Lecture 7: MOSFET, IGBT, and Switching Loss

ECE 481: Power Electronics
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MOSFET body diode

- $p$-$n$ junction forms an effective diode, in parallel with the channel
- negative drain-to-source voltage can forward-bias the body diode
- diode can conduct the full MOSFET rated current
- diode switching speed not optimized — body diode is slow, $Q_s$ is large
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

A simple MOSFET equivalent circuit

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

\[
C_{d}(V_{ds}) = \frac{C_{d}}{\sqrt{1 + \frac{V_{ds}}{V_{th}}}}
\]

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

Buck converter example

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

\[ W_c = \frac{1}{2} (C_{ds} + C_j) V_c^2 \]
MOSFET nonlinear $C_{ds}$

Approximate dependence of incremental $C_{ds}$ on $i_{ds}$:

$$C_{ds}(t_n) = C_0 \sqrt{\frac{V_{ds}}{V_{th}}} = C_{ds0} \sqrt{\frac{1}{i_{dsn}}}$$

Energy stored in $C_{ds}$ at $v_{ds} = V_{DS}$:

$$W_{C_0} = \int_{v_{th}}^{V_{DS}} v_{ds} i_{ds} \, dt = \int_{v_{th}}^{V_{DS}} v_{ds} C_{ds}(v_{ds}) \, dv_{ds}$$

$$W_{C_0} = \int_{v_{th}}^{V_{DS}} C_{ds}(v_{ds}) \sqrt{\frac{1}{i_{ds}}} \, dv_{ds} = \frac{1}{3} C_{d}(V_{th}) V_{DS}^2$$

— same energy loss as linear capacitor having value $\frac{1}{3} C_{d}(V_{th})$

Characteristics of several commercial power MOSFETs

<table>
<thead>
<tr>
<th>Part number</th>
<th>Rated max voltage</th>
<th>Rated max current</th>
<th>$R_{on}$</th>
<th>$Q_I$ (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRLHM620</td>
<td>20V</td>
<td>40A</td>
<td>0.0025Ω</td>
<td>52nC</td>
</tr>
<tr>
<td>EPC2015</td>
<td>40V</td>
<td>33A</td>
<td>0.004Ω</td>
<td>10.5nC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF510</td>
<td>100V</td>
<td>5.6A</td>
<td>0.54Ω</td>
<td>8.3nC</td>
</tr>
<tr>
<td>BF540</td>
<td>100V</td>
<td>20A</td>
<td>0.077Ω</td>
<td>72nC</td>
</tr>
<tr>
<td>APT10M255BNR</td>
<td>100V</td>
<td>75A</td>
<td>0.025Ω</td>
<td>171nC</td>
</tr>
<tr>
<td>BRF740</td>
<td>400V</td>
<td>10A</td>
<td>0.55Ω</td>
<td>63nC</td>
</tr>
<tr>
<td>MTM15N40E</td>
<td>400V</td>
<td>15A</td>
<td>0.3Ω</td>
<td>110nC</td>
</tr>
<tr>
<td>APT5025BN</td>
<td>500V</td>
<td>23A</td>
<td>0.25Ω</td>
<td>83nC</td>
</tr>
<tr>
<td>APT100R1BNR</td>
<td>1000V</td>
<td>11A</td>
<td>1.0Ω</td>
<td>150nC</td>
</tr>
<tr>
<td>IPW60R099CP</td>
<td>600V</td>
<td>31A</td>
<td>0.1Ω</td>
<td>60nC</td>
</tr>
<tr>
<td>IPW90R0340C3</td>
<td>900V</td>
<td>15A</td>
<td>0.34Ω</td>
<td>93nC</td>
</tr>
<tr>
<td>TPH3006PD</td>
<td>600V</td>
<td>17A</td>
<td>0.15Ω</td>
<td>6nC</td>
</tr>
<tr>
<td>CMF20120</td>
<td>1200V</td>
<td>24A</td>
<td>0.098Ω</td>
<td>49nC</td>
</tr>
</tbody>
</table>
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 p 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

\[ P_{sw} = \frac{1}{f} \int_{t_{on}} p_x(t) dt = (W_{on} + W_{off}) f_c \]

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>HGTG32N6082</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-21E</td>
<td>1200V</td>
<td>500A</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: HVIGBTs
  - 650 kHz switching frequencies in 600 V devices

4.2.5. Thyristors (SCR, GTO, MCT)

The SCR

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Equivalent Circuit</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode (A)</td>
<td>Q1, Q2</td>
<td>K</td>
</tr>
<tr>
<td>Gate (G)</td>
<td>Anode</td>
<td>G</td>
</tr>
<tr>
<td>Cathode (K)</td>
<td></td>
<td>P</td>
</tr>
</tbody>
</table>

\[ n \rightarrow Q_1 \rightarrow Q_2 \rightarrow K \]

\[ p \rightarrow Q_1 \rightarrow Q_2 \rightarrow K \]

\[ n \rightarrow Q_1 \rightarrow Q_2 \rightarrow K \]

\[ p \rightarrow Q_1 \rightarrow Q_2 \rightarrow K \]
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-bipolar two-quadrant switch
- 5000-6000V, 1000-2000A devices

4.3. Switching loss

- Energy is lost during the semiconductor switching transitions, via several mechanisms:
  - Transistor switching times
  - Diode stored charge
  - 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
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

Some other sources of this type of switching loss

Schottky diode
- Essentially no stored charge
- Significant reverse-biased junction capacitance

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
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
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

\[ \langle i_g \rangle = I_g = \frac{\text{area under curve}}{T_s} = \frac{DT_s I_L + t_r I_L + Q_r}{T_s} = DI_L/I_s + t_r I_s/Q_r + Q_r/T_s \]

Construction of Equivalent Circuit Model

From inductor volt-second balance: \[ \langle v_L \rangle = 0 = DV_g - V \]
From capacitor charge balance: \[ \langle i_C \rangle = 0 = I_L - V/R \]
\[ \langle i_g \rangle = I_g = DI_L + t_r I_L / T_s + Q_r / T_s \]

The two independent current sources consume power

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

equal to the switching loss induced by diode reverse recovery.
Solution of model

Output:
\[ V = DV_g \]

Efficiency:
\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \]
\[ P_{\text{out}} = VI_L \]
\[ P_{\text{in}} = V_g (DI_L + t_r I_L / T_s + Q_r / T_s) \]

Combine and simplify:
\[ \eta = \frac{1}{1 + f_s (t_r / D + Q_r R / D^2 V_g)} \]

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

$\langle i_C \rangle = \langle i_d \rangle - V/R = 0$

$= - V/R + I_L(D'T_s - t_r)/T_s - Q_r/T_s$

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

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

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 Ω
- Recovered charge 5 µCoul
- 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