6.334 Lecture Notes — Switching Losses + Snubbers

Review

Transistor : switch (on - off) or current source

Ideal Switches
- instantaneously turn on and turn off
- on-state : zero voltage drop or zero resistor
- off-state : zero current flow or infinite resistor
- no parasitics

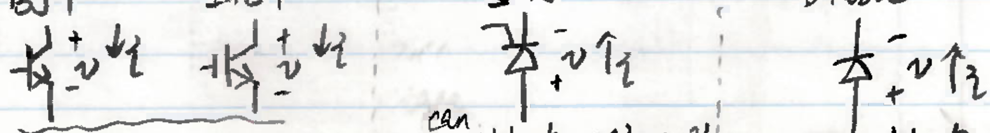
⇒ zero loss

Practical Switches
- finite time for turn on and turn off
- on-state : a voltage drop or a resistor
- off-state : leakage current
- parasitics : include a parallel capacitor
  - may include an anti-parallel diode

⇒ non-zero losses {
- conduction loss
- switching loss ← snubbers
- gating loss
- other losses

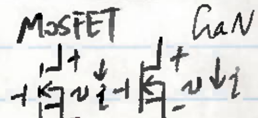
on-state: a voltage drop

	fully-controlled		half-controlled	uncontrolled
recall DC/DC lecture 2	BJT	IGBT	SCR	Diode
can:	block $+v$, carry $+i$		can: block $+v$ or $-v$, carry $+i$	can: block $-v$, carry $+i$



on-state: a resistor

MOSFET GaN HEMT



can: block $+v$
carry $+i$ or $-i$

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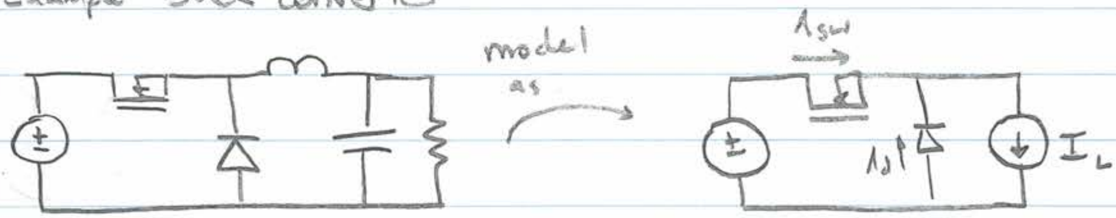
Semiconductor Losses (Back of the envelope)

Example: Buck converter:



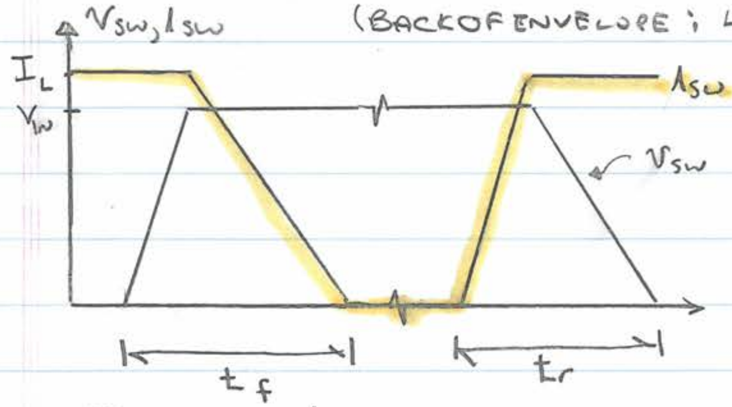
Device Conduction losses:

mosFETs look ~ resistor $\quad P_{FET,COND} \approx i^2_{sw,rms} R_{dson} = (I_L^2 D) R_{ds,on}$

Diodes look ~ const drop $\quad P_{d,cond} \approx \langle i_d \rangle V_{d,on} = I_L D' V_{d,on}$

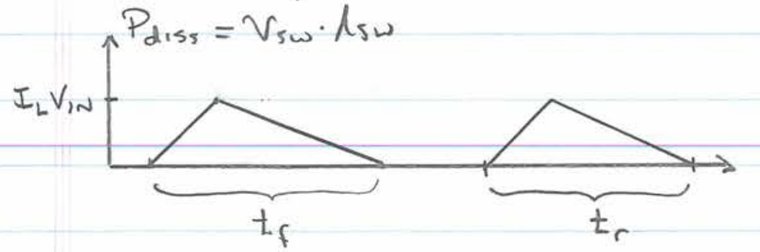
Device Switching losses: {occur as switches turn on and off}

(BACK OF ENVELOPE; LINEAR v, i transitions) → Assume non-ideal switch, ideal diode



★ TURN OFF OF MOSFET

Current falls AFTER device voltage rises, because diode can't turn on (carry current) until $v_d \to 0$



