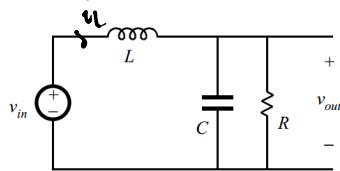


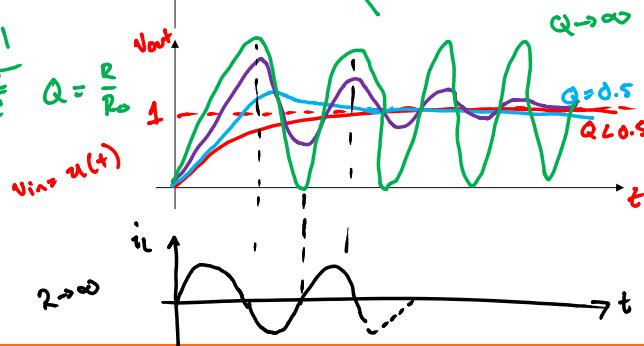
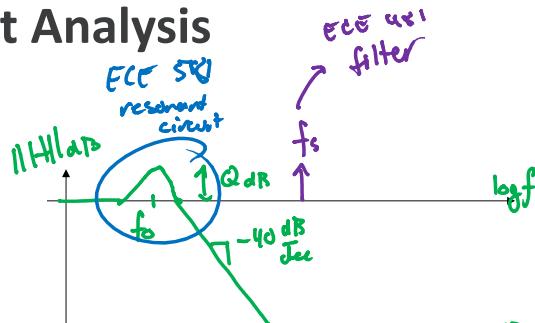
Resonant Circuit Analysis



$$H(s) = \frac{1}{s^2 L C + \frac{1}{s^2} + 1}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad R_0 = \sqrt{\frac{L}{C}}$$

$$Q = \frac{R}{R_0}$$



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Soft Switching

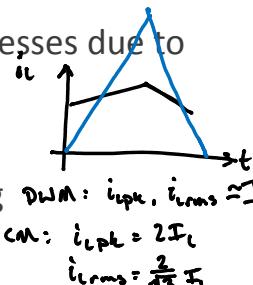
- Advantages

- Reduced switching loss
- Possible operation at higher switching frequency
- Lower EMI

Incorporating parasitics into operation

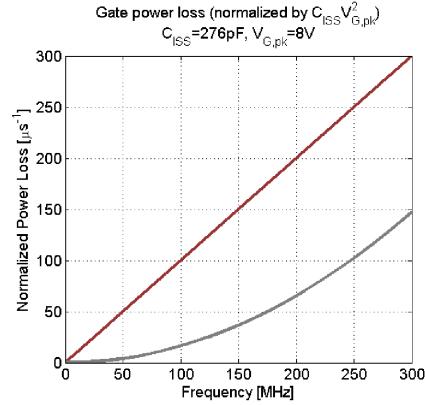
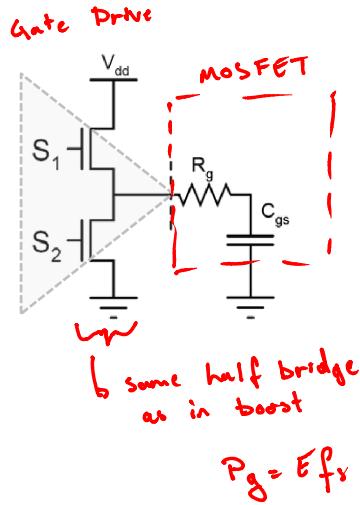
- Disadvantages

- Increased current and/or voltage stresses due to circulating current
- Higher peak and rms current values
- Complexity of analysis and modeling



