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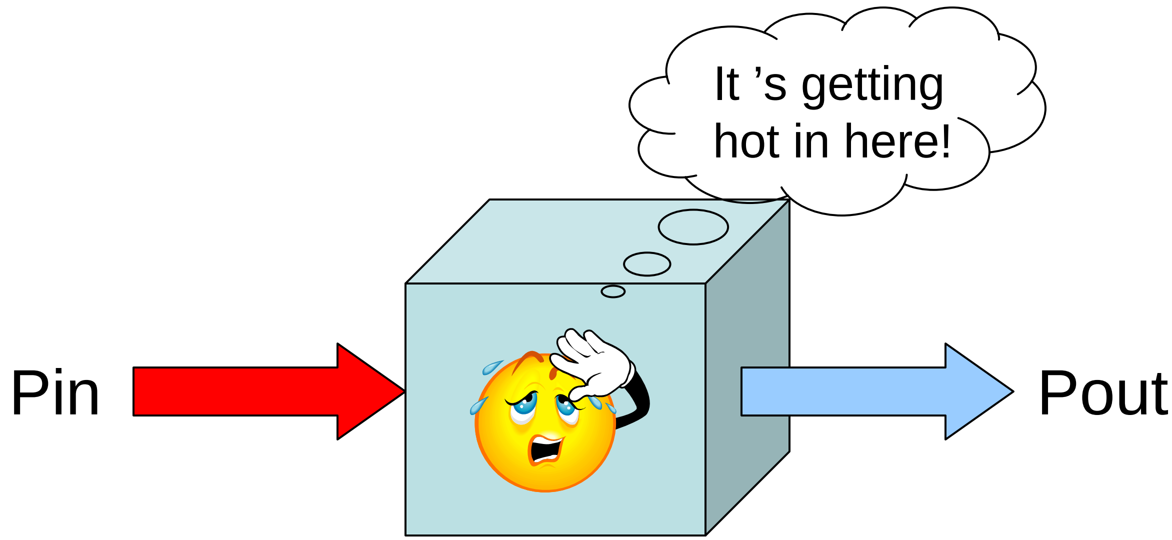
Switcher Efficiency & Snubber Design

Agenda

- SMPS Basics
- Control Methods
- Losses
- Example: Buck
- Example: Boost
- BJTs vs. MOSFETs
- Snubber Design

SMPS Basics

The goal of a converter is to deliver power



The conversion mechanism generates heat...

Heat means that the energy transfer is not perfect

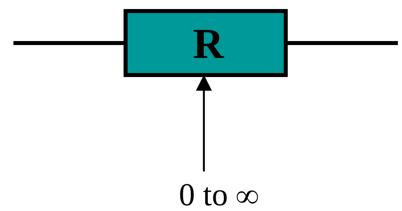
η=Pout/Pin is called the **efficiency**

$$Ploss = Pin - Pout = \frac{Pout}{\eta} - Pout = Pout \cdot \left(\frac{1}{\eta} - 1\right)$$

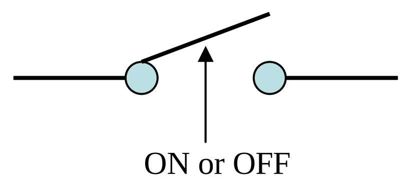
A 50% efficiency means Ploss = Pout
e.g. Pout = 100 W ➔Ploss = 100 W
Pin = 150 W, Pout = 100 W ➔η = 66%

Two different options exist to build a converter:

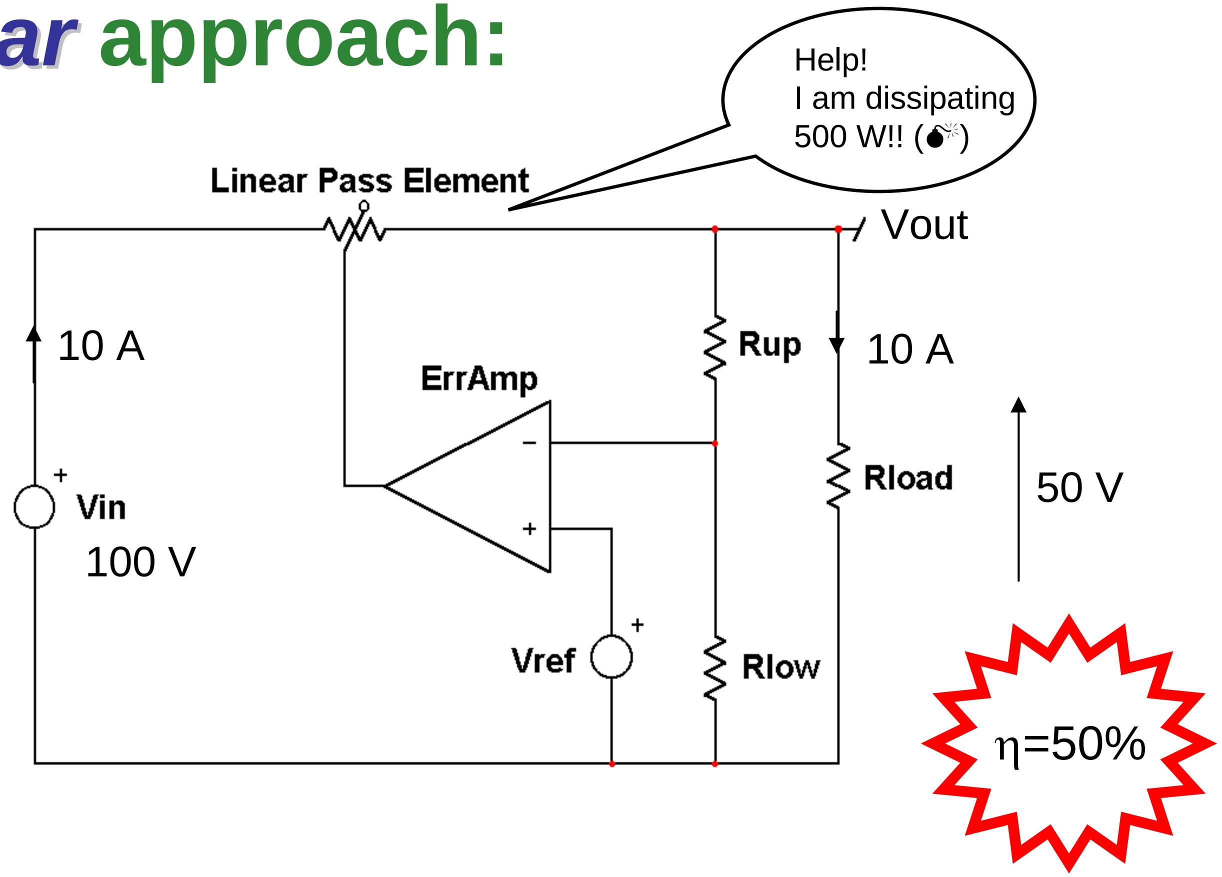
The **linear** approach:
➔ efficiency is poor
➔ good noise performance
➔ acceptable when (Vout-Vin) is small
➔ can only decrease the input level