★ TURN ON OF MOSFET

Current in mosfet must rise to full value (diode current goes to 0) before diode turns off + blocks voltage

t_f, t_r governed by devices + drivers

$$P_{sw,fet} \approx \left[\frac{1}{2} t_f I_L V_{IN} + \frac{1}{2} t_r I_L V_{IN} \right] f_{sw}$$

(Based on approximate linear transitions. Other losses and diode losses exist)

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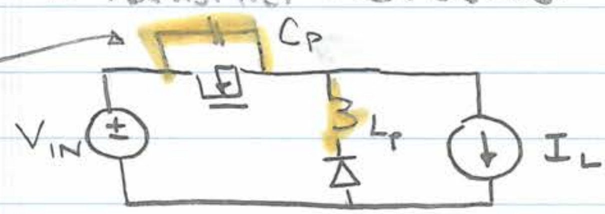
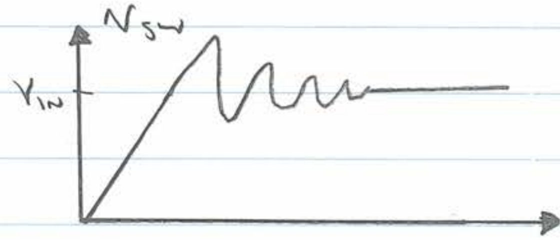
Note: major loss component $\propto f_{sw}$. We want $f_{sw} \uparrow$ to make $L, C \downarrow$ but losses ultimately limit us.

We would like $t_r, t_f \downarrow$ to reduce switching loss, but other factors come into play:

1. Parasitics + Overshoot

lose capacitor energy $\Delta W = \frac{1}{2} C_p V_{IN}^2$ on switch turn on





overvoltage on switch at turn off

2. EMI

High $\frac{di}{dt}, \frac{dv}{dt}$ lead to EMI, may affect control circuits

$\frac{di}{dt} \rightarrow$ magnetic coupling $\quad v = L_M \frac{di}{dt}$

$\frac{dv}{dt} \rightarrow$ capacitive coupling $\quad i = C \frac{dv}{dt}$

3. Rate limits

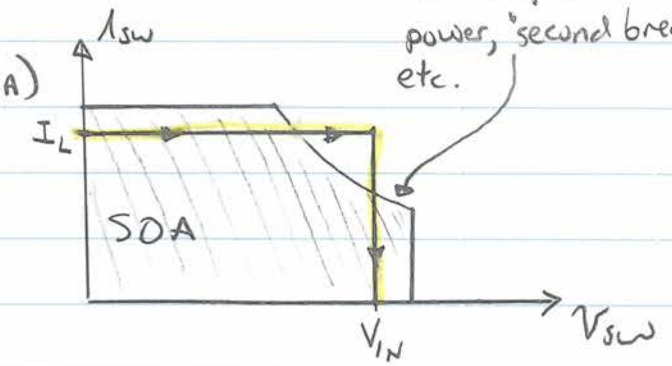
Some devices (BJT, GTO, MCT) have limits on allowed $\frac{dv}{dt}, \frac{di}{dt}$ → MOSFETs are immune to these effects.

high $\frac{di}{dt} \rightarrow$ destroy device on turn on

high $\frac{dv}{dt} \rightarrow$ can trigger device back on

4. SAFE OPERATING AREA (SOA)

Some devices cannot sustain high simultaneous v, i.



Limit may be instantaneous power, "second breakdown", etc.

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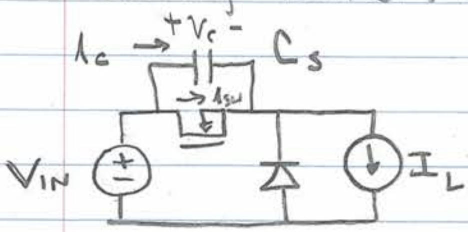
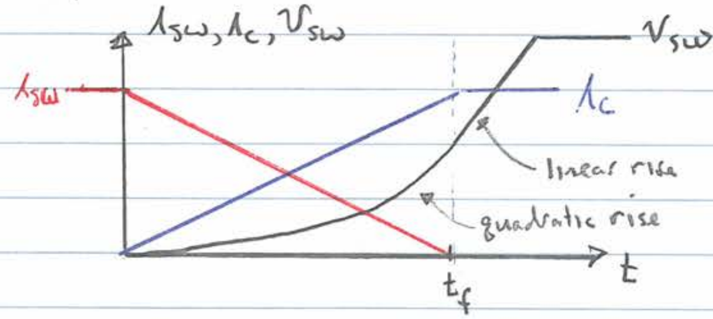
Snubbers
1. Control switching locus
2. Reduce internal device dissipation

Suppose we placed a capacitor across the device during turn off:





