Announcements

Systers Skill Series

Soldering Workshop

Come sharpen your soldering skills with Systers and IEEE East TN

Wednesday, September 16, 2015
4:30PM
MK 336
Refreshments Provided

MOSFET Cross Section
Power MOSFET in Ohmic Region

MOSFET Static Characteristics

Max current of a MOSFET determined by \( I_{ds} \) rather than \( I_{max} \)

\[ V_{gs, on} \text{ range} \]

\[ \uparrow V_{gs} \text{ to} \downarrow I_{ds} \]
MOSFET Depletion capacitance

MOSFET Equivalent Circuit
Switching Losses: Output Capacitance

Assume $C_1$ and $C_2$ are fixed.

1. **MOSFET Turn-off**
   - $V_{ds} = \frac{1}{3} C_{ds} V_g^2$ -> stored in $C_{ds}$
   - $E_d^o = -\frac{1}{3} C_{ds} V_g^2$ -> supplied by $C_2$

2. **MOSFET Turn-on**
   - $E_d^+ = \frac{1}{3} C_{ds} V_g^2$ -> additional in MOSFET
   - $E_d = \frac{1}{3} C_{ds} V_g^2$ -> Also stored in MOSFET

Power loss due to capacitive switching even in an ideal switch!

\[
P_{sw} = \int_0^{V_g} i(V_g - V_c) \, dt
\]

\[
P_{sw} = \int_0^{V_g} C(V_g - V_c) \frac{dv_c}{dt} \, dt
= \int_0^{V_g} C(V_g - V_c) \, dv_c
= \int_0^{V_g} CV_g \, dv_c - \int_0^{V_g} C V_c \, dv_c
= CV_g^2 - CV_c^2 = \frac{1}{2} CV_g^2
\]
Averaged Equivalent Circuit Model – Switching Loss

- The methods of Chapter 3 can be extended to include switching loss in the converter equivalent circuit model
  - Include switching transitions in the converter waveforms
  - Model effects of diode reverse recovery, etc.
- To obtain tractable results, the waveforms during the switching transitions must usually be approximated
- Things that can substantially change the results:
  - Ringing caused by parasitic tank circuits
  - Snubber circuits

The Modeling Approach

- Sketch the converter waveforms
  - Including the switching transitions (idealizing assumptions are made to lead to tractable results)
  - In particular, sketch inductor voltage, capacitor current, and input current waveforms
- The usual steady-state relationships:
  - $\langle v_L \rangle = 0$, $\langle i_C \rangle = 0$, $\langle i_g \rangle = I_g$
- Use the resulting equations to construct an equivalent circuit model, as usual
Buck Converter Example

- Ideal MOSFET, $p-n$ diode with reverse recovery
- Neglect semiconductor device capacitances, MOSFET switching times, etc.
- Neglect conduction losses
- Neglect ripple in inductor current and capacitor voltage

Assumed waveforms

- Diode recovered charge $Q_r$, reverse recovery time $t_r$
- These waveforms assume that the diode voltage changes at the end of the reverse recovery transient
  - a "snappy" diode
  - Voltage of soft-recovery diodes changes sooner
  - Leads to a pessimistic estimate of induced switching loss
Inductor volt-second & Cap-Charge balance

As usual: \( \langle v_L \rangle = 0 = D V_g - V \)

Also as usual: \( \langle i_C \rangle = 0 = I_L - V/R \)

Average input current

\( \langle i_g \rangle = I_g = (\text{area under curve})/T_s \)
\( = (D T_i L + t_i I_L + Q_i)/T_s \)
\( = D I_L + t_i I_L / T_s + Q_i / T_s \)
Construction of Equivalent Circuit Model

From inductor volt-second balance: \( \langle v_L \rangle = 0 = DV_g - V \)
From capacitor charge balance: \( \langle i_C \rangle = 0 = I_L - V/R \)

Input port of model

\( \langle i_g \rangle = I_g = DI_L + t_I L/T_s + Q_r/T_s \)
**Combine for complete model**

The two independent current sources consume power

\[ V_g \left( t_{IL}/T_s + Q_r/T_s \right) \]

equal to the switching loss induced by diode reverse recovery.

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**Solution of model**

**Output:**

\[ V = DV_g \]

**Efficiency:**

\[ \eta = \frac{P_{out}}{P_{in}} \]

\[ P_{out} = VI_L \]

\[ P_{in} = V_g \left( DI_L + t_{IL}/T_s + Q_r/T_s \right) \]

Combine and simplify:

\[ \eta = \frac{1}{1 + \frac{f_s}{D} \left( t_r/D + Q_r R / D^2 V_g \right)} \]
Predicted Efficiency vs Duty Cycle

• Switching frequency 100 kHz
• Input voltage 24 V
• Load resistance 15 Ω
• Recovered charge 0.75 µCoul
• Reverse recovery time 75 nsec

• (no attempt is made here to model how the reverse recovery process varies with inductor current)

• Substantial degradation of efficiency
• Poor efficiency at low duty cycle

Boost Converter Example

• Model same effects as in previous buck converter example:
• Ideal MOSFET, $p$–$n$ diode with reverse recovery
• Neglect semiconductor device capacitances, MOSFET switching times, etc.
• Neglect conduction losses
• Neglect ripple in inductor current and capacitor voltage
Boost converter

As usual: \( \langle v_L \rangle = 0 = V_g - D'V \)

Also as usual: \( \langle i_g \rangle = I_L \)
Capacitor charge balance

\[ \langle i_C \rangle = \langle i_d \rangle - \frac{V}{R} = 0 \]
\[ = -\frac{V}{R} + I_L (D'T_s - t_r)/T_s - Q_r/T_s \]

Collect terms: \( V/R = I_L (D'T_s - t_r)/T_s - Q_r/T_s \)

Construct model

The result is:

\[ I_s = I_L \]

\[ D' : 1 \]

The two independent current sources consume power

\[ V (t_r I_L/T_s + Q_r/T_s) \]

equal to the switching loss induced by diode reverse recovery
Predicted $M$ vs duty cycle

- Switching frequency 100 kHz
- Input voltage 24 V
- Load resistance 60 $\Omega$
- Recovered charge 5 $\mu$Coul
- Reverse recovery time 100 nsec
- Inductor resistance $R_L = 0.3$ $\Omega$
- (inductor resistance also inserted into averaged model here)

![Boost converter with diode reverse recovery](image)

With $R_L$ only

With $R_L$ and diode reverse recovery