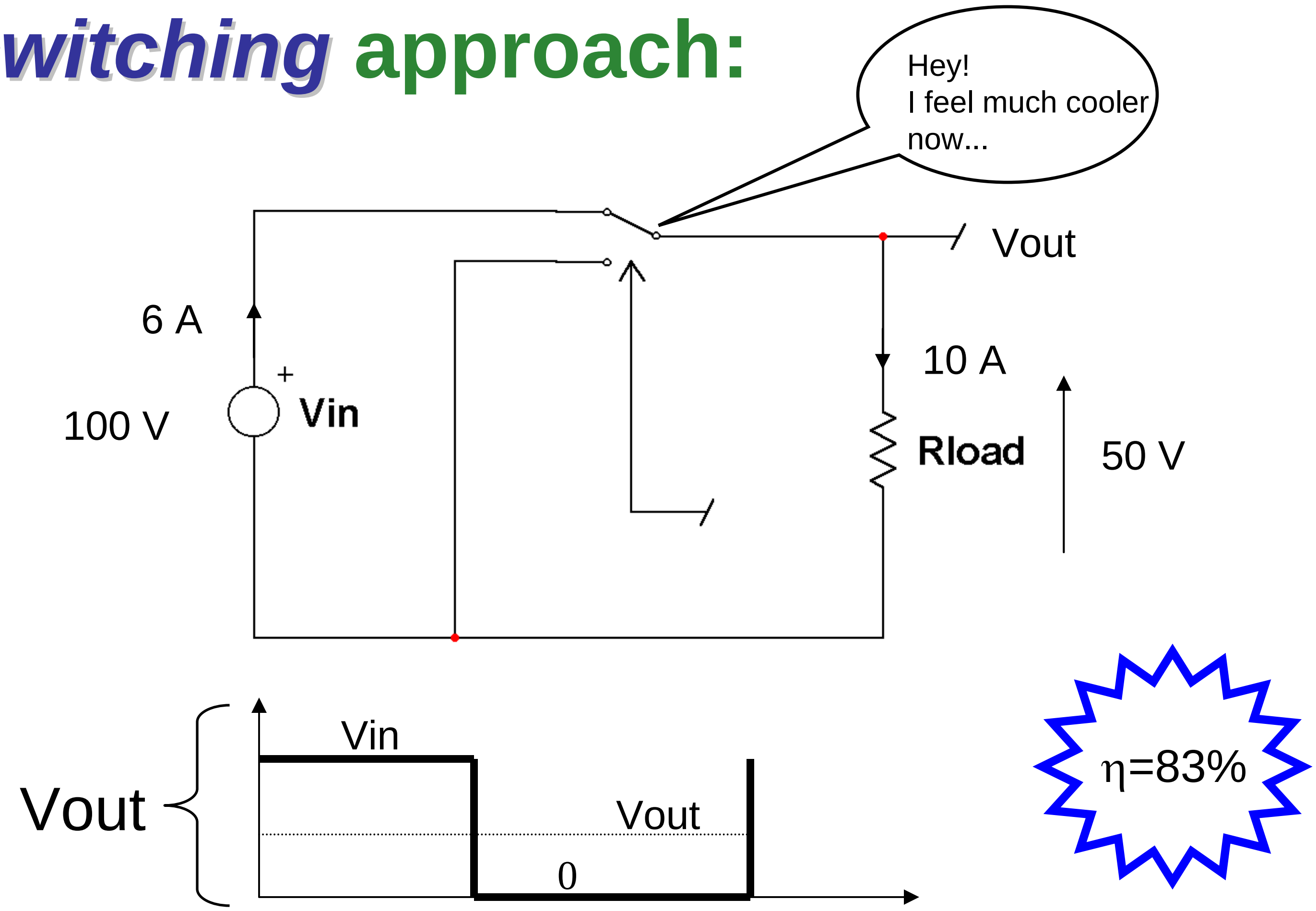
The **switching** approach:
➔ efficiency is high
➔ noise performance is poor
➔ works with large (Vout-Vin)
➔ increase/decrease/invert the input level



The *linear* approach:

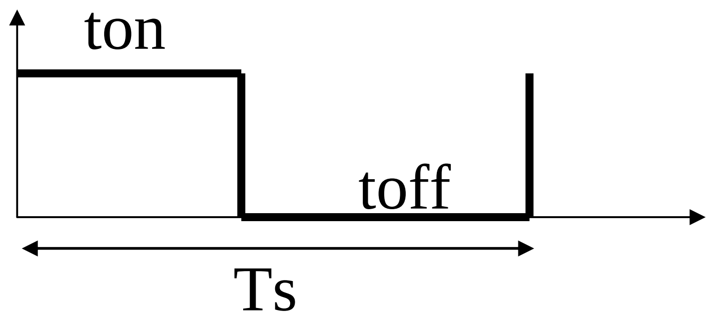


The *switching* approach:

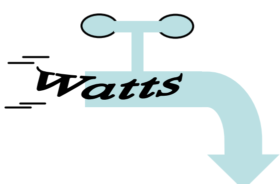


Controlling the power flow

$$Vout_{avg} = \frac{1}{Ts} \cdot \int_0^{Ts} Vout(t) \cdot dt = \frac{ton}{Ts} \cdot Vin = D \cdot Vin$$



$$D = \frac{ton}{Ts}$$ (Duty-cycle)



