Massachusetts Institute of Technology

Laboratory for Electromagnetic and Electronic Systems

Architectures, Topologies, and Design Methods for Miniaturized VHF Power Converters

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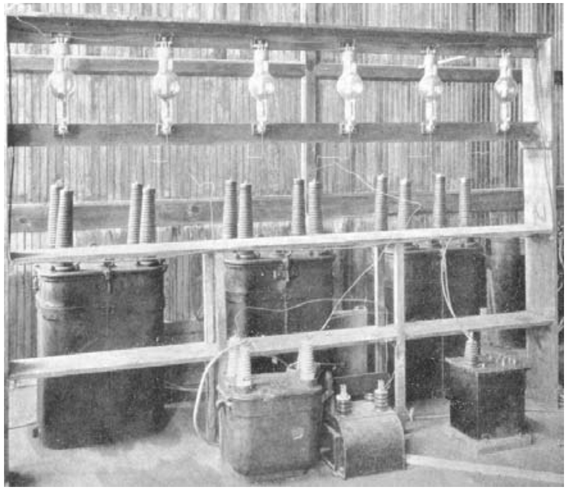
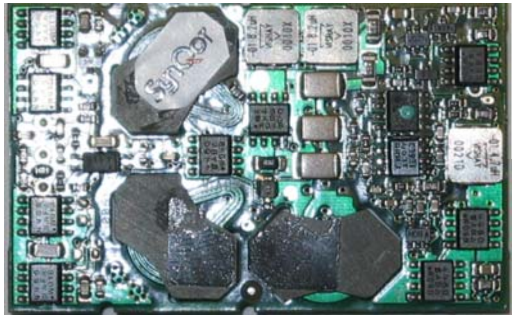
PwrSOC `08

Cork, Ireland Sept. 2008



20 kW Kenotron Rectifier, Circa 1926
(From Principles of Rectifier Circuits,
Prince and Vogdes, McGraw Hill 1927)



Server Power Supply, Circa 2006
(Manufactured by Synqor)

??

Circa 2016

Motivation

- Passive energy storage components are the key to
  - Miniaturization
  - Integration
  - Performance (bandwidth, …)

- Energy storage requirements vary inversely with switching frequency: C, L proportional to f^{-1}

- *But how does volume scale? (look at simple case only)*
  - Consider only ac conductor loss (e.g., as in a coreless design)
  - Keep passive component *impedances* constant vs. f

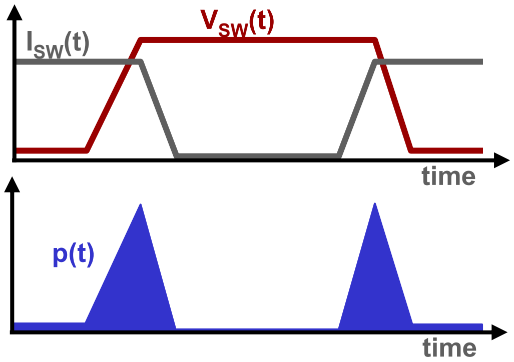
- At constant η (constant Q): Volume proportional to $f^{-3/2}$
- At constant heat flux: Volume proportional to $f^{-1/2}$

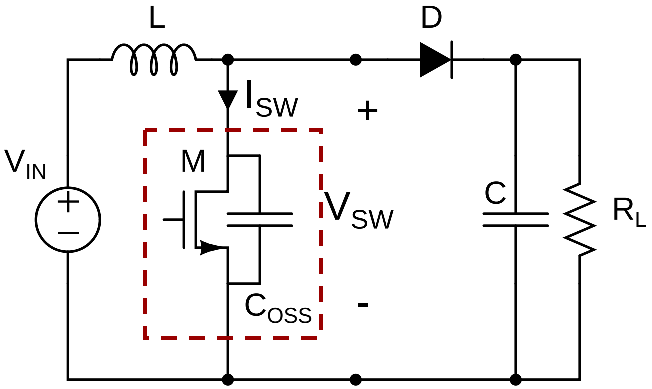
  with Q improving as $f^{1/3}$

Switching Frequency Limitations

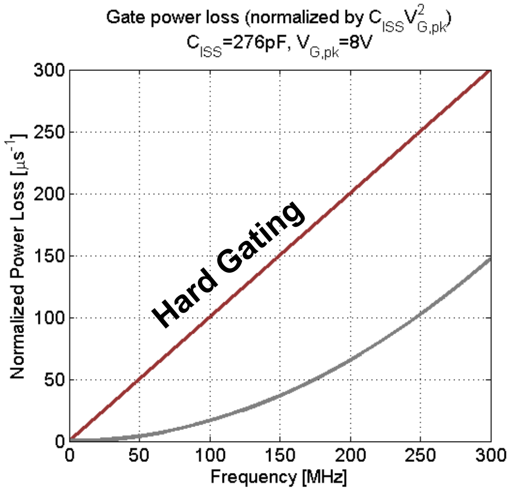
- **Loss mechanisms in conventional power electronics limit switching frequency**

