Lecture 7: MOSFET, IGBT, and Switching Loss

ECE 481: Power Electronics
Prof. Daniel Costinett
Department of Electrical Engineering and Computer Science
University of Tennessee Knoxville
Fall 2013

Announcements

- Homework #3 posted this afternoon
  - Plots in homeworks: label all salient features
  - Assignment clarity: Box answers, staple sheets, include course number
- Course E-mail list
- No office hours tomorrow
- No class next week
- Midterm Exam 1 handed out on 9/26
MOSFET On-State

\[ R_{on} \approx \left( R_{sub} + R_{epi} + R_{ds} \right) \]

At high \( V_{BR} \), the drain current is small.
Typical MOSFET characteristics

- Off state: $V_{GS} < V_{th}$
- On state: $V_{GS} >> V_{th}$
- MOSFET can conduct peak currents well in excess of average current rating —characteristics are unchanged
- on-resistance has positive temperature coefficient, hence easy to parallel

\[ R_{on} = \frac{1}{\frac{1}{R_{th}} + 250 \, \Omega} \]

MOSFET Datasheet

600V CoolMOS™ C6 Power Transistor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{GS}$</td>
<td>650</td>
<td>V</td>
</tr>
<tr>
<td>$R_{DS(sat)}$</td>
<td>2.9</td>
<td>(\Omega)</td>
</tr>
<tr>
<td>$U_{DSS}$</td>
<td>6.7</td>
<td>(\mu)</td>
</tr>
<tr>
<td>$I_{DS}$</td>
<td>6</td>
<td>A</td>
</tr>
<tr>
<td>$F_{max} @ 400V$</td>
<td>0.76</td>
<td>(\mu)</td>
</tr>
<tr>
<td>Body diode di/dt</td>
<td>500</td>
<td>A/(\mu)</td>
</tr>
</tbody>
</table>

Drain-source on-state resistance $R_{DS(on)}$

\[ R_{DS(on)} = \frac{1}{\frac{1}{R_{th}} + 250 \, \Omega} \]

Infineon

IPD60R2K0C6
MOSFET: Off State

\[ V_{gs} \approx 0V \]

\[ V_s > 0V \]
A simple MOSFET equivalent circuit

- \( C_{gs} \): large, essentially constant
- \( C_{gd} \): small, highly nonlinear
- \( C_{dh} \): intermediate in value, highly nonlinear
- Switching times determined by rate at which gate driver charges/discharges \( C_{gs} \) and \( C_{gd} \)

\[
C_{ds}(v_{ds}) = C_0 \sqrt{\frac{v_{ds}}{V_{th}}} = \frac{C_0}{\sqrt{\frac{v_{ds}}{V_{th}}}}
\]
Switching loss caused by semiconductor output capacitances

Buck converter example:

Energy lost during MOSFET turn-on transition (assuming linear capacitances):

\[ P_{\text{on}} = \frac{1}{2} C_{d\text{on}} V_{\text{th}}^2 \]

\[ P_{\text{on}} = \frac{1}{2} C_{d\text{on}} V_{\text{th}}^2 \]

MOSFET nonlinear $C_{ds}$

Approximate dependence of incremental $C_{ds}$ on $V_{th}$:

\[ C_{ds}(V_{th}) = C_0 \sqrt{\frac{V_{th}}{V_{th}^2}} = \frac{C_0}{\sqrt{V_{th}}} \]

Energy stored in $C_{ds}$ at $V_{th} = V_{\text{off}}$:

\[ W_{c_{ds}} = \int_{0}^{V_{\text{off}}} C_{ds}(V_{th}) \, dV_{th} = \frac{1}{2} C_{ds}(V_{\text{off}}) V_{\text{off}}^2 \]

\[ W_{c_{ds}} = \int_{0}^{V_{\text{off}}} C_{ds}(V_{th}) \, dV_{th} = \frac{1}{2} C_{ds}(V_{\text{off}}) V_{\text{off}}^2 \]

— same energy loss as linear capacitor having value $\frac{1}{2} C_{ds}(V_{\text{off}})$.
Current Research in Wide Bandgap Materials

MOSFET: conclusions

- A majority-carrier device: fast switching speed
- Typical switching frequencies: tens and hundreds of kHz
- On-resistance increases rapidly with rated blocking voltage
- Easy to drive
- The device of choice for blocking voltages less than 500V
- 1000V devices are available, but are useful only at low power levels (100W)
- Part number is selected on the basis of on-resistance rather than current rating