I_L diverted through C_s while switch turns off:

$$i_{sw} = I_L(1 - t/t_f) \quad 0<t<t_f$$

$$i_c = I_L \frac{t}{t_f} \quad 0<t<t_f$$

$$v_c = \frac{1}{C}\int_0^t i_c\,dt = \frac{I_L t^2}{2t_f C} \quad 0<t<t_f$$

$$P_{diss,sw} = i_{sw}\cdot v_c = I_L(1 - t/t_f)\cdot\frac{I_L t^2}{2t_f C} \quad 0<t<t_f$$

$$E_{diss} = \int_0^{t_f} i_{sw}\cdot v_c\,dt = \frac{I_L^2}{2t_f C}\int_0^{t_f}\left(t^2 - \frac{t^3}{t_f}\right)dt$$

$$\boxed{E_{diss} = \frac{I_L^2}{2t_f C}\left(\frac{1}{3}t_f^3 - \frac{1}{4}t_f^3\right) = \frac{I_L^2 t_f^2}{24\,C}}$$

We reduce device turn-off loss with the capacitor!

We also store energy in the capacitor $E_{stored} = \frac{1}{2}C V_{in}^2$

This is $\geq \frac{1}{2} C \frac{I_L^2 t_f^4}{4t_f^2 C^2} = \frac{I_L^2 t_f^2}{8C}$

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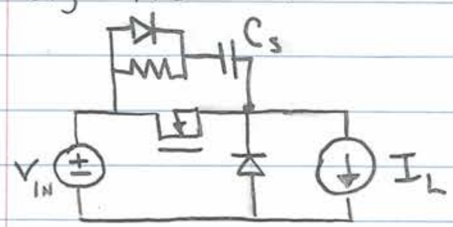
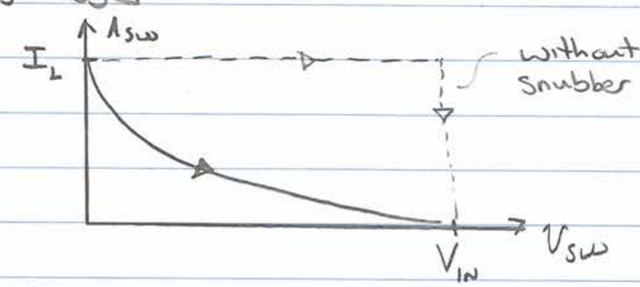
So: we reduce device loss @ turn off. as C↑ loss ↓

★ But ! @ switch turn on, E_{stored} on cap gets dumped into switch!
- → could destroy switch!
- → dumped energy increases as C↑

To build effective snubbers, we remove or recover the stored energy in some other fashion!

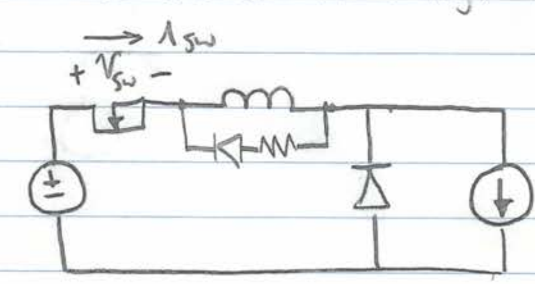
e.g. RCD turn-off snubber

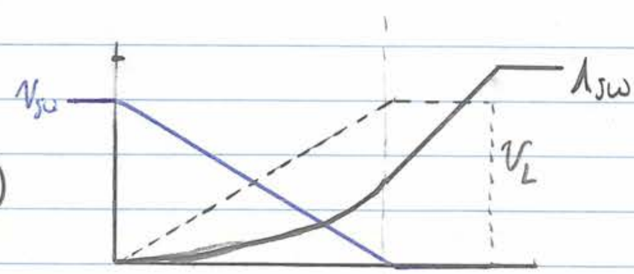




- During turn off, Cs is effectively in parallel w/ the switch
- when switch is on, capacitor stored energy is <u>slowly</u> dissipated in R (we need some on-time to complete the discharge
- snubber only operates during switching transitions
  - ⇒ SWITCHING LOCUS IMPROVED (SOA, lower $\frac{dV}{dt}$)
  - ⇒ <u>DEVICE LOSS REDUCED</u> (BUT TOTAL DEVICE + RESISTOR LOSS IS TYPICALLY HIGHER!)

we can do similar things at device turn on!





- Reduces Switch turn on losses
  - → Total switch + Resistor losses may be higher with snubber
  - → does not reduce loss associated with parasitic capacitance across the switch
  - → controls switching Locus (SOA, dI/dt ↓)
  - → results in slightly increased switch voltage

NOTE: INSERT DIODE RECOVERY?

→ Could also describe gate drive techniques to get differential on/off transitions