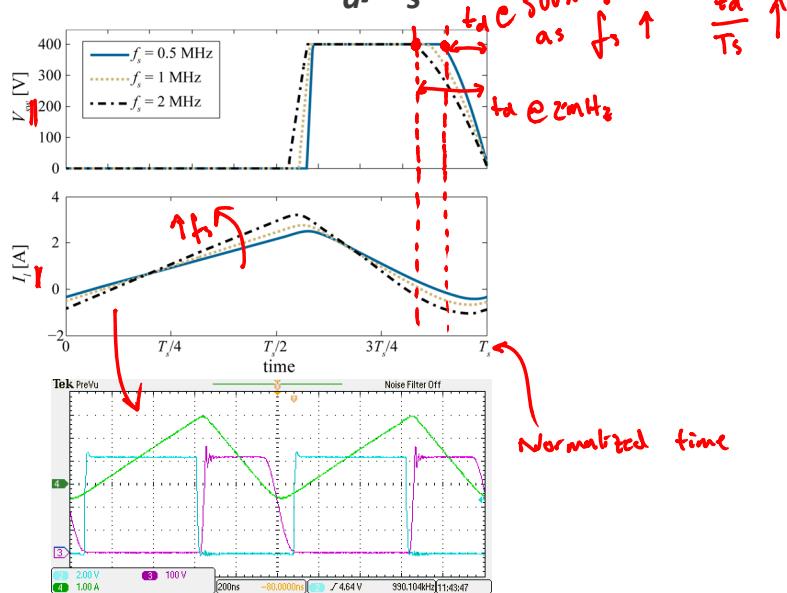
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Limitations: Gate Drive

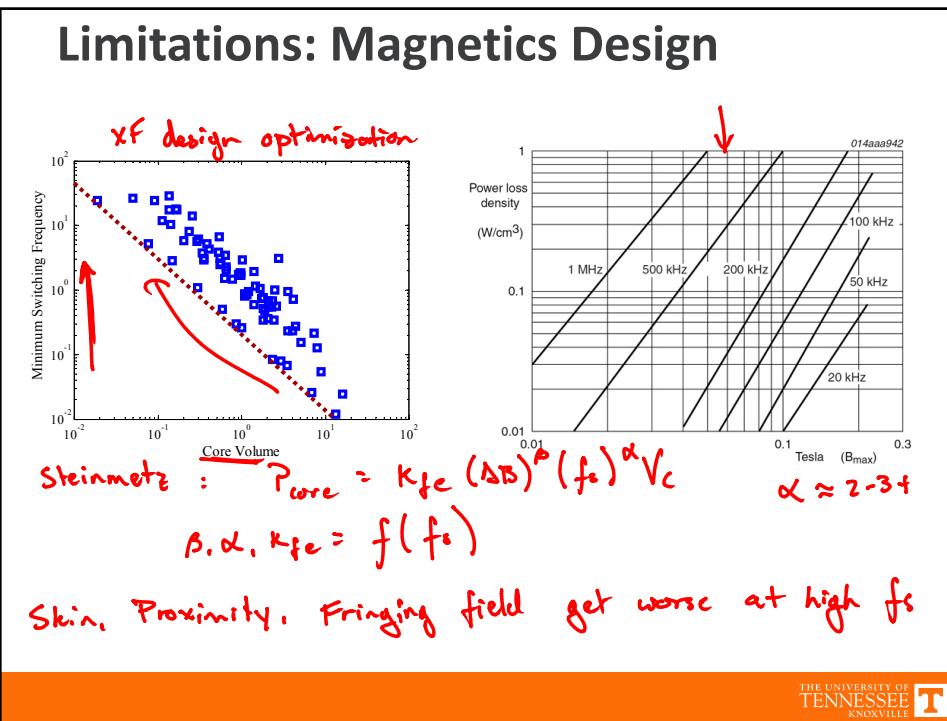
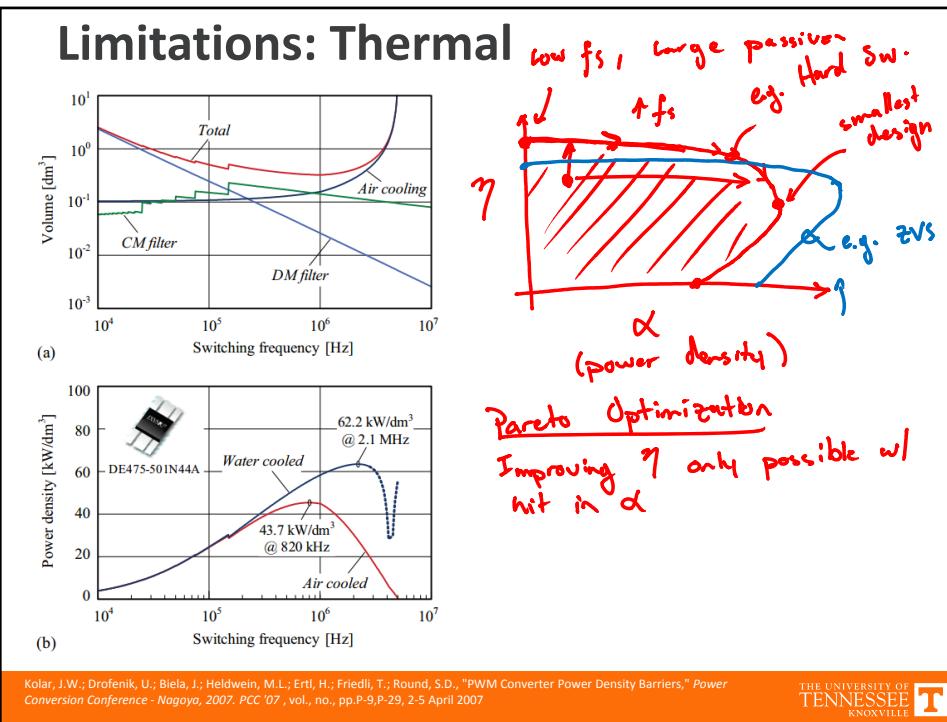


