Resonant Circuits

\[ \frac{\text{d}v_{\text{out}}}{\text{d}t} + \left( \frac{\text{d}v_{\text{in}}}{\text{d}t} \right) V_{\text{out}} - V_{\text{in}} = 0 \]  

Transient analysis

- \( v_{\text{in}} \) and \( v_{\text{out}} \)
- \( L \) and \( C \)
- \( R \)

\[ \begin{align*}
\text{Diff Eq:} & \quad L \frac{\text{d}i}{\text{d}t} + R \frac{\text{d}v}{\text{d}t} = 0 \\
\text{Laplace:} & \quad L \frac{\text{d}v}{\text{d}t} + R \frac{\text{d}v}{\text{d}t} = 0 \\
\text{Numerical approaches:} & \quad \text{techniques from JFL}
\end{align*} \]

Small ripple approximation (SRA) does not generally apply:

- \[ i_L \approx I_L \]
- \[ v_{\text{out}} \approx V \]

Filter elements:
- "Large" L & C, SRA applies

Resonant elements:
- "Small" L & C, SRA doesn't apply
Resonant Circuit Analysis

\[ v_{in} \]

\[ v_{out} \]

\[ L \]

\[ C \]

\[ R \]

\[ \frac{1}{\omega_0^2} = \frac{1}{LC} \]

\[ Q = \frac{R}{R_0} \]

\[ R_0 = \sqrt{LC} \]

\[ ECE \text{ set } f_0 \text{ location} \]

\[ ECE \text{ set } \text{reversal} \]

\[ -40 \text{ dB/dec} \]

\[ \text{significant attenuation of } f_0 \text{ & harmonics} \]

\[ Q > > 0.5 \]

\[ Q < < 0.5 \]

\[ \text{Unit}(t) \]

\[ f_0 \]

\[ f_0 \]

\[ f_0 \]

\[ f_0 \]
Soft Switching

• Advantages
  – Reduced switching loss
  – Possible operation at higher switching frequency
  – Lower EMI

• Disadvantages
  – Increased current and/or voltage stresses due to circulating current
  – Higher peak and rms current values
  – Complexity of analysis and modeling
Limitations: Gate Drive

Preceding motivation assumes $v_{gs}$ still square wave

Gate power loss (normalized by $C_{iss} V_{G, pk}^2$)

$C_{iss} = 276 \text{pF}$, $V_{G, pk} = 8 \text{V}$

Normalized Power Loss [$\text{J/s}$]

Frequency [MHz]

$0$, $50$, $100$, $150$, $200$, $250$, $300$
Limitations: $t_d/T_s$
Limitations: Thermal

(a) Graph showing volume vs. switching frequency for different cooling methods.

(b) Graph showing power density vs. switching frequency for different devices.

Limitations: Magnetics Design

At HF ac loss mechanisms (skin, proximity, fringing core) get worse.

Core loss \( \frac{P_{\text{core}}}{V_{\text{core}}} = k_\text{f} (AB)^{\beta} (f_0)^{\alpha} \)

\( \frac{1}{2} AB \) \( 2f_0 \)
Limitations: Circuit Modeling

150-to-400V, 150W Boost

EXPERIMENTAL EXAMPLE
ZVS with Si diode

- **ZVS turn-ON**
  - Eliminated losses due to $C_{sw}$ discharge during turn-ON transient
  - Eliminated losses due to MOSFET $di/dt$ during turn-ON transient
- **Diode reverse recovery still impacts the waveforms and losses**
- **Increased current ripple**
  - Increased conduction losses (by $>30\%$)
  - Increased $dv_{ds}/dt$ upon turn-OFF, MOSFET turn-OFF speed is more important

---

D. Costinett, D. Maksimovic, R. Zane, A. Rodriguez and A. Vázquez, "Comparison of reverse recovery behavior of silicon and wide bandgap diodes in high frequency power converters"
Loss Breakdown: Soft-Switched Si Boost

$f_s = 100 \text{ kHz}$

$P_{loss} = 5.7 \text{ W, } \eta = 98.1\%$

Reverse-recovery: 21% of the total loss

$f_s = 1 \text{ MHz}$

$P_{loss} = 17.7 \text{ W, } \eta = 94.4 \%$

Experiment: $\eta = 95.1 \%$

Reverse-recovery: 68% of the total loss
Soft-switched SiC diode

SiC diode, “soft-switched” operation

Only 2nd-order switching loss mechanisms remain

\[ f_s = 1 \text{ MHz} \]

