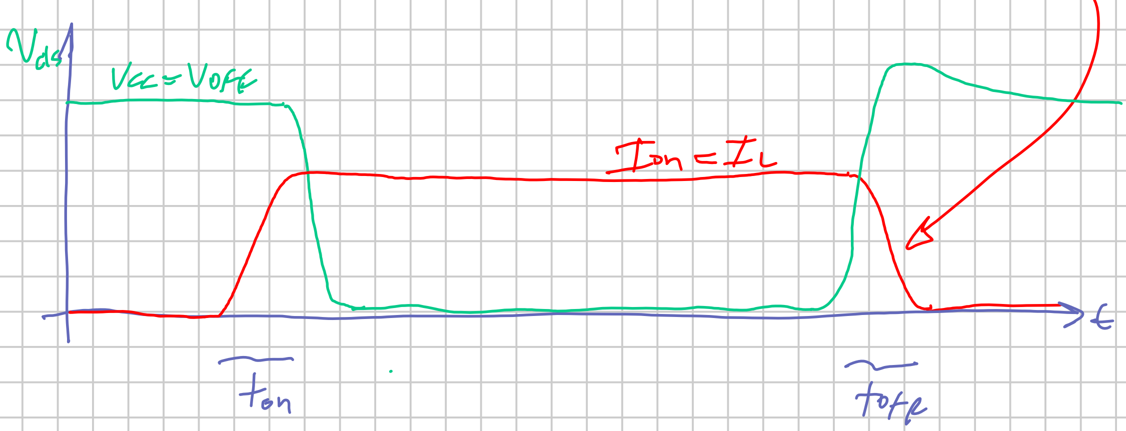
I_L → assumed to be constant

→ turn off snubber

The design must achieve 2 objectives → 1) The capacitor should be big enough to avoid voltage overshoot during turn-off

2) $\tau = RC$ should be short enough so the capacitor discharges completely before the switch turns off and starts to get charged again

As seen before the current changes linearly during turn off



$$i_{sw}(t)\Big|_{t_{off}} = I_L - \frac{I_L}{t_{off}} t$$

During turn off $i_C = I_L - i_{SW} = \frac{I_L}{t_{off}} t$

$$V_C = \int_0^{t_{off}} \frac{i_C}{C} dt = \int_0^{t_{off}} \frac{I_L t\, dt}{t_{off} C} = \underbrace{\frac{I_L t^2}{2 t_{off} C}}_{V_C(t)|_{t_{off}}} \Bigg|_0^{t_{off}} = \frac{I_L t_{off}}{2C}$$

$$U_{SW_{toff}} = \int_0^{t_{off}} V_C(t)\, i_{SW}(t)\, dt = \int_0^{t_{off}} \left(\frac{I_L t^2}{2C t_{off}}\right)\left(I_L - \frac{I_L}{t_{off}} t\right) dt$$

$$U_{SW_{toff}} = \frac{I_L^2}{24C} t_{off}^2$$

The capacitor will be charged until it reaches V_{off}; hence, it accumulates an energy of

$$U_C = \frac{1}{2} C V_{off}^2$$

This energy is dissipated in the resistance during turn on:

Recall that inductive commutation has a loss of

$$P_{SW}\Big|_{IC} = \frac{V_{off} I_L t_{sw}}{a} f$$

$a = 2$ ideal diode

$a = 1.5$ real diode

With a snubber

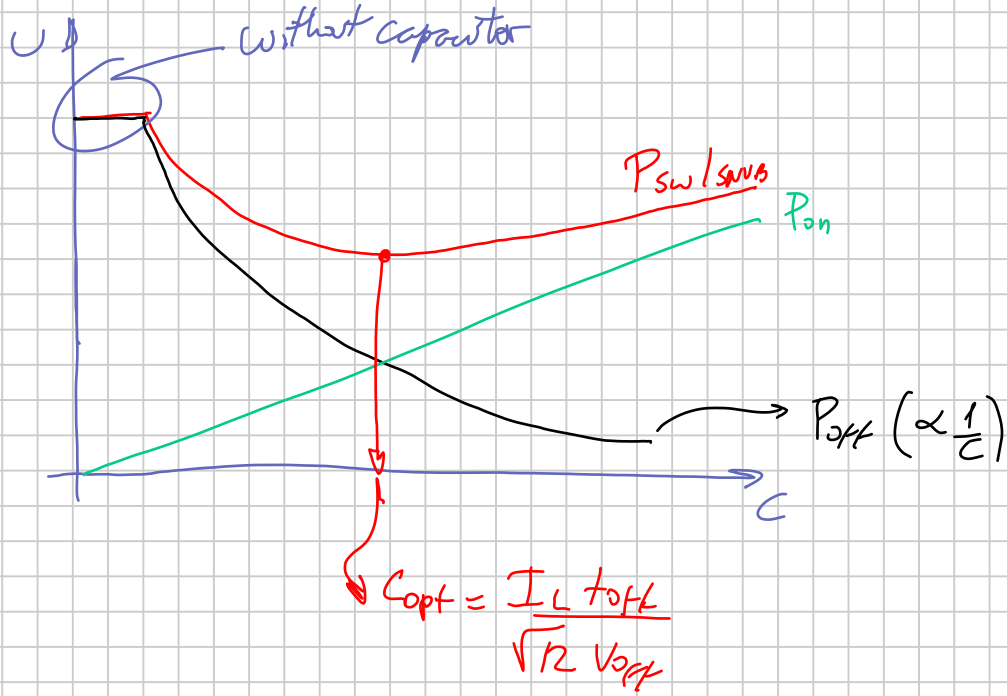
$$P_{SW}\Big|_{SNUB} = \Bigg(\underbrace{\frac{I_L^2 t_{off}^2}{24C}}_{P_{off}} + \underbrace{\frac{1}{2} C V_{off}^2}_{P_{on}}\Bigg) f$$