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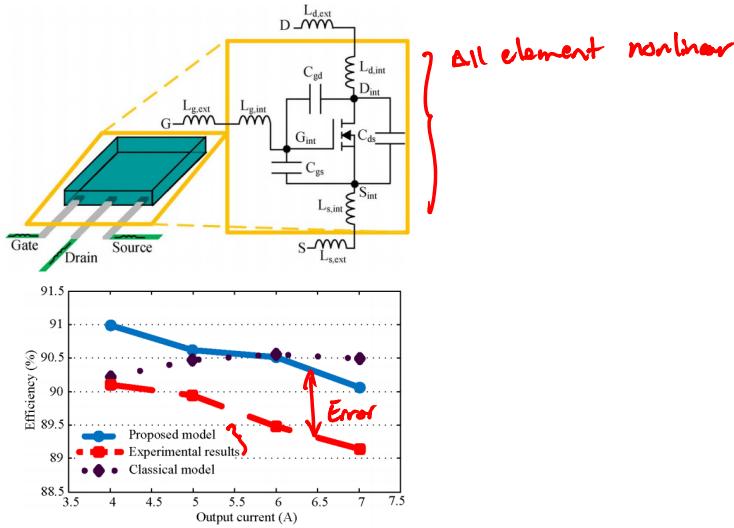
Limitations: t_d/T_s



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Limitations: Circuit Modeling



Rodríguez, M.; Rodríguez, A; Mijaya, P.F.; Lamar, D.G.; Zúñiga, J.S., "An Insight into the Switching Process of Power MOSFETs: An Improved Analytical Model," *Power Electronics, IEEE Transactions on*, vol.25, no.6, pp.1626-1640, June 2010

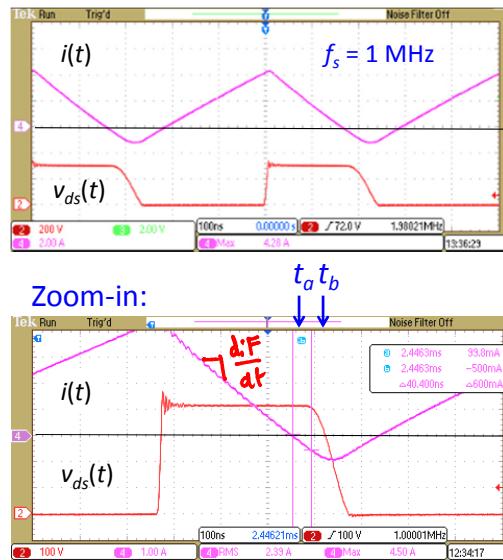


150-to-400V, 150W Boost
EXPERIMENTAL EXAMPLE

Diodes { Si P-N
SiC Schottky



ZVS with Si diode



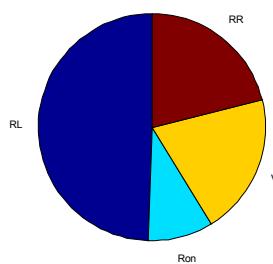
- **ZVS turn-ON**
 - Eliminated losses due to C_{sw} discharge during turn-ON transient
 - Eliminated losses due to MOSFET di_f/dt during turn-ON transient
- Diode reverse recovery still impacts the waveforms and losses
- **Increased current ripple**
 - Increased conduction losses (by >30%)
 - Increased 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"



