Power Semiconductors

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# Transient Simulation Applications

- Medium to high power applications
- Converter applications include
  - HVdc, FACTS, Custom Power Devices
  - Interface for fuel cells, photovoltaic, micro-turbine, some wind
  - SMES, battery energy storage, flywheels
  - Adjustable speed drives
  - Active filters
  - Static transfer switches, solid state breakers
Types of Studies

- Predict response of converter controls
  - System conditions
  - Some stability studies
  - Protection studies
  - Harmonic studies
  - Response to sags
  - Transients from converter operation
Converter Modeling

- Averaged/fundamental component models
- State space models
- Switching models
  » equivalent
  » detailed
Ideal Switch
Device Models

• Turn on at next time step after command
• Turn off at next time step after command or
• At time step after next current zero crossing for diodes and thyristor
• Switch time equal to simulation time step
• When device is off = open circuit
• When device is on = short circuit
<table>
<thead>
<tr>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequencies of interest much slower than switch turn-on and turn-off times</td>
</tr>
<tr>
<td>Combining series/parallel combinations of devices into one equivalent switch</td>
</tr>
<tr>
<td>Converter losses aren’t important</td>
</tr>
<tr>
<td>Device voltage and current stresses aren’t important</td>
</tr>
</tbody>
</table>
Detailed Device Models

- Will vary with device in question
- Appropriate degree of detail varies
  - Application
  - Software, including available libraries
- Represent actual turn-on, turn-off delay
- On state resistance or voltage drop
- Gate driver circuit dynamics
Applications Requiring Detailed Device Models

- Converter voltage/current stresses
- Converter switching and conduction losses
- High switching frequency/slow devices
- Insulation transients in converter-fed machines and transformers
- Electromagnetic interference studies
- Thermal analysis
- Design of device protection
Common Devices

- In General Use:
  - Power Diode (pn junction and Shottky barrier)
  - Thyristor/Silicon Controlled Rectifier (SCR), Converter grade
  - Gate Turn Off Thyristor (GTO)
  - Insulated Gate Bipolar Transistor (IGBT)
Common Devices

- Emerging Devices (some in applications)
  - MOS Controller Thyristor (MCT)
  - Gate Commutated Thyristor (GCT/IGCT)
  - MOS Turn-off Thyristor (MTO)
  - Static Induction Transistor/Thyristor (SIT/SiTh)
  - Smart Power Devices/Power ICs
Model Implementations: Ideal Switch

- EMTP-like program built-in models
  - Controller switch
  - Diode/Thyristor
    - can force commutate also
    - Meant to model mercury arc valve
    - Does have setting for minimum turn-on voltage
  - Controlled ideal switch
    - open/close at next time step
Creating Approximate Model

- Point by point non-linearity inserted in circuit to represent turn-on characteristic
- Controlled current or voltage source in place of switch
- Difficult to make general purpose switch this way (often fixed V or I limits)
- Non-linear element or source based on characteristic or equations
Gathering Data for Model

- How much information on the application is available
  - Are you expected to treat it as a black box?
  - Control data available?
  - If the answers to these are no, you have limited options
Diode Model: Gathering Data

- Forward drop
  - Nominal from data sheet
  - Varies with current & Temp

### Major Ratings and Characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>80EPF..</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{F(AV)}$ Sinusoidal waveform</td>
<td>80</td>
<td>A</td>
</tr>
<tr>
<td>$V_{RRM}$</td>
<td>1000 to 1200</td>
<td>V</td>
</tr>
<tr>
<td>$I_{FSM}$</td>
<td>1100</td>
<td>A</td>
</tr>
<tr>
<td>$V_F$ @ 40 A, $T_J=25^\circ C$</td>
<td>1.2</td>
<td>V</td>
</tr>
<tr>
<td>$T_J$</td>
<td>-40 to 150</td>
<td>°C</td>
</tr>
</tbody>
</table>

![Graph showing forward voltage drop characteristics](image)

Fig. 7 - Forward Voltage Drop Characteristics

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Diode Model: Gathering Data

- **Reverse recovery**
  - Nominal data given in data sheet
  - $I_{rr}$ varies as $I_F^{1/2}$ and $(\text{di}_r/\text{dt})^{1/2}$
  - $t_{rr}$ varies as $I_F^{1/2}$ and $(\text{di}_r/\text{dt})^{-1/2}$
  - Snap factor: $S = t_b/t_a$

### Recovery Characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>80EPF.</th>
<th>Units</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{rr}$</td>
<td>480</td>
<td>ns</td>
<td>$I_F \geq 80A_{pk}$</td>
</tr>
<tr>
<td>$I_{rr}$</td>
<td>7.1</td>
<td>A</td>
<td>$25A/\mu s$</td>
</tr>
<tr>
<td>$Q_{rr}$</td>
<td>2.1</td>
<td>$\mu C$</td>
<td>$25^\circ C$</td>
</tr>
<tr>
<td>$S$</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Approximate Characteristic

- Can use straight line approximation
- Calculate losses and peak inverse voltage
- Formula on data sheets (ex: International Rectifier Sheets)
Diode Model Calculations

- Inverse voltage
  - Overshoots $V_R$ by lead inductance
    - $(2.5\text{nH/mm}) \times I_{rr}/t_b$

- Current
  - Calculated from Circuit topology

- Losses
  - Conduction: $P_{\text{lossC}} = V_F \times I_F \times t_{\text{on}}/T$
  - Reverse recovery:
    - $P_{\text{lossS}} = f_{\text{sw}} \times [V_F \times Q_a + (5V_{rr} - 2V_R) \times Q_b/3)]$
Assuming Data?