Pulse **W**idth **M**odulation (PWM) control

Control Methods

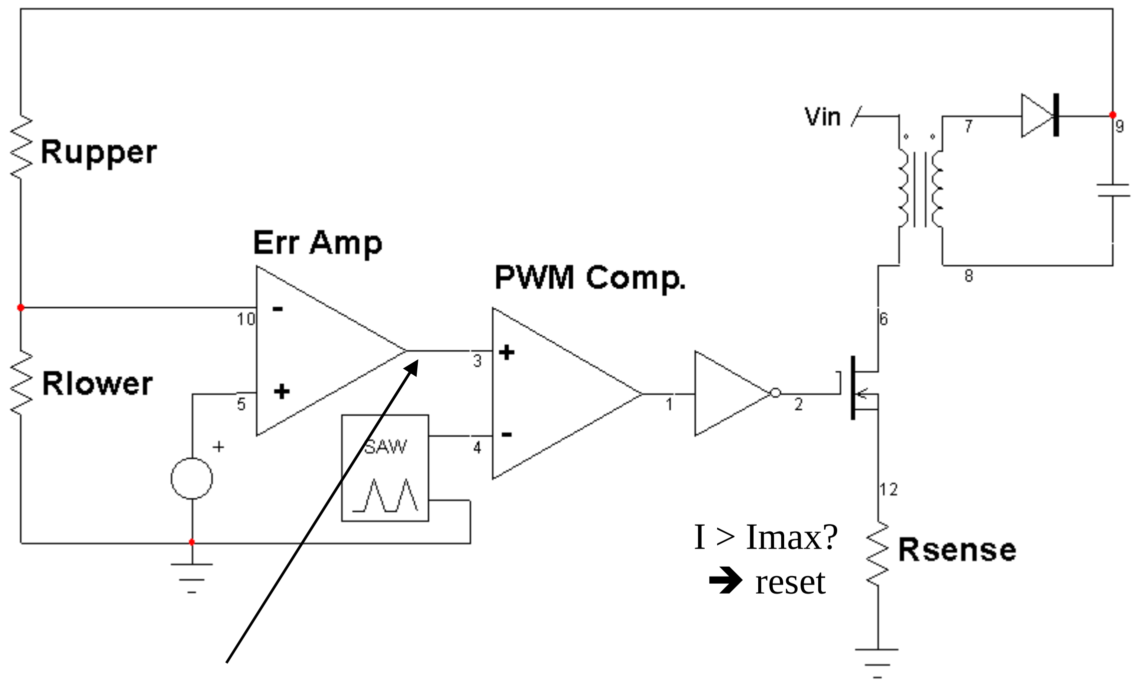
Regulation, keeping an output signal constant by…

- adjusting the ***duty-cycle*** via the PWM block
- regulating the inductor ***peak*** current
- regulating the inductor ***average*** current
- adjusting the ***switching*** frequency
- ***off*** time adjustment
- …

Current-mode control… (regulating the inductor peak current)
Voltage-mode control… (adjusting the duty-cycle via the PWM block)

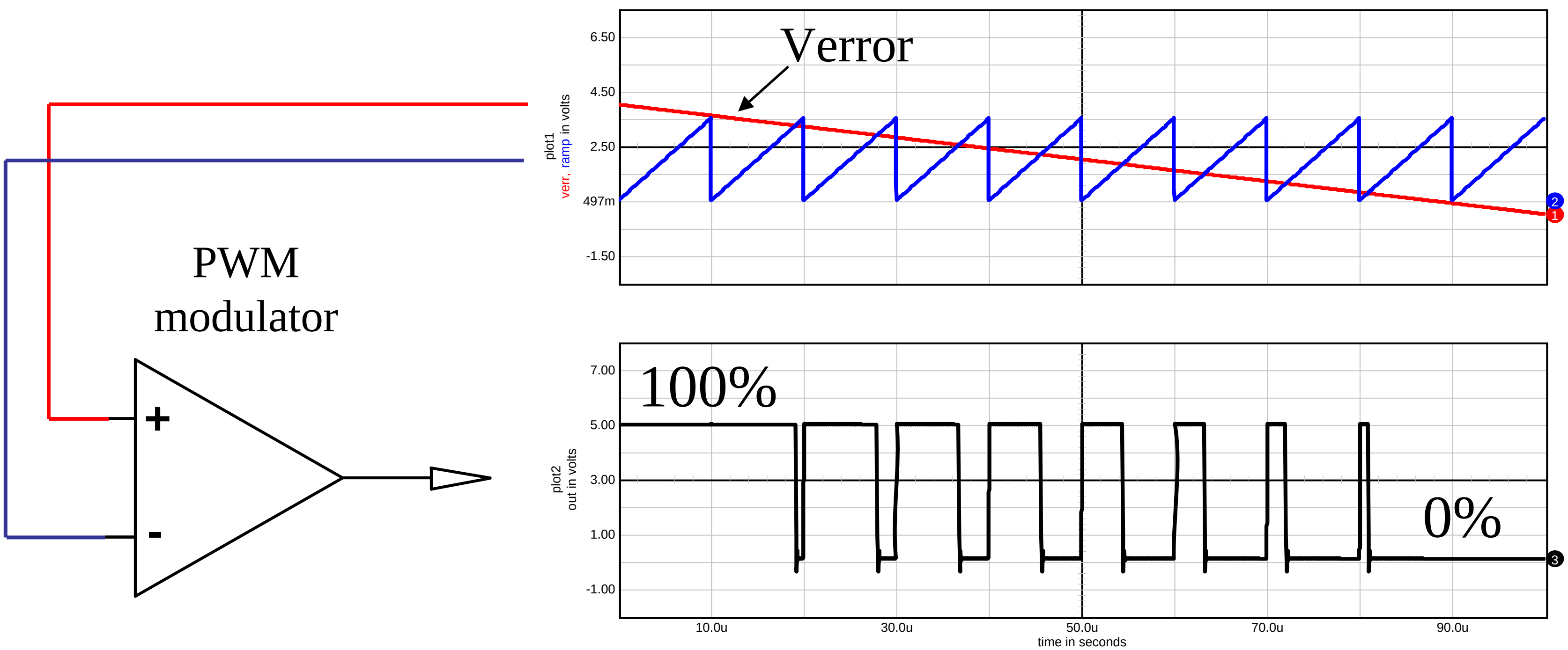
Two most popular methods!