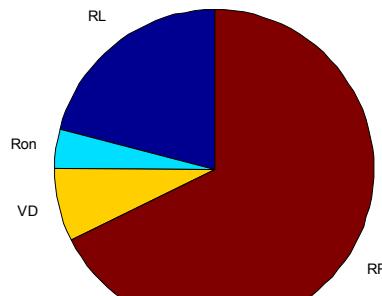
Loss Breakdown: Soft-Switched Si Boost

$$f_s = 100 \text{ kHz} \\ P_{loss} = 5.7 \text{ W}, \eta = 98.1\%$$



Reverse-recovery:
21% of the total loss

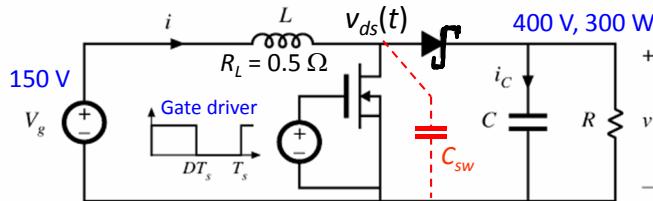
$$f_s = 1 \text{ MHz} \\ P_{loss} = 17.7 \text{ W}, \eta = 94.4 \% \\ \text{Experiment: } \eta = 95.1 \%$$



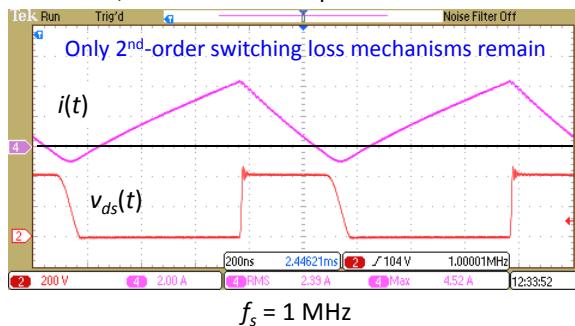
Reverse-recovery:
68% of the total loss



Soft-switched SiC diode



SiC diode, "soft-switched" operation



MOSFET

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

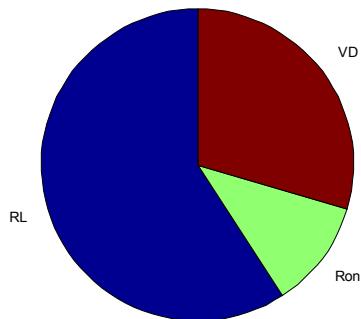
SiC diode

- $t_{rr} = 0, Q_{rr} = 0$
- $2C_{d,Qeq} - C_{d,eq} = 64 \text{ pF}$
- $V_D = 1.8 \text{ V}$

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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
 $P_{loss} = 4.5 \text{ W}$

Experiments:

98.7% at 1 MHz
98.0% at 2 MHz

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

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VHF power electronics [11]

| Component | Resonant Design Value | Type |
|------------|-----------------------|---------------------|
| L_F | 33 nH | Coilcraft 1812SMS |
| L_{2F} | 12.5 nH | Coilcraft A04TG |
| L_{rect} | 22 nH | 1812SMS |
| C_{2F} | 39 pF | ATC100A |
| C_{rect} | 10 pF | ATC100A |
| C_{out} | 75 μ F | Multilayer Ceramics |
| C_{in} | 22 μ F | Multilayer Ceramics |
| S_{main} | | Freescale MRF69090 |
| D | | Fairchild S310 |

| Component | Conventional Design Value | Type |
|-------------|---------------------------|-------------------------|
| L_{boost} | 10 μ H | Coilcraft D03316T-103ML |
| C_{out} | 75 μ F | Multilayer Ceramics |
| C_{in} | 22 μ F | Multilayer Ceramics |
| S_{main} | | LT1371HV |
| D | | Fairchild S310 |

Converter Efficiencies vs. Output Power

[11] D.J. Perreault, et.al. "Opportunities and challenges in very high frequency power conversion," IEEE APEC 2009.

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WBG Devices

Standard hard-switched PWM operation at 50 MHz
 dv_{ds}/dt dominated by probe (4 pF) capacitance

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

FOM for switching applications
 $C_{ds}R_{on} \approx 1 \Omega\text{pF}$
 $C_gR_{on} \approx 10 \Omega\text{pC}$

750 ps

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,"

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Topics Covered

- Course Topics

- High Frequency Power Conversion
 - Switching losses and device selection
 - Resonance in power electronics
 - Soft switching (ZVS and ZCS)
 - Magnetics design
- Non-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