MOSFET

- \( \frac{di_f}{dt} = 200 \text{ A/μs} \)
- \( C_{ds,eq} = 45 \text{ pF} \)
- \( R_{on} = 0.15 \text{ Ω} \)

SiC diode

- \( t_{rr} = 0, Q_{rr} = 0 \)
- \( 2C_{d,Qeq} - C_{d,eq} = 64 \text{ pF} \)
- \( V_D = 1.8 \text{ V} \)
Soft-switched Boost with SiC diode

Conduction losses only, 2nd-order switching losses not included in the model

Power supply technology limits become dominated by:

- Magnetics
- 2nd-order switching loss mechanisms, e.g. gate-drive losses, parasitic inductances (layout and packaging)
- Gate-drive circuitry and controllers to support high-frequency operation

Experiments:
- 98.7% at 1 MHz
- 98.0% at 2 MHz

100 kHz or 1 MHz

98.5% efficiency

\[ P_{\text{loss}} = 4.5 \text{ W} \]
VHF power electronics [11]

<table>
<thead>
<tr>
<th>Component</th>
<th>Resonant Design</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{LF}$</td>
<td>33 nH</td>
<td>Coilcraft 1812SMS</td>
</tr>
<tr>
<td>$L_{2F}$</td>
<td>12.5 nH</td>
<td>Coilcraft A04TG</td>
</tr>
<tr>
<td>$L_{rect}$</td>
<td>22 nH</td>
<td>1812SMS</td>
</tr>
<tr>
<td>$C_{2F}$</td>
<td>39 pF</td>
<td>ATC100A</td>
</tr>
<tr>
<td>$C_{rect}$</td>
<td>10 pF</td>
<td>ATC100A</td>
</tr>
<tr>
<td>$C_{OUT}$</td>
<td>75 µF</td>
<td>Multilayer Ceramics</td>
</tr>
<tr>
<td>$C_{IN}$</td>
<td>22 µF</td>
<td>Multilayer Ceramics</td>
</tr>
<tr>
<td>$S_{main}$</td>
<td></td>
<td>Freescale MRF69060 Fairchild S310</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Conventional Design</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{Lout}$</td>
<td>10 µH</td>
<td>Coilcraft D03316F-103ML</td>
</tr>
<tr>
<td>$C_{OUT}$</td>
<td>75 µF</td>
<td>Multilayer Ceramics</td>
</tr>
<tr>
<td>$C_{IN}$</td>
<td>22 µF</td>
<td>Multilayer Ceramics</td>
</tr>
<tr>
<td>$S_{main}$</td>
<td></td>
<td>LT1371HV</td>
</tr>
<tr>
<td>$D$</td>
<td></td>
<td>Fairchild S310</td>
</tr>
</tbody>
</table>

Converter Efficiencies vs. Output Power

WBG Devices

TriQuint TGF2023-02
12W, DC-to-18 GHz
RF/microwave HEMT

FOM for switching applications

\[ C_{ds} R_{on} \approx 1 \, \Omega \text{pF} \]
\[ Q_g R_{on} \approx 10 \, \Omega \text{pC} \]

Standard hard-switched PWM operation at 50 MHz:
\[ \frac{dv_{ds}}{dt} \] dominated by probe (4 pF) capacitance

Emerging GaN HEMT devices may enable completely new RF-based design approaches in power electronics

M. Rodríguez, G. Stahl, D. Costinett and D. Maksimović, "Simulation and characterization of GaN HEMT in high-frequency switched-mode power converters,"
Topics Covered

• High Frequency Power Conversion
  - Switching losses and device selection
  - Nonlinear device capacitances
  - Resonance in power electronics
  - Soft switching (ZVS and ZCS)

• Resonant Converters
  - State-plane analysis
  - Resonant converter topologies
  - Sinusoidal analysis
  - AC-modeling and frequency modulation

• Non-resonant soft switching converters
  - State-plane analysis
  - Constant frequency control
  - Resonant switches
  - Modeling and Simulation
  - Discrete time models

• Switched capacitor converters
  - SSL and FSL operation
  - Charge vector modeling
  - Soft-charging operation

• Applications and practical issues of high frequency converters