The voltage-mode method



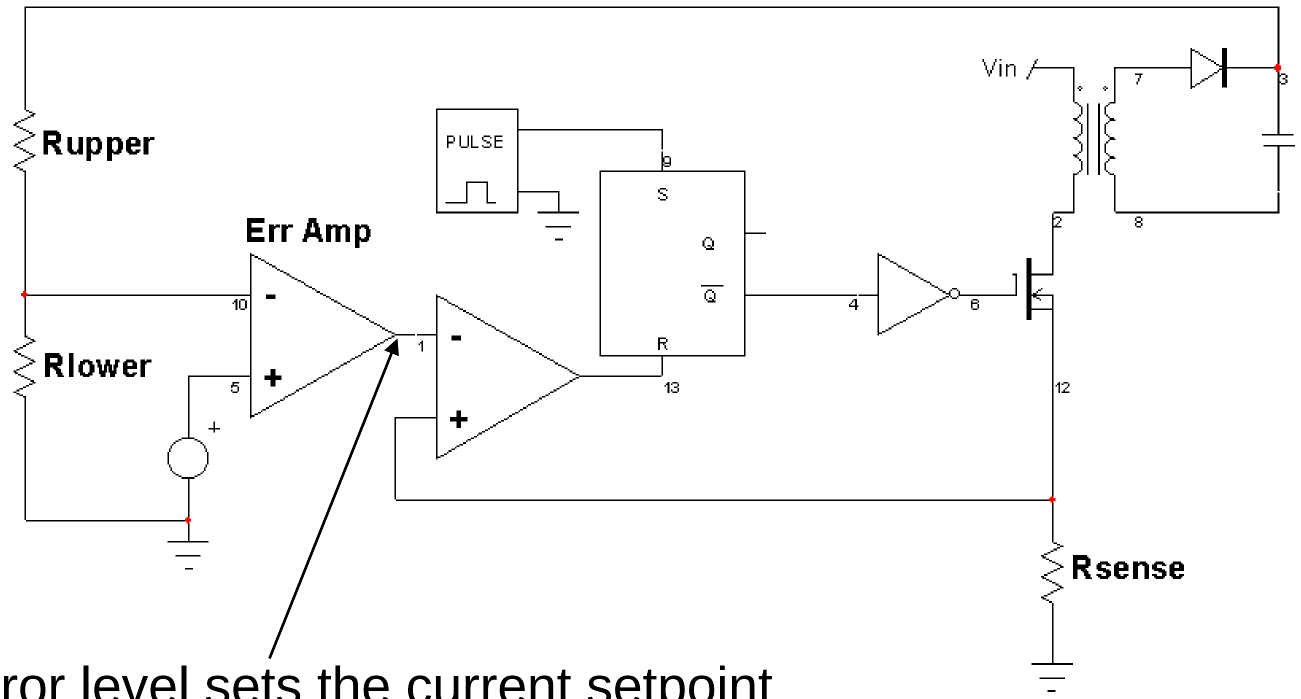
The error level sets the duty-cycle

The duty-cycle factory…



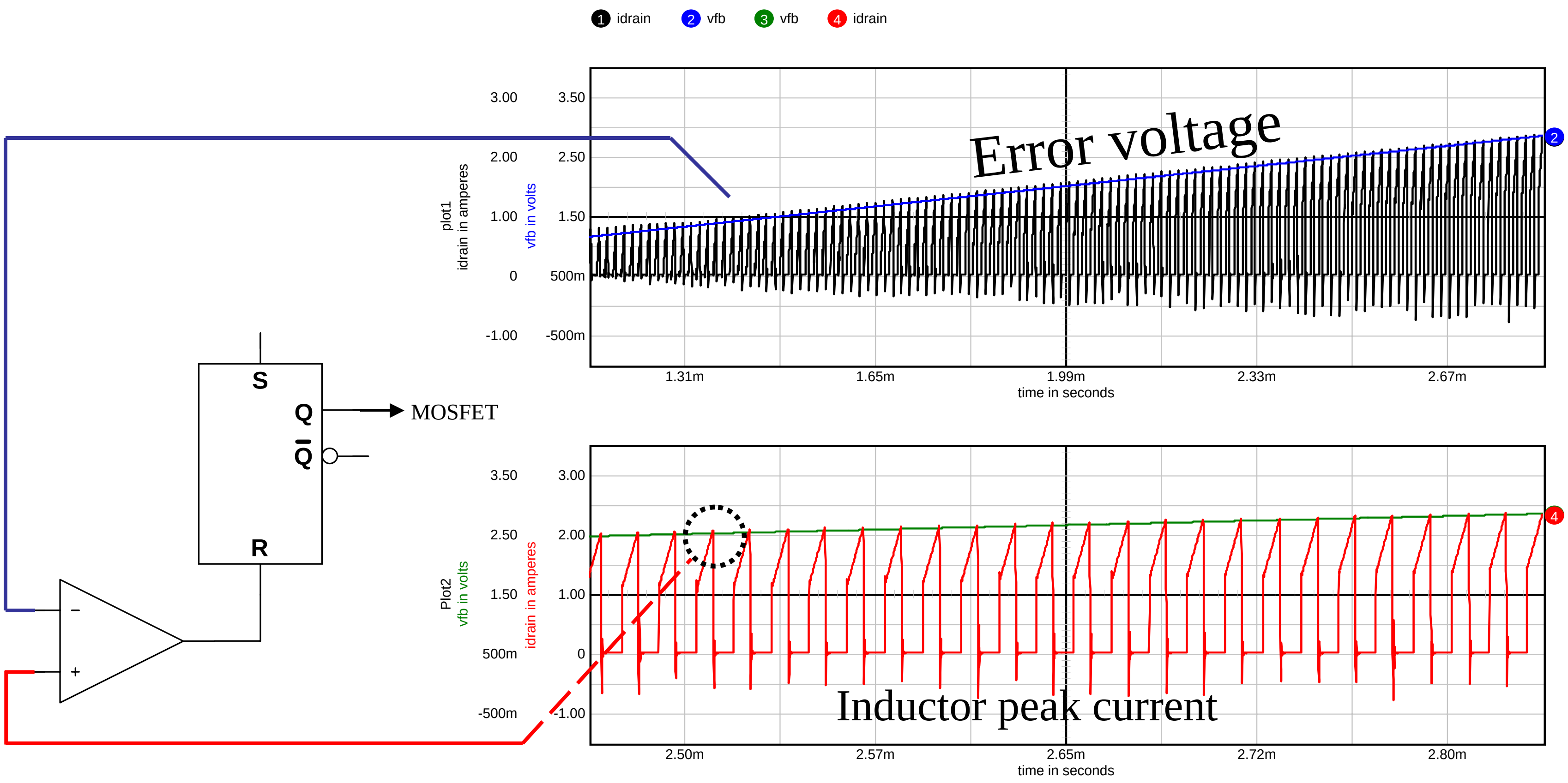
A ramp is compared to a DC level, the error voltage

The current-mode method



The error level sets the current setpoint

The peak follows the error voltage



Losses

Losses

$$P_{out} = P_{in} - P_{SW} - P_{Con} - P_{IC}$$

P_{SW}: Switching Losses

P_{Con}: Conduction Losses

P_{IC}: Power consumed by the chip

IC Losses

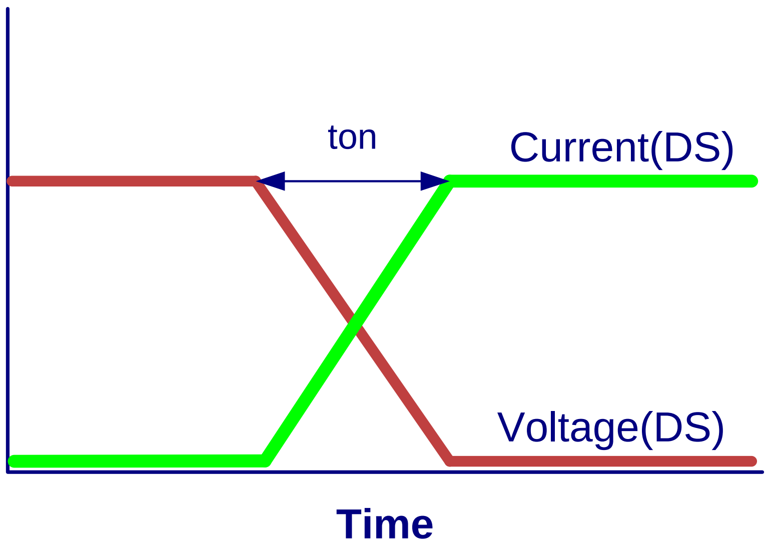
$$P_{IC} = V_{in} I_q$$

Vin: IC input voltage

Iq: Quiescent current (read from the data sheet)

Switching Losses

- Losses which occur when the power switch is turned on or off.
- During this transition the voltage and current on the FET are both high.
- Different for Buck and Boost configurations.