4.2.3. Bipolar Junction Transistor (BJT)

- Interdigitated base and emitter contacts
- Vertical current flow
- npn device is shown
- minority carrier device
- on-state: base-emitter and collector-base junctions are both forward-biased
- on-state: substantial minority charge in p and n regions, conductivity modulation
Conclusions: BJT

- BJT has been replaced by MOSFET in low-voltage (<500V) applications
- BJT is being replaced by IGBT in applications at voltages above 500V
- A minority-carrier device: compared with MOSFET, the BJT exhibits slower switching, but lower on-resistance at high voltages

4.2.4. The Insulated Gate Bipolar Transistor (IGBT)

- A four-layer device
- Similar in construction to MOSFET, except extra p region
- On-state: minority carriers are injected into n-region, leading to conductivity modulation
- Compared with MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to 1700V)
The IGBT

Symbol

collector

gate

emitter

Equivalent circuit

Location of equivalent devices

Current tailing in IGBTs
Switching loss due to current-tailing in IGBT

Example: buck converter with IGBT

transistor turn-off transition

\[ P_{sw} = \frac{1}{2} \int_{t_1}^{t_2} p_i(t) \, dt = (W_{on} + W_{off}) \cdot f \]

Characteristics of several commercial devices

<table>
<thead>
<tr>
<th>Part number</th>
<th>Rated max voltage</th>
<th>Rated avg current</th>
<th>( V_f ) (typical)</th>
<th>( t_f ) (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single-chip devices</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HGTG32N60E2</td>
<td>600V</td>
<td>32A</td>
<td>2.4V</td>
<td>0.62( \mu )s</td>
</tr>
<tr>
<td>HGTG30N120D2</td>
<td>1200V</td>
<td>30A</td>
<td>3.2V</td>
<td>0.58( \mu )s</td>
</tr>
<tr>
<td><strong>Multiple-chip power modules</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CM400HA-12E</td>
<td>600V</td>
<td>400A</td>
<td>2.7V</td>
<td>0.3( \mu )s</td>
</tr>
<tr>
<td>CM400HA-24E</td>
<td>1200V</td>
<td>600A</td>
<td>2.7V</td>
<td>0.3( \mu )s</td>
</tr>
</tbody>
</table>
Conclusions: IGBT

- Becoming the device of choice in 500 to 1700V+ applications, at power levels of 1-1000kW
- Positive temperature coefficient at high current — easy to parallel and construct modules
- Forward voltage drop: diode in series with on-resistance, 2-4V typical
- Easy to drive — similar to MOSFET
- Slower than MOSFET, but faster than Darlington, GTO, SCR
- Typical switching frequencies: 3-30kHz
- IGBT technology is rapidly advancing:
  - 3300 V devices: HV/IGBTs
  - 150 kHz switching frequencies in 600 V devices

4.2.5. Thyristors (SCR, GTO, MCT)

The SCR

- symbol
- equiv circuit
- construction
The Silicon Controlled Rectifier (SCR)

- Positive feedback — a latching device
- A minority carrier device
- Double injection leads to very low on-resistance, hence low forward voltage drops attainable in very high voltage devices
- Simple construction, with large feature size
- Cannot be actively turned off
- A voltage-biased two-quadrant switch

\[ I_{AK} \]
\[ V_{AK} \]

5000-6000V, 1000-2000A devices

Transistor Selection

**Figure 1:** Power Semiconductor devices and applications
Transistor Selection

Figure 2-14: Summary of power semiconductor device capabilities. All devices except the MCT have a relatively mature technology, and only evolutionary improvements in the device capabilities are anticipated in the next few years. However, MCT technology is in a state of rapid expansion, and significant improvements in the device capabilities are possible, as indicated by the expansion arrow in the diagram.

