6.622 Power Electronics *Prof. David Perreault*

Lecture 15 - Switching losses and snubbers

1 Review

<u>Transistor</u>: Switch (on-off) or current source 

<u>Ideal switches</u>

Instantaneously turn on and off
On-state: Zero voltage drop or zero resistor
Off-state: zero current flow or infinite resistor
No parasites ⇒ zero loss

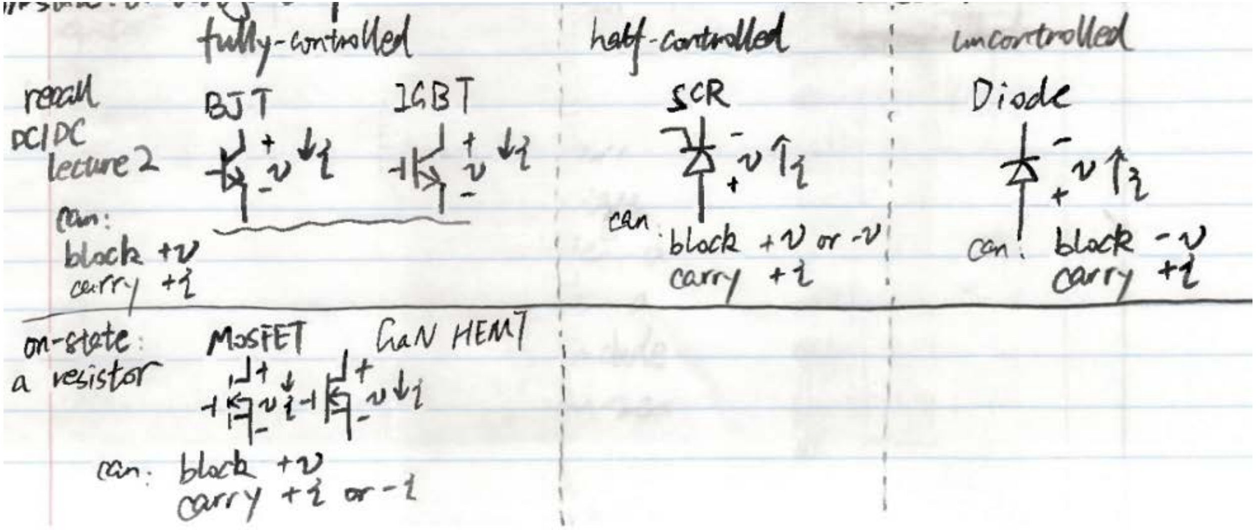
<u>Practical switches</u> Finite time for turn on and turn off

On-state: a voltage drop of a resistor

Off-state: leakage current

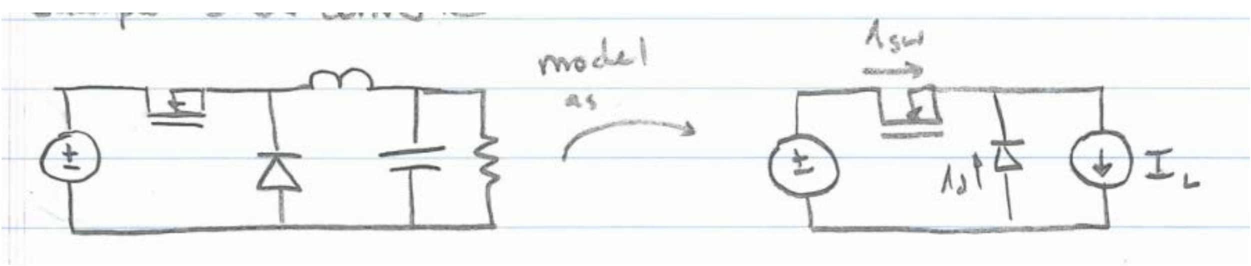
Parasitics: include a parallel capacitor, may include an anti-parallel diode ⇒ non-zero loss including conduction loss, switching loss (snubbers), gating loss, other losses

On-state: a voltage drop



2 Semiconductor losses (back of the envelope)

Example buck converter:



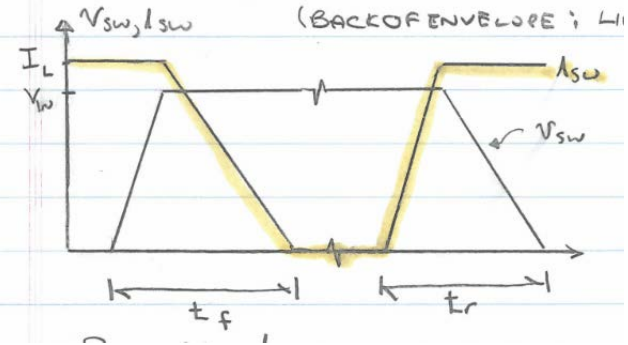
Device conduction losses:

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

diodes look const drop $P_{d,cond} \approx < i_d > V_{d,on} = (I_L D') V_{d,on}$

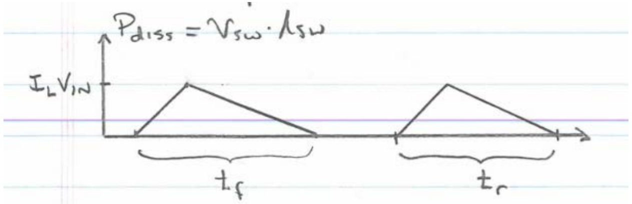
Device switching losses: occur as switches turn on and off

(Back of envelope: linear v,i transitions)



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

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

t_f, t_r governed by devices and drivers

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

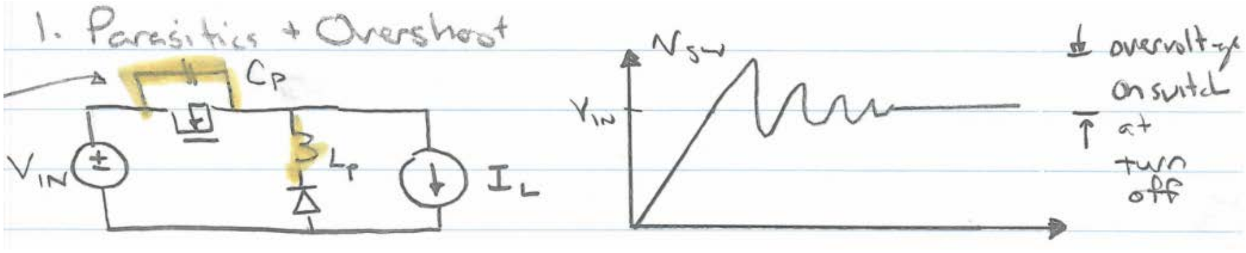
(Based on approximate linear transitions. Other losses and diode losses exist)

Note: major loss component $\approx f_{sw}$. 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 factor come into play:

1. Parasitics and overshoot

   Lose capacitor energy $W = \frac{1}{2} C_p V_{in}^2$ on switch turn on

2. EMI

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

$\frac{di}{dt}$ → magnetic coupling $v = L_{\mu}\frac{di}{dt}$

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

3. Rate limits

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

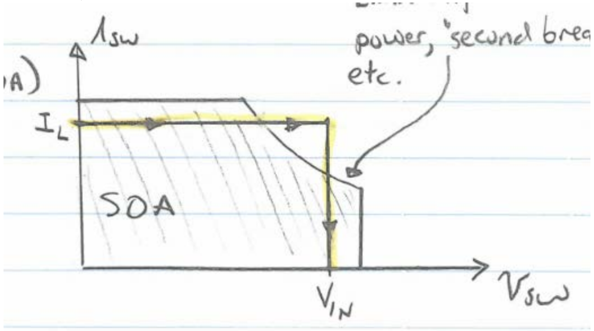
   high $\frac{di}{dt}$ → destory device on turn on

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

4. Safe operations area (SOA)

   Some devices cannot sustain high <u>simultaneous</u> v,i.

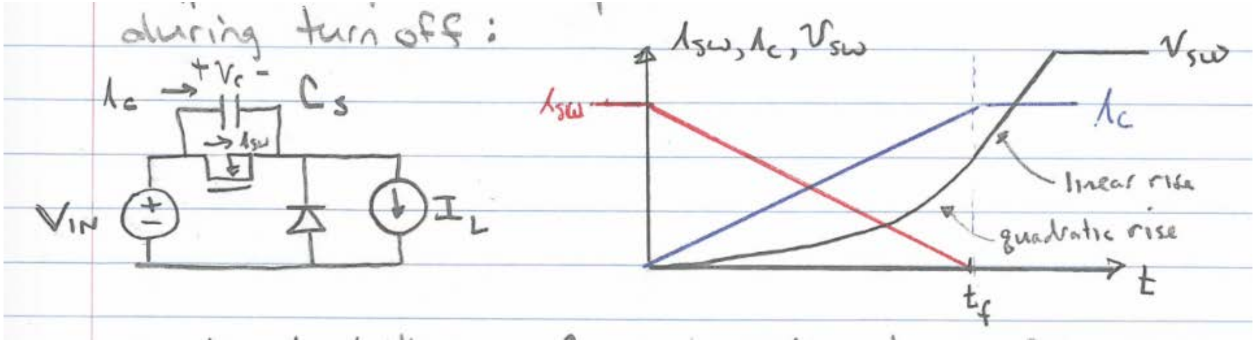
   Limit maybe instantaneous power, "second breakdown", etc.