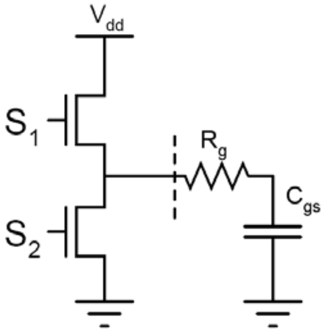
Switching loss (∝ *f*)



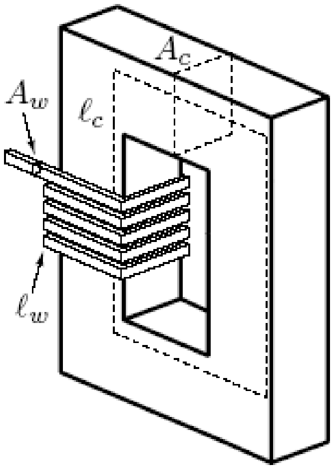


Gating loss (∝ *f*)





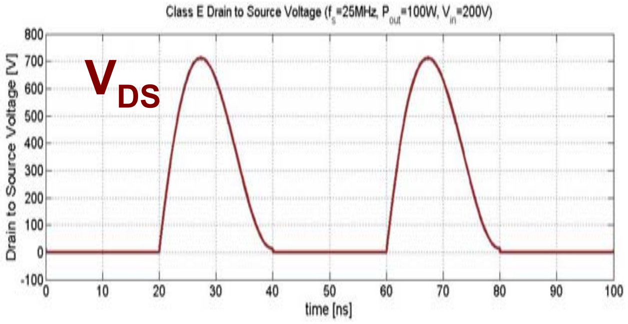
Core loss in magnetic materials (∝ *f* ^{k})

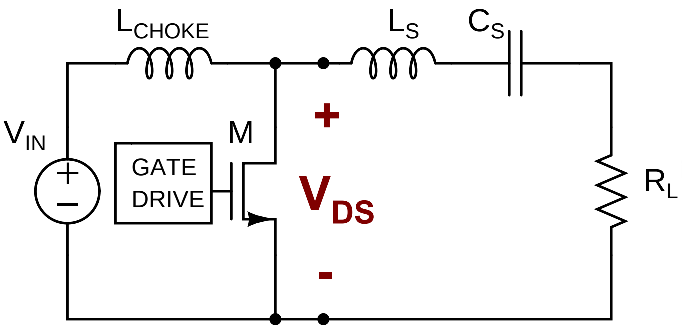


Switching Frequency Solutions

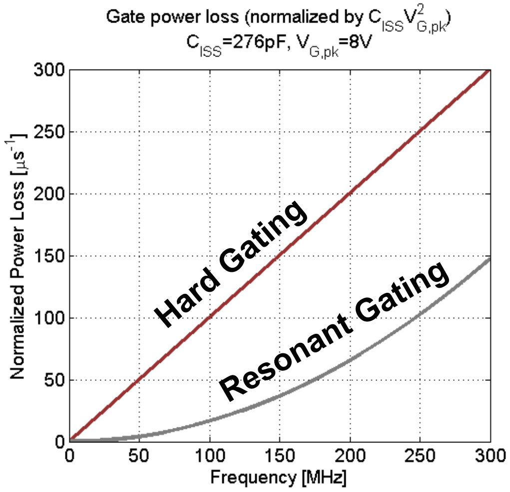
- **Minimize frequency dependent device loss, switch fast enough to eliminate or change magnetic materials**

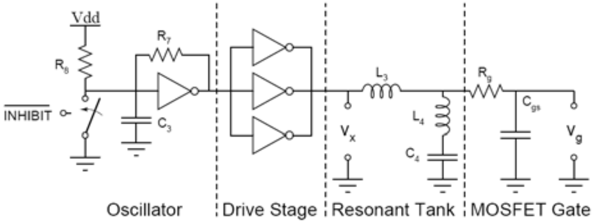
ZVS Soft Switching





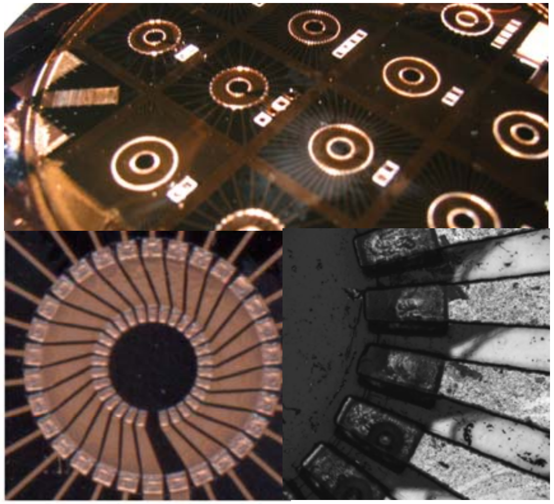
Resonant Gating

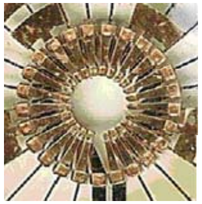




(From J.R. Warren, M.Eng. Thesis, MIT, Sept. 2005)