Transistor Hybridization

<table>
<thead>
<tr>
<th>IGBT</th>
<th>Superjunction MOSFET</th>
<th>Hybrid MOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel Operation</td>
<td>Parallel Operation</td>
<td>Parallel Operation</td>
</tr>
</tbody>
</table>

- **IGBT**
  - Small Current
  - High Temp
  - Large Current

- **Superjunction MOSFET**
  - Small Current
  - Large Current

- **Hybrid MOS**
  - Small Current
  - Large Current

**Table Characteristics**

<table>
<thead>
<tr>
<th>VD Characteristics</th>
<th>IGBT</th>
<th>Superjunction MOSFET</th>
<th>Hybrid MOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Current</td>
<td>X</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>High Current</td>
<td>O</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>High-Speed Switching</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Significantly lower yearly power consumption

**Legend**

- X: Excellent for steady-state operation
- O: Ideal for instantaneous large currents
4.3. Switching loss

- Energy is lost during the semiconductor switching transitions, via several mechanisms:
  - Transistor switching times
  - Diode stored charge $Q_D$
  - Energy stored in device capacitances and parasitic inductances
  - Semiconductor devices are charge controlled
  - Time required to insert or remove the controlling charge determines switching times

Some other sources of this type of switching loss

- Schottky diode (majority carrier)
  - Essentially no stored charge $Q_r=0$ but $C_j>0$
- Transformer leakage inductance
  - Effective inductances in series with windings
  - A significant loss when windings are not tightly coupled
- Interconnection and package inductances
  - Diodes
  - Transistors
  - A significant loss in high current applications
4.3.4. Efficiency vs. switching frequency

Add up all of the energies lost during the switching transitions of one switching period:

\[ W_{\text{tot}} = W_{\text{on}} + W_{\text{off}} + W_{\text{diode}} + W_{\text{f}} + \ldots \]

Average switching power loss is

\[ P_{\text{sw}} = \frac{W_{\text{tot}}}{f_s} \]

Total converter loss can be expressed as

\[ P_{\text{tot}} = P_{\text{on}} + P_{\text{off}} + W_{\text{diode}} f_s \]

where \( P_{\text{fixed}} \) = fixed losses (independent of load and \( f_s \))

\[ P_{\text{on}} = \text{conduction losses} \]

---

Efficiency vs. switching frequency

\[ P_{\text{tot}} = P_{\text{on}} + P_{\text{off}} + W_{\text{diode}} f_s \]
Inclusion of Switching Loss in the Averaged Equivalent Circuit Model

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

Extension of Chapter 3 Methods

- 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 balance and capacitor charge balance

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

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

Average input current

\( \langle i_g \rangle = I_g = \frac{\text{(area under curve)}}{T_s} \)

\( = \frac{(DT L + t_f L + Q_f)/T_s}{T_s} \)

\( = DI_L + t_f L / T_s + Q_f / T_s \)
Construction of Equivalent Circuit Model

From inductor volt-second balance: \( \langle v_L \rangle = 0 = D V_g - V \)

From capacitor charge balance: \( \langle c \rangle = 0 = I_L - V/R \)

Input port of model

\[ \langle i_g \rangle = I_g = D I_L + t_r I_L/T_s + Q_r/T_s \]
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

Solution of model

*Output:*

\[ V = DV_g \]

*Efficiency:*

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

\[ P_{out} = V I_L \quad P_{in} = V_g (D I_L + t_{IL} / T_s + Q_r / T_s) \]

Combine and simplify:

\[ \eta = 1 / \left[ 1 + f_s (t_s / D + Q_r R / D^2 V_g) \right] = \frac{1}{1 + f_s (\cdot)} \]
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

Transistor and diode waveforms have same shapes as in buck example, but depend on different quantities.

Inductor volt-second balance and average input current

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

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

\[ \langle i_C \rangle = \langle i_d \rangle - \frac{V}{R} = 0 \]

\[ = -\frac{V}{R} + I_t (D'T_\text{s} - t_r)/T_\text{s} - Q_r/T_\text{s} \]

Collect terms: \( V/R = I_t (D'T_\text{s} - t_r)/T_\text{s} - Q_r/T_\text{s} \)

Construct model

The result is:

The two independent current sources consume power

\[ V \left( t_i I_L/T_\text{s} + Q_r/T_\text{s} \right) \]

equal to the switching loss induced by diode reverse recovery
Predicted $V/V_g$ 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)

**Summary**

- The averaged modeling approach can be extended to include effects of switching loss
- Transistor and diode waveforms are constructed, including the switching transitions. The effects of the switching transitions on the inductor, capacitor, and input current waveforms can then be determined
- Inductor volt-second balance and capacitor charge balance are applied
- Converter input current is averaged
- Equivalent circuit corresponding to the the averaged equations is constructed