We want that

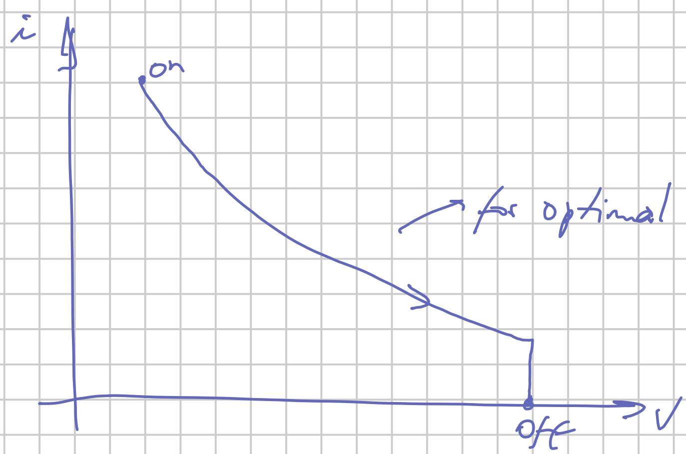
$$P_{SW}\Big|_{IC} > P_{SW}\Big|_{SNUB}$$

If $a = 2$ (ideal diode)

$$\frac{I_L^2}{12C} t_{off}^2 + C V_{off}^2 < I_L V_{off} t_{sw}$$



With optimal snubber $a \simeq 3.5$ $(a = \sqrt{12})$



From condition (2) above:

If $\tau = RC < \frac{t_{cond}}{2} \rightarrow$ More than 98% of the capacitor energy is discharged before turn-off

Thus $\rightarrow RC < \frac{DT}{2} \rightarrow R < \frac{DT}{2C}$

The resistor power rating is the average power given by the energy stored in the capacitor

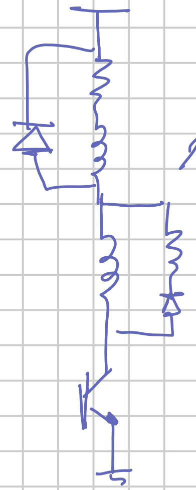
$$P_R = \frac{1}{2} C V_{off}^2 f$$

The capacitor serves to avoid overshoots during turn off, so it reduces losses during turn off

For turn on transitions the dual circuit is needed.

Dual of capacitor → Inductor

Turn-on snubber



Snubber's inductor limits the rate of rise of switch current during switching

After the switch turns off the energy dissipates through the diode and resistance

Assuming linear voltage transient

$$v_L = V_{off} \frac{t}{t_{on}}$$

$$U_{sw_{t_{on}}} = \int_0^{t_{on}} v_{sw} \, i_{sw} \, dt = \int_0^{t_{on}} V_{off} \left(1 - \frac{t}{t_{on}}\right)\left(\frac{V_{off}}{L} \frac{t^2}{2 t_{on}}\right) dt$$

Hence

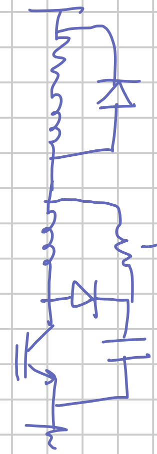
$$P_{sw}\Big|_{snub} = \left(\frac{V_{off}^2 \, t_{on}^2}{24 L} + \frac{1}{2} L I_{on}^2 \right) f$$

optimal → $L_{opt} = \frac{V_{off} \, t_{on}}{\sqrt{12} \, I_{on}}$

Additional condition: $\frac{L}{R} < \frac{(1-D)T}{2} \longrightarrow R > \frac{2L}{(1-D)T}$

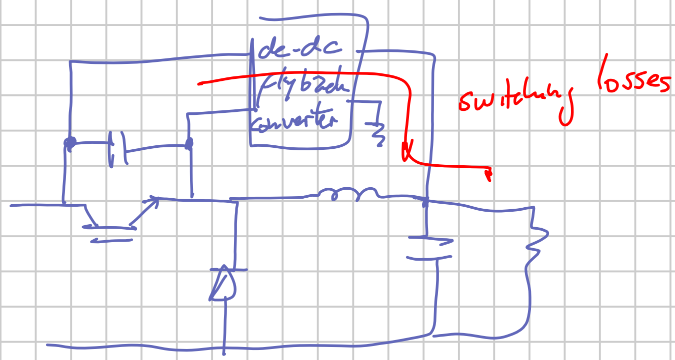
↓

Combined snubbers



Must dissipate $\rightarrow \frac{1}{2}CV_{off}^2 + \frac{1}{2}LI_{on}^2$

Lossless snubbers $\rightarrow$ losses are re-injected to the output (like a car turbo charger)



Additional techniques $\rightarrow$ resonant methods