Switching Losses (Buck)

$$P_{SW} = \frac{1}{2} V_{in} I_{out} (t_{on} + t_{off}) F_{SW}$$

V_{in}: Input Voltage

I_{out}: Average inductor current

t_{on}: Turn on time of high side switch

t_{off}: Turn off time of high side switch

F_{SW}: Switching frequency

Switching Losses (Boost)

$$P_{SW} = \frac{1}{2} V_{out} \frac{I_{out}}{1-D} (t_{on} + t_{off}) F_{SW}$$

V_{out}: Output Voltage

D: Duty Cycle

I_{out}: Average inductor current

t_{on}: Turn on time of high side switch

t_{off}: Turn off time of high side switch

F_{SW}: Switching frequency

Reducing Switching Losses

- Increase gate drive strength
  - Increases cost (die area)
  - Increases EM emissions
- Decrease frequency
  - Requires a larger value inductor
- Use a smaller FET
  - Increases conduction losses

Conduction Losses

- Losses which occur when current flows through a resistive path (I^2*R), such as a FET, or a diode ($V*I$).
- Major contributors include:
  - Power Switch $R_{ds,on}$
  - Freewheeling Diode
  - Inductor DCR
- Different for synchronous and non-synchronous mode designs.

Conduction Losses (Non-Synchronous)

$$P_{Con} = I_L{}^2 R_{ds,on} D + I_L V_{diode}(1-D) + I_L{}^2 R_{DCR}$$

I_L: RMS current through the inductor

$R_{ds,on}$: On resistance of the power switch

D: Duty cycle

V_{diode}: Forward voltage of the diode

R_{DCR}: Winding resistance of the inductor

Conduction Losses (Synchronous)

$$P_{Con} = I_L{}^2 R_{ds,on1} D + I_L{}^2 R_{ds,on2}(1 - D) + I_L{}^2 R_{DCR}$$

I_L: RMS current through the inductor

$R_{ds,on1}$: On resistance of the high side switch

D: Duty cycle

$R_{ds,on2}$: On resistance of the low side switch

R_{DCR}: Winding resistance of the inductor

Example: Buck

Example: NCV8851 Evaluation Board

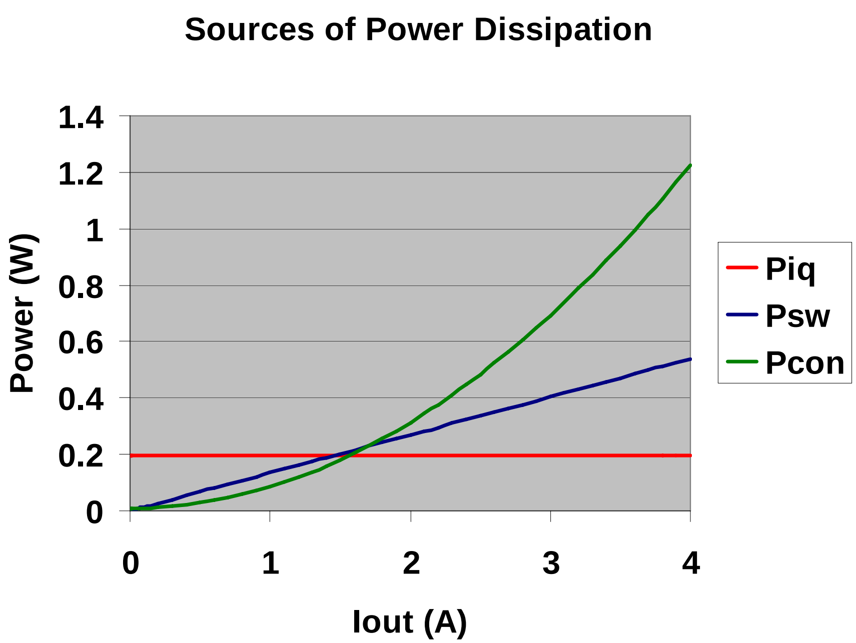
- Synchronous buck converter
- V_{in} = 13.2 V
- V_{out} = 5 V
- $I_{out,max}$ = 4 A
- F_{SW} = 170 kHz
- Inductor: Wurth Electronics 7447709150 15 uH
- Power switch (both): ON Semiconductor NTD5407N

Example: NCV8851 Evaluation Board

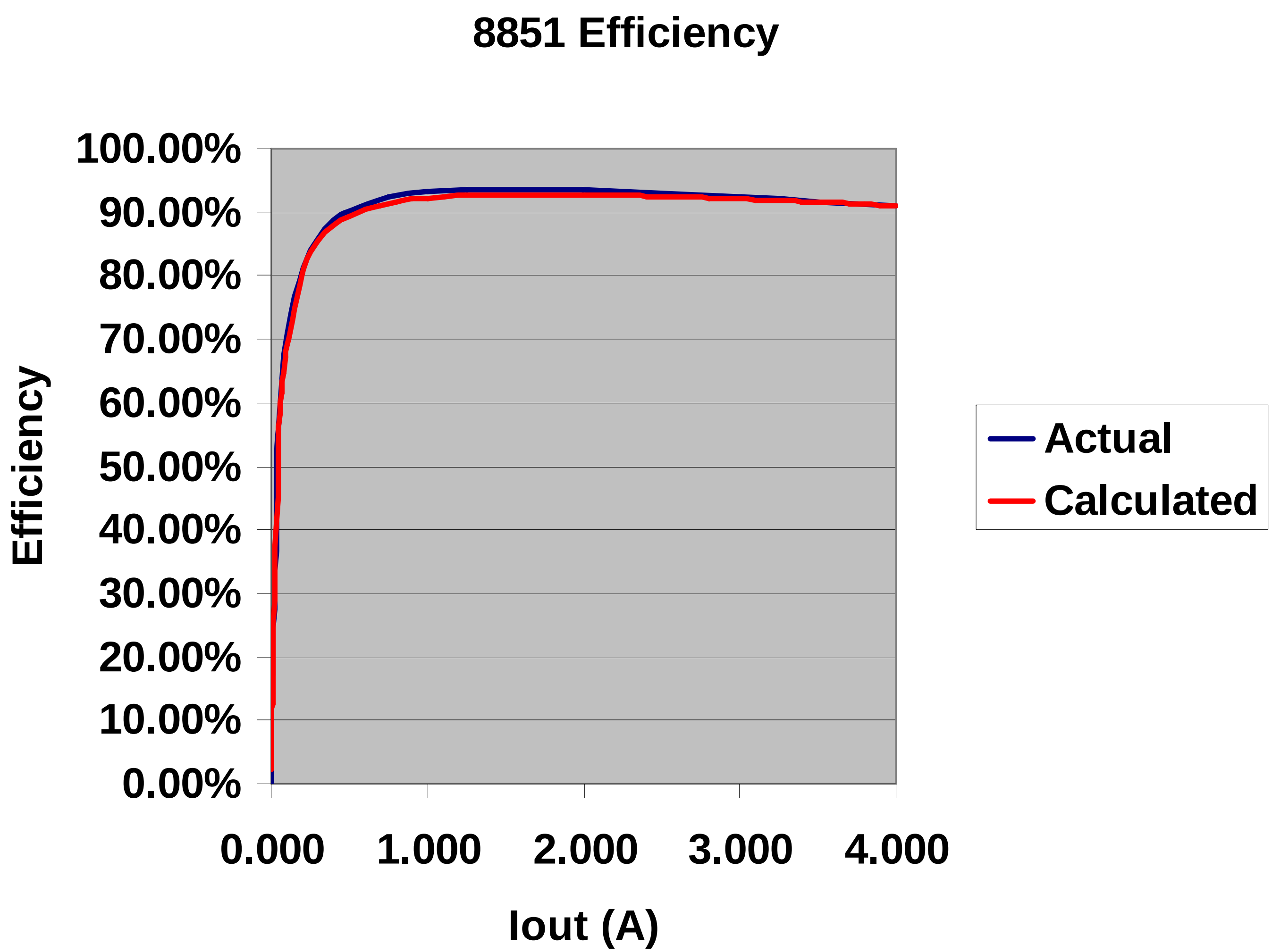
- $D = Vin / Vout = 5\ V / 13.2\ V = 0.379$
- $t_{on} = 5$ ns (empirical)
- $t_{off} = 7$ ns (empirical)
- $R_{ds,on1} = R_{ds,on2} = 50\ m\Omega$ (including self heating temperature effects)
- $R_{DCR} = 26\ m\Omega$
- $I_q = 15$ mA
- $I_L = Sqrt(I_{out}^2 + (0.609\ A)^2 / 3)$