• Use specs for known device in approximate class (converter ratings)
  » Speed: recovery time or rise/fall times
  » Forward voltage
  » Peak current

• Relative importance
  » Speed in each case
  » $V_F$ for active devices; $I_F$ for diodes
IGBT Model: Gathering Data

- Forward voltage drop
  - Nominal from data sheet
  - Varies with current and temperature
  - Protection methods often use as an overcurrent indicator

- Current rise / fall times
  - Nominal from data sheet
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qg</td>
<td></td>
<td>160</td>
<td>250</td>
<td>nC</td>
<td>IC = 24A</td>
</tr>
<tr>
<td>Qge</td>
<td></td>
<td>27</td>
<td>40</td>
<td></td>
<td>VCC = 400V, VBE = 15V</td>
</tr>
<tr>
<td>Qgc</td>
<td></td>
<td>53</td>
<td>80</td>
<td></td>
<td>See Fig. 8</td>
</tr>
<tr>
<td>td(on)</td>
<td></td>
<td>47</td>
<td></td>
<td>ns</td>
<td>TJ = 25°C</td>
</tr>
<tr>
<td>tr</td>
<td></td>
<td>24</td>
<td></td>
<td></td>
<td>IC = 24A, VCC = 800V</td>
</tr>
<tr>
<td>td(off)</td>
<td></td>
<td>110</td>
<td>170</td>
<td></td>
<td>VGE = 15V, RG = 5.0Ω</td>
</tr>
<tr>
<td>tf</td>
<td></td>
<td>180</td>
<td>260</td>
<td></td>
<td>Energy losses include &quot;tail&quot; and diode reverse recovery.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>See Fig. 9, 10, 18</td>
</tr>
<tr>
<td>L_E</td>
<td></td>
<td>13</td>
<td></td>
<td>nH</td>
<td>Measured 5mm from package</td>
</tr>
<tr>
<td>Ciss</td>
<td></td>
<td>3600</td>
<td></td>
<td>pF</td>
<td>VGE = 0V</td>
</tr>
<tr>
<td>Coes</td>
<td></td>
<td>160</td>
<td></td>
<td></td>
<td>VCC = 30V, f = 1.0MHz</td>
</tr>
<tr>
<td>Crss</td>
<td></td>
<td>31</td>
<td></td>
<td></td>
<td>See Fig. 7</td>
</tr>
<tr>
<td>trr</td>
<td></td>
<td>90</td>
<td>135</td>
<td>ns</td>
<td>TJ = 25°C, TJ = 125°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>164</td>
<td>245</td>
<td></td>
<td>See Fig.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>IF = 16A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>VR = 200V</td>
</tr>
<tr>
<td>dI(peak)/dt</td>
<td></td>
<td>120</td>
<td></td>
<td>A/µs</td>
<td>TJ = 25°C, TJ = 125°C</td>
</tr>
<tr>
<td>During t_b</td>
<td></td>
<td>76</td>
<td></td>
<td></td>
<td>See Fig.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>dl/dt = 200A/µs</td>
</tr>
</tbody>
</table>

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IGBT Model: Gathering Data

- Voltage rise/fall times
  - Assumed brief compared to current rise/fall times
- Current
  - Peak device current is load peak current plus diode reverse recovery current
IGBT Model: Gathering Data

- Gate delay
  - Depends on $R_{\text{gate}}$, $C_{gs}$
  - $C_{gs} = C_{\text{ies}}$ on data sheets

- Switching losses
  - Given on data sheet
  - Assumed proportional to $V_S$ and Switching frequency
IGBT Model Calculations

• Voltage
  » Blocking: Link voltage $V_S$
  » Conducting: Forward voltage $V_F$
  » Rise transient influenced strongly by antiparallel diodes (bridge type circuit)

• Current
  » Conducting: Circuit calculations with source $V_{FWD}$
  » Rise and fall transients at given rise/fall times
IGBT Model Calculations

• Losses
  » Conduction: \( P_{\text{lossC}} = V_{\text{FWD}} \cdot I_C \cdot t_{\text{on}} / T \)
  » Switching: \( P_{\text{lossS}} = V_S \cdot (I_L \cdot t_a + Q_a + Q_b / 2) \)
More Detailed Models

- **SPICE / Saber**
  - Data available from mfgs.
  - “Plug and play” black box models
  - Accurate predictions

- **Developing Your Own**
  - Simplify the rest of the circuit
  - Obtain V, I transients and loss estimates
Switching Model
Simplifications

- Ideal device or simple forward source model
  » Enables prediction of behavior over many cycles
  » Calculate peak device stresses
  » Calculate losses and apply to thermal model
  » Economize on simulation time
- More detailed (SPICE/Saber) models for accurate switching transients
Creating Approximate Model

- Use controlled switch for diode to allow current reversal (need to control turn-off)
- Switch in series with voltage source for on-state voltage drop (or resistor for some devices)
- Create slope for turn-on/turn-off delay with passive circuit elements (L, C, R)
Conclusions

• Ideal switch models usually adequate
• Data for devices in specific converter may be hard to get
• Can approximate by assuming
  » Kind of device
  » Voltage, current, speed class
  » Use data for similar devices
Conclusions

- Best data available from device specification sheets
- Very detailed device models in Saber
- Some models available for Pspice
- Approximate device models often adequate

  » Know your application and needs
  » Is the rest of the model accurate enough now