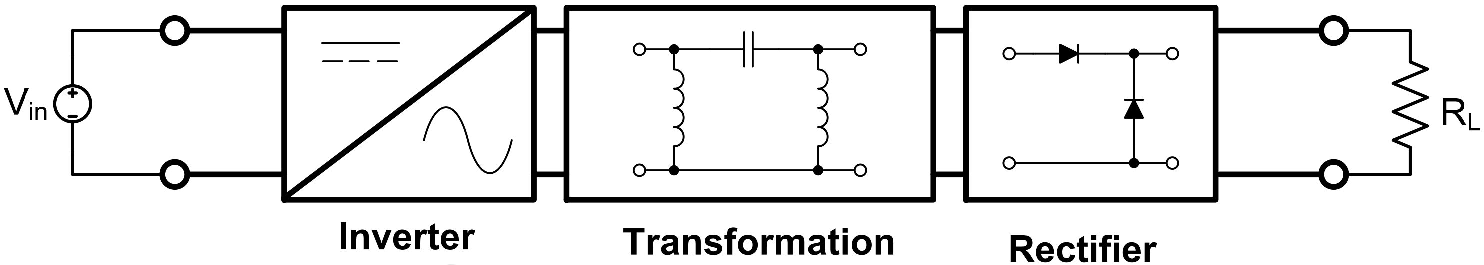
Coreless Magnetics or low-permeability RF materials

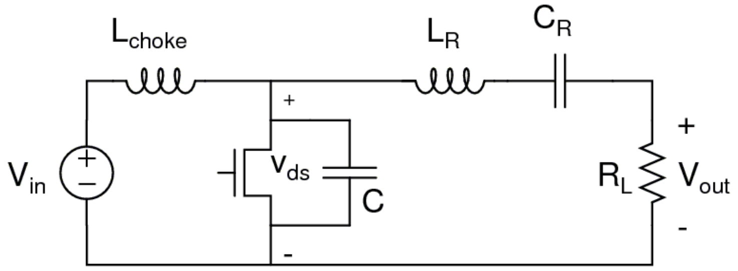


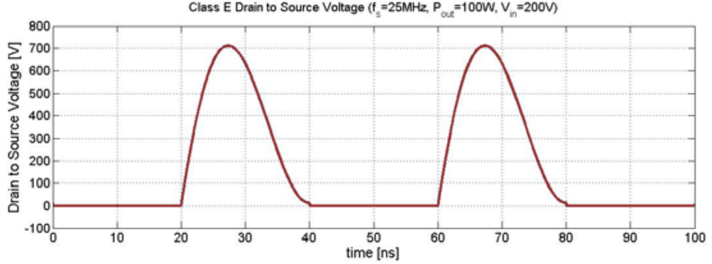


Microfabricated Coreless Inductors
Joshua Phinney, MIT, 2004

Topology Implications







- **As frequency increases**
  - ☐ **Driving high-side switches becomes impractical**
  - ☐ **Controlling commutation among devices becomes challenging**
  - ☐ **Topology *must* absorb parasitics**
    - **device capacitances, interconnect inductance, …**

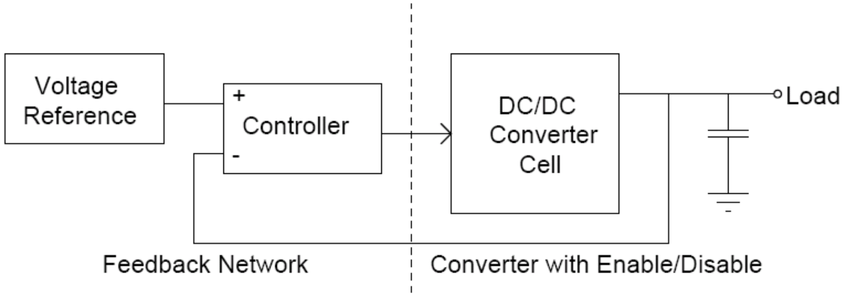
- **ZVS switching / resonant gating constrain control**
  - ☐ **Duty ratio and frequency control limited**
  - ☐ **Only efficient over a narrow load range**