Example: NCV8851 Evaluation Board

- **P_{IC}** = 13.2 V * 15 mA
  = **0.198 W**
- **P_{SW}** = (1/2) * 13.2 V * I_{out} * (5 ns + 7 ns) * 170 kHz
  = **0.01346 * I_{out} W**
- **P_{CON}** = (I_{out}^2 + 0.12378 A^2) * (50 mΩ) * (0.379) + (I_{out}^2 + 0.12378 A^2) * (50 mΩ) * (0.621) + (I_{out}^2 + 0.12378 A^2) * 26 mΩ = **(0.076 * I_{out}^2 + 0.009407) W**



Example: NCV8851 Results



Example: Boost

Example: NCV8871 Sample Application

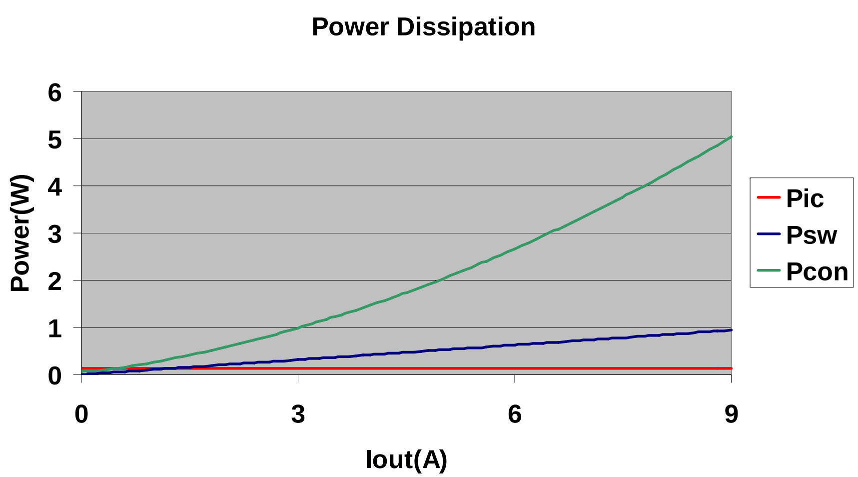
- Non-synchronous boost converter
- V_{in} = 13.2 V
- V_{out} = 18 V
- $I_{out,max}$ = 9 A
- F_{SW} = 170 kHz
- Inductor: Vishay IHLP6767GZER330M11 33 uH
- Power Switch: ON Semiconductor NTD5803 x 2
- Diode: ON Semiconductor MBRB1645T4G

Example: NCV8871 Sample Application

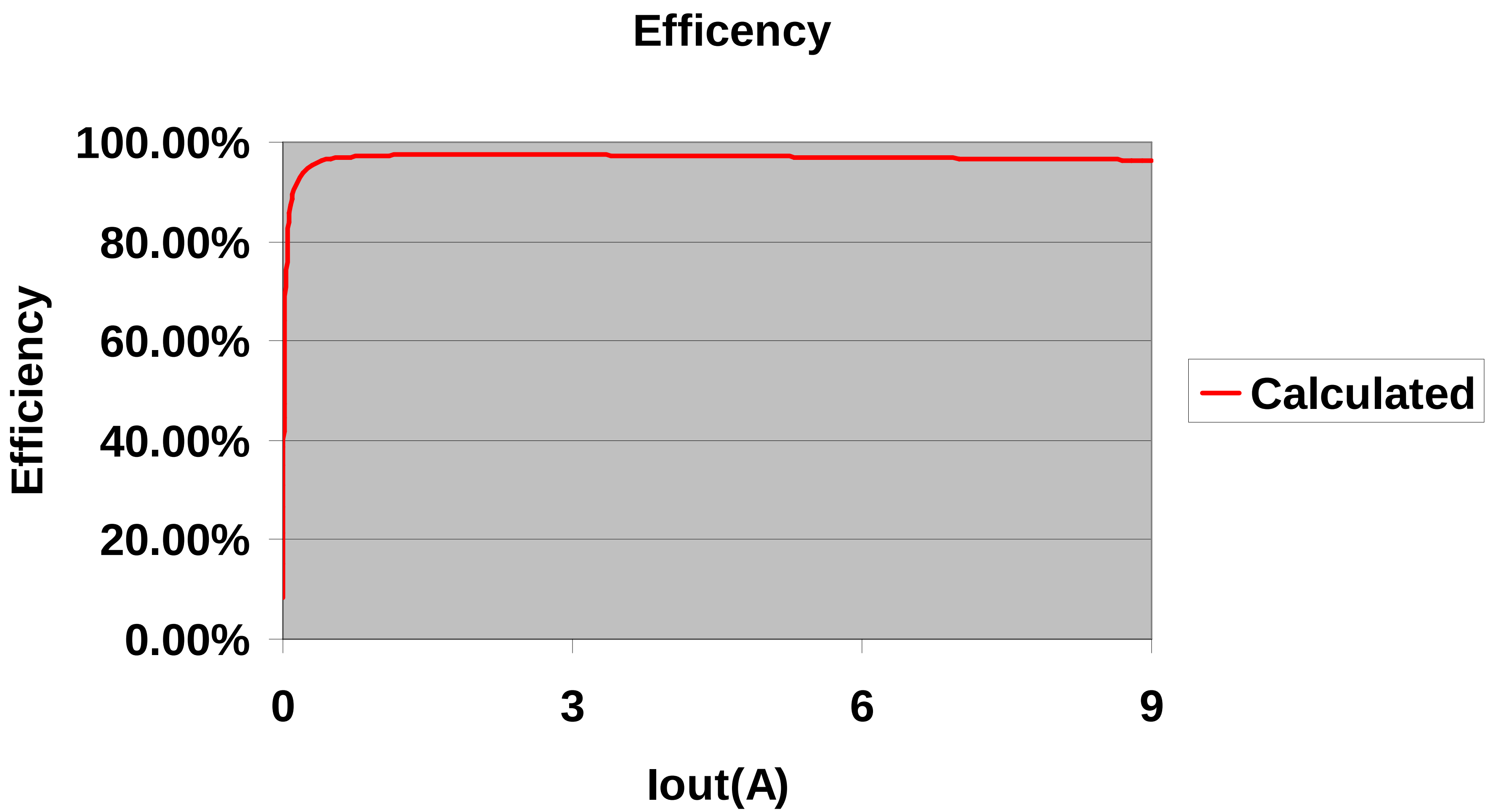
- $D = 1 – (V_{in} / V_{out}) = 0.267$
- t_{on} = 30 ns
- t_{off} = 20 ns
- $R_{ds,on}$ = (12 mΩ) / 2 = 6 mΩ (including temperature effects)
- R_{DCR} = 37 mΩ
- I_q = 10 mA
- IL = Sqrt ((Iout / (1 – D)) ^ 2 + (0.3137)^2 / 3)