3 Snubbers

1. Control switching losses
2. Reduce <u>internal</u> device dissipation

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



I_L diverted through C_s while switch turns off:

$$i_s w = I_L(1 - \frac{t}{t_f}), 0 < t < t_f$$

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

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

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

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

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

We reduce device turn-off loss with the capacitor!

We also <u>store</u> energy in the capacitor $E_{stored} = \frac{1}{2}CV_{in}^2$

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

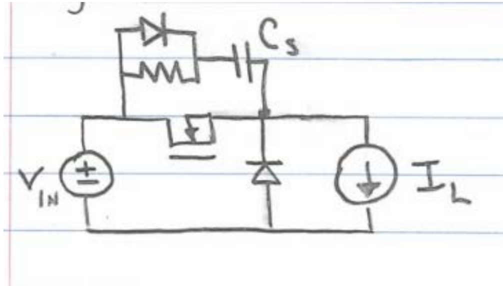
So: we reduce device loss @ turn off as C ↑ loss ↓

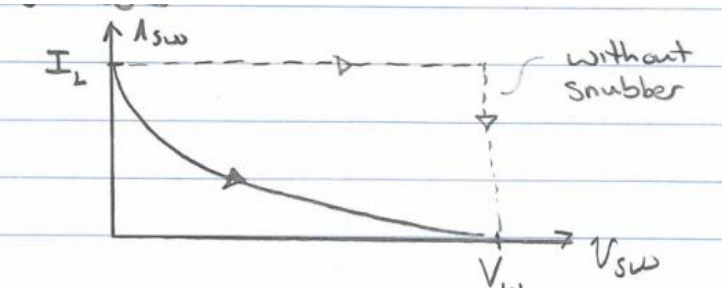
But: @ switch turn on, E_{stored} on cap gets dumped into switch!

- Could destroy switch!
- dumped energy increases as C↑

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

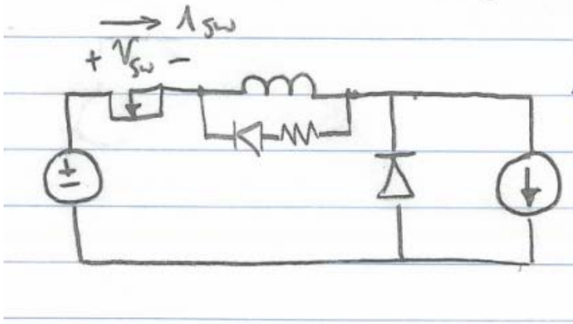
e.g. RCD turn-off snubber

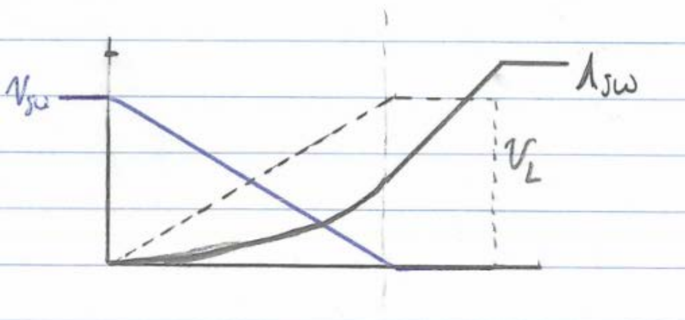




- During turn off, C_s is effectively in parallel w/ the switch
- when switch is on, capacitor stored energy is <u>slowly</u> dissipated in R (we need some on-time to complete the discharge)
- Snubber only operates during switching transitions
  ⇒ switching locus improved (SOA, lower $\frac{dv}{dt}$)
  ⇒ <u>device</u> loss reduced (but total device and resistor loss is typically higher!)

We can do similar things at device turn on!





Reduces <u>switch</u> turn on losses

- Total switch and resistor losses maybe higher with snubber
- does not reduce loss assocaited with parasitic capacitance across the switch
- controls switching locus (SOA, $\frac{di}{dt}$ ↓)
- results in slightly increased switch voltage

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

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