Announcements

- Office Hours:
  - Shortened office hours today: 1:30-2:20
  - Earlier office hours tomorrow: 8:30-9:30

Switching Nonidealities
Application Example: EV LV Bus

Electrification tailored to fit

Fuel saving with low voltage technology
Fuel saving and electric driving
100% electric driving

CO₂ Reduction

Electric Vehicle
Plug-in Hybrid
Full Hybrid
48 V Hybrid

12 V Start-Stop
48 V Eco Drive
**EV Networks**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_g$</td>
<td>12 V</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>48 V</td>
</tr>
<tr>
<td>$R_{out}$</td>
<td>48 $\Omega$</td>
</tr>
<tr>
<td>$\Delta V_{out}$</td>
<td>0.1 V</td>
</tr>
</tbody>
</table>
Baseline Design

- Use TI WebBench (webench.ti.com) to get a baseline design

Equivalent Circuit Model

\[ V = \left( \frac{1}{D} \right) \left( V_s - D V_P \right) \left( \frac{D^2 R}{D^2 R + R_s + DR_m + D'R_P} \right) \]

\[ \frac{V}{V_s} = \left( \frac{1}{D} \right) \left( 1 - \frac{D V_P}{V_s} \right) \left( \frac{1}{1 + R_s + DR_m + D'R_P} \right) \left( \frac{1}{D^2 R} \right) \]
### Device Parameters

#### Diode

#### MOSFET

#### Inductor

<table>
<thead>
<tr>
<th>Part number</th>
<th>Inductance ($L$)</th>
<th>Series Resistance ($r_s$)</th>
<th>DC Resistance ($r_d$)</th>
<th>GCM (1kHz)</th>
<th>I(V)</th>
<th>SRF (1kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRR0405100K</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRR0405200K</td>
<td>2.2</td>
<td>2.0</td>
<td>2.0</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRR0405300K</td>
<td>3.3</td>
<td>3.0</td>
<td>3.0</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRR0405400K</td>
<td>4.7</td>
<td>4.0</td>
<td>4.0</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRF04104720K</td>
<td>2.2</td>
<td>2.0</td>
<td>2.0</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### LTSpice Simulation

<table>
<thead>
<tr>
<th>$L$</th>
<th>$C_{out}$</th>
<th>$f_s$</th>
<th>$\eta$ (Sim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22uH</td>
<td>22uF</td>
<td>202k</td>
<td>93.9%</td>
</tr>
</tbody>
</table>
Diode Switching Waveforms

Power Diodes
Forward Biased Diode

Diode Stored Charge

The diode equation:
\[ q(t) = Q_0 \left( e^{\lambda \tau_L t} - 1 \right) \]

Charge control equation:
\[ \frac{dq(t)}{dt} = i(t) - \frac{q(t)}{\tau_L} \]

With:
\( \lambda = 1/(26 \text{ mV}) \) at 300 K
\( \tau_L = \) minority carrier lifetime

(above equations don’t include current that charges depletion region capacitance)

In equilibrium: \( dq/dt = 0 \), and hence
\[ i(t) = \frac{q(t)}{\tau_L} = \frac{Q_0}{\tau_L} \left( e^{\lambda \tau_L t} - 1 \right) \equiv I_0 \left( e^{\lambda \tau_L t} - 1 \right) \]
Diode Turn-On

Diode Turn-Off

Depletion region, reverse biased

Removal of stored minority charge q
Diode Reverse Recovery

Datasheet RR Characteristics

Fig. 10 - Typical Stored Charge vs. \( \frac{dl_i}{dt} \)

Fig. 9 - Typical Reverse Recovery Time vs. \( \frac{dl_i}{dt} \)
Types of Power Diodes

*Standard recovery*
Reverse recovery time not specified, intended for 50/60Hz

*Fast recovery and ultra-fast recovery*
Reverse recovery time and recovered charge specified
Intended for converter applications

*Schottky diode*
A majority carrier device
Essentially no recovered charge
Model with equilibrium $i-v$ characteristic, in parallel with depletion region capacitance
Restricted to low voltage (few devices can block 100V or more)

Paralleling Diodes

Attempts to parallel diodes, and share the current so that $i_1 = i_2 = i/2$, generally don’t work.

Reason: thermal instability caused by temperature dependence of the diode equation.

Increased temperature leads to increased current, or reduced voltage.

One diode will hog the current.

To get the diodes to share the current, heroic measures are required:

- Select matched devices
- Package on common thermal substrate
- Build external circuitry that forces the currents to balance