Example: NCV8871 Sample Application

- $\mathbf{P_{IC}}$ = 13.2 V * 10 mA = **0.132 W**
- $\mathbf{P_{SW}}$ = (1/2) * 18 V * I_{out} / (1-0.267) * (20 ns + 30 ns) * 170 kHz = **0.10436 * I_{out} W**
- $\mathbf{P_{CON}}$ = (I_{out}^2 + 0.0328 A^2) * (12 mΩ) * (0.267) + Sqrt(I_{out}^2 + 0.0328 A^2) * (0.5V) * (0.733) + (I_{out}^2 + 0.0328 A^2) * 37 mΩ = **(0.0402 * I_{out}^2 + Sqrt(I_{out}^2 + 0.0328)*0.3665 + 0.00131869 W**



Example: NCV8871 Results



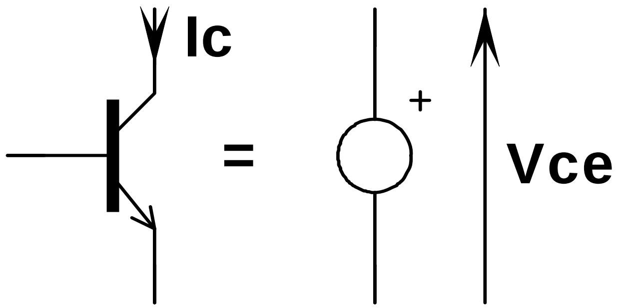
BJTs vs. MOSFETs

Switches and converters…

- ❑ The bipolar transistor is often used:

1. In high voltage - high current applications
2. In low-cost converters

$$\Rightarrow P_{cond} = Vce_{sat} \cdot Ic_{avg}$$



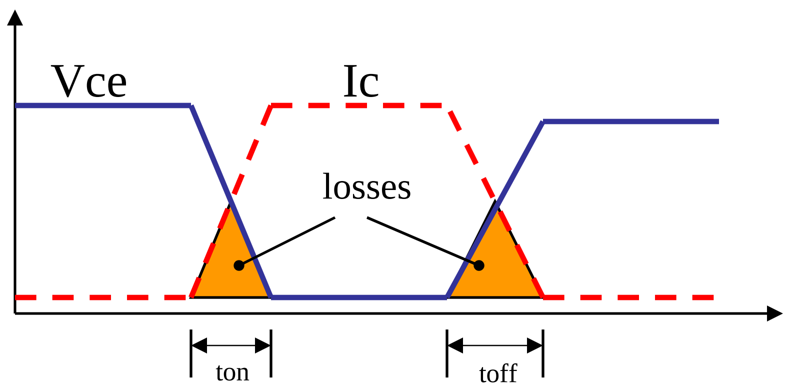
When saturated…

The bipolar transistor

Switches and converters…

- The bipolar transistor switching losses:

1. Depend on temperature (storage time, current tail)
2. Watch-out for hot spots!
3. Often needs proportional drive (shallow saturation)



$$Psw = \frac{Vce \cdot Ic \cdot (ton + toff)}{3 \cdot Tsw}$$

If ton = toff…

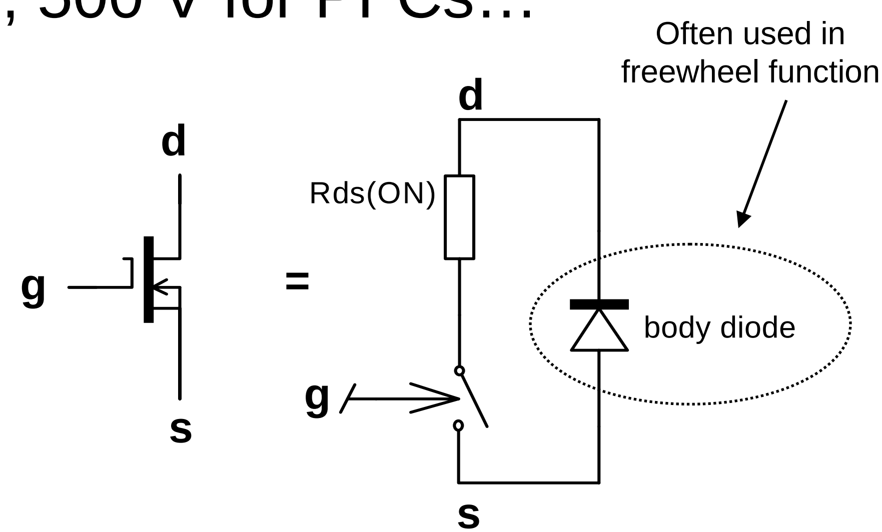
The bipolar transistor

Switches and converters…

- ❑ The MOSFET transistor is the most popular:

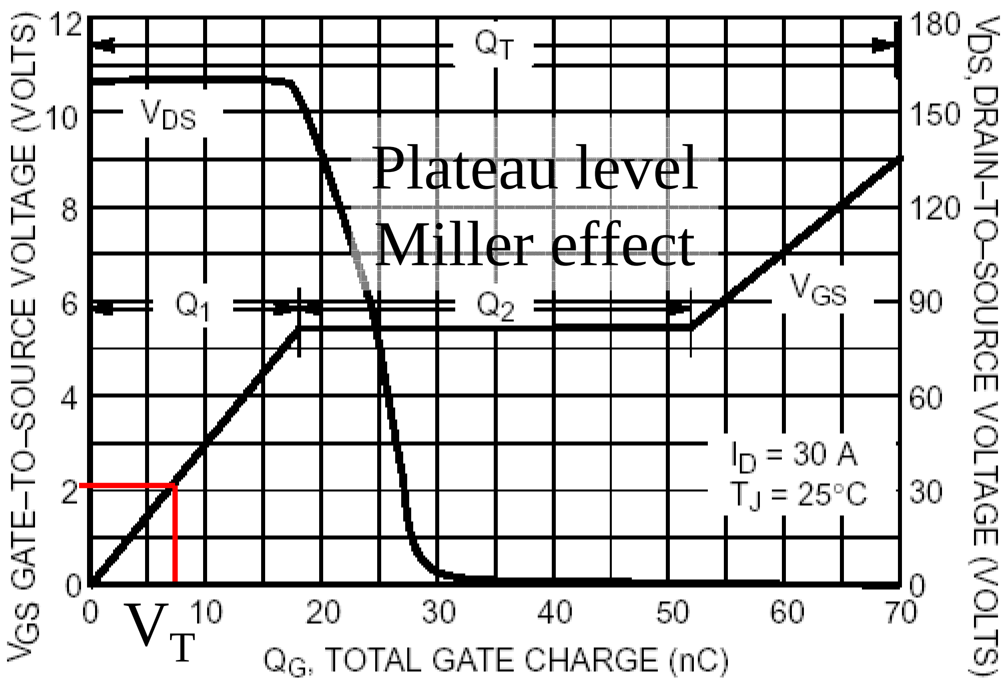
1. Ease of drive (capacitive input)
2. Avalanche rugged
3. BVdss of 600 V for SMPS, 500 V for PFCs…

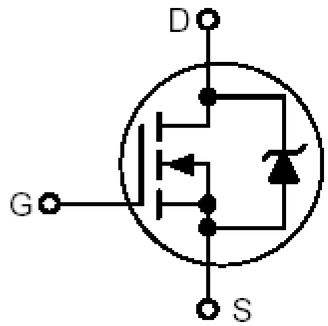
$$Pcond = I_{dRMS}^{2} \cdot Rds_{(ON)}$$

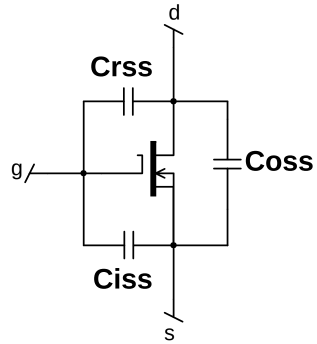


The MOSFET transistor

To enhance a MOSFET, bring it charge





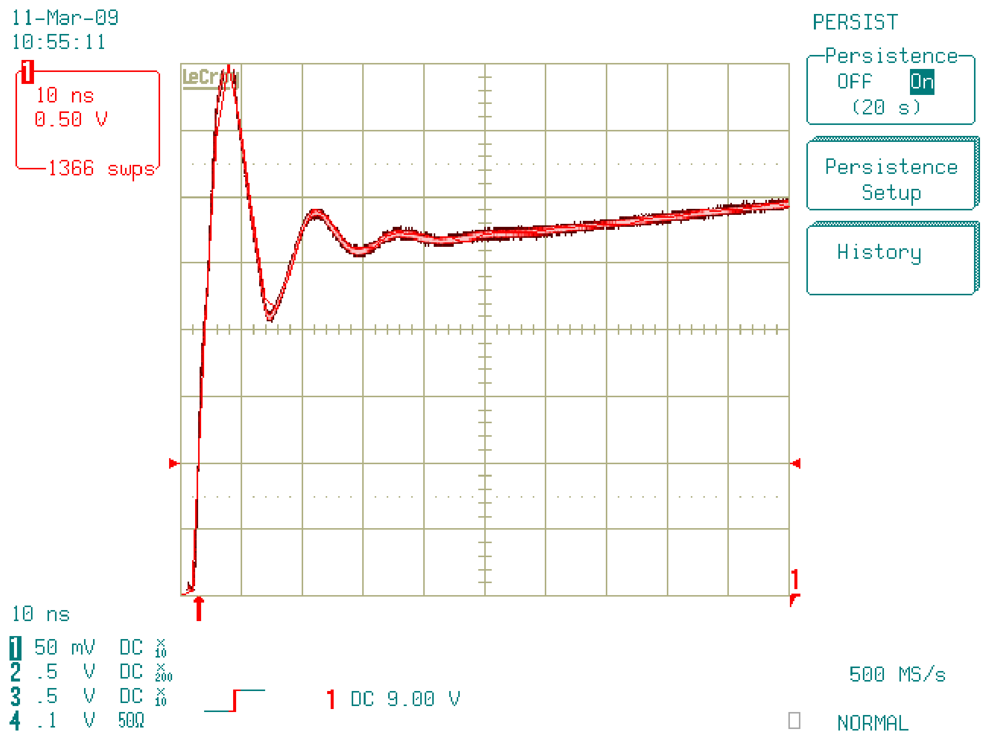


How many coulombs to turn on the MOSFET: Q = i x t…

Snubber Design

When is it needed?

- Parasitic inductances and capacitances from the power devices form a RLC filter that resonates
- Excessive ringing can cause damage to the devices



Snubber Design

- Measure the frequency of the ringing (f_c) at maximum input voltage
  - Use a low capacitance probe
- Find out either the L or C of the circuit
  - L is dominated by the top power switch
  - C is dominated by the body diode of the bottom power switch or the capacitance of the freewheeling diode
- Calculate the characteristic impedance of the circuit
  - If L is known: $Z = 2\pi f_c L$
  - If C is known: $Z = 1 / (2 \pi f_c C)$

Snubber Design

- Choose $R_{SNUB} = Z$
- Choose $C_{SNUB} = 1 / (2 \pi f R)$
- Power dissipation in R_{SNUB} is $CV^2 f_s$
- Put R_{SNUB} and C_{SNUB} in series across the device causing ringing.
- Test in circuit. R_{SNUB} can be fine turned further to reduce ringing if it is found to be insufficient

For More Information

- View the extensive portfolio of power management products from ON Semiconductor at www.onsemi.com

- View reference designs, design notes, and other material supporting automotive applications at www.onsemi.com/automotive