Light Load Operation

- $I_{rms} \approx 3.9A$
- Conduction losses ↑ relative to small-ripple type boost

Light Load – Diode Operation
### Hard-switched Si devices

![Circuit Diagram](image)

**MOSFET**
- \(\frac{di}{dt} = 200\ A/\mu s\)
- \(C_{\text{par}} = 45 \text{ pF}\)
- \(R_{\text{on}} = 0.15 \Omega\)

**Si diode**
- \(t_{\text{tr}} = 40\ ns\)
- \(Q_{\text{rr}} = 60\ nC\)
- \(2C_{\text{d,eq}} - C_{\text{d,par}} = 22 \text{ pF}\)
- \(V_{\text{p}} = 1.5\ V\)

### Loss breakdown: Si Boost

- \(f_s = 100\ kHz\)
- \(P_{\text{loss}} = 10.6\ W, \eta = 96.6\%\)

- **Conduction losses:** RL, Ron, VD
- **Switching losses:** "RR" reverse recovery, "Cap" \(C_{\text{par}}\) discharge

- \(f_s = 1\ MHz\)
- \(P_{\text{loss}} = 84.7\ W, \eta = 78.0\%\)

*Experiment* \(\eta = 81.2\%\)

Reverse-recovery: 54% of the total loss

Reverse-recovery: 77% of the total loss

*Pulsed measurement, continuous operation not feasible due to thermal runaway*
Efficiency: hard-switched Si Boost

η [%]

Switching frequency $f_s$

ZVS with Si diode

• ZVS turn-ON
  • Eliminated losses due to $C_{sw}$ discharge during turn-ON transient
  • Eliminated losses due to MOSFET $dl_i/dt$ 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
Loss Breakdown: Soft-Switched Si Boost

- **$f_s = 100$ kHz**
  - $P_{\text{loss}} = 5.7$ W, $\eta = 98.1\%$
  - Reverse-recovery: 21% of the total loss

- **$f_s = 1$ MHz**
  - $P_{\text{loss}} = 17.7$ W, $\eta = 94.4\%$
  - Experiment: $\eta = 95.1\%$
  - Reverse-recovery: 68% of the total loss

Efficiency: soft-switched Si Boost

- $\eta [%]$ vs. Switching frequency $f_s$
  - **Soft-switched**
  - **Hard-switched**
  - **Extended practical $f_s$ range**

Experiment:

- $\eta = 95.1\%$
Hard-Switched SiC Schottky Diode

MOSFET
• $di/dt = 200$ A/$\mu$s
• $C_{ds,eq} = 45$ pF
• $R_{on} = 0.15$ $\Omega$

SiC diode
• $t_r = 0$, $Q_r = 0$
• $2C_{d,eq} - C_{d,eq} = 64$ pF
• $V_D = 1.8$ V

$f_s = 1$ MHz

Loss Breakdown: hard-switched SiC diode

$f_s = 100$ kHz
$P_{loss} = 5$ W, $\eta = 98.4\%$

$f_s = 1$ MHz
$P_{loss} = 15.7$ W, $\eta = 95.0\%$

Experiment: $\eta = 94.7\%$
Efficiency comparison

η [%]

Switching frequency $f_s$

Extended practical $f_s$ range

Soft-switched SiC Schottky diode

SiC diode, soft-switched operation

MOSFET
- $di/dt = 200$ A/$\mu$s
- $C_{ds,eq} = 45$ pF
- $R_{on} = 0.15$ $\Omega$

SiC diode
- $t_r = 0$, $Q_m = 0$
- $2C_{d,eq} = 64$ pF
- $V_D = 1.8$ V

Only 2nd-order switching loss mechanisms remain

$\eta = 98.5$

$\eta = 97.5$

$\eta = 96.5$

$\eta = 95.5$

$\eta = 94.5$

$\eta = 93.5$

$\eta = 92.5$

$\eta = 91.5$

$\eta = 90.5$

$\eta = 89.5$

$\eta = 88.5$

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$\eta = 15.5$

$\eta = 14.5$

$\eta = 13.5$

$\eta = 12.5$

$\eta = 11.5$

$\eta = 10.5$

$\eta = 9.5$

$\eta = 8.5$

$\eta = 7.5$

$\eta = 6.5$

$\eta = 5.5$

$\eta = 4.5$

$\eta = 3.5$

$\eta = 2.5$

$\eta = 1.5$

$\eta = 0.5$

$\eta = 0$
Soft-switched Boost with SiC diode

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

100 kHz or 1 MHz
98.5% efficiency

\[ P_{\text{loss}} = 4.5 \text{ W} \]

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

Soft-switched Boost with SiC diode

Efficiency comparison

\( \eta \ [%] \)

<table>
<thead>
<tr>
<th>Switching frequency ( f_s )</th>
<th>Hard switched P-N Si</th>
<th>Soft-switched P-N Si</th>
<th>( *2^{nd}-\text{order switching losses not modeled} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kHz</td>
<td></td>
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</tr>
<tr>
<td>100 kHz</td>
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<td></td>
<td></td>
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<tr>
<td>1 MHz</td>
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</tbody>
</table>

95% 95.5 96% 96.5 97% 97.5 98% 98.5 99% 99.5 100%
Limitations: $t_d/T_S$

- Loss
- Loss

Limitations: 2nd Order Loss Mechanisms

- $L_s$ - Raising losses due to $\frac{1}{2}LI^2$
- $R_g$, $G_g$

References:
- Texas Instruments, "Optimizing MOSFET Characteristics by Adjusting Gate Drive Amplitude"
Limitations: Gate Drive

Limitations: Magnetics Design

- Core loss: \( P_{\text{core}} = K_{\text{fe}} \cdot (AB)^\alpha \cdot f_s \cdot V_c \)
- \( \Delta B = \int \frac{V_c}{N_c} \, dt \rightarrow \Delta B \downarrow \, f_s \uparrow \)
- Going to high freq: \( K_{\text{fe}}, \alpha, \beta = f(f_s) \)
- Additional mechanism: Proximity loss, Skin effect, fringing

Texas Instruments, "Selection of External Bootstrap Diode for LM510X Devices"
Limitations: Thermal

10kW rectifier 230Vac → 881Vdc

\[ P = \text{const} \quad \text{(big assumption!)} \]

\[ \frac{\text{power}}{\text{volume}} \]

Example VHF Resonant Boost

\( \Phi_o \) Boost Converter

75 MHz, 14W, 85% efficiency
Topics Covered

- **Course Topics**
  - High Frequency Power Conversion
    - Switching losses and device selection
    - Resonance in power electronics
    - Soft switching (ZVS and ZCS)
    - Magnetics design
  - Quasi-resonant soft switching converters
    - Constant frequency control
    - State-plane analysis
    - Resonant switches
    - Modeling and Simulation
    - Discrete time models
  - Resonant Converters
    - Resonant converter topologies
    - Sinusoidal analysis
    - AC-modeling and frequency modulation
    - State-plane analysis
  - Applications and practical issues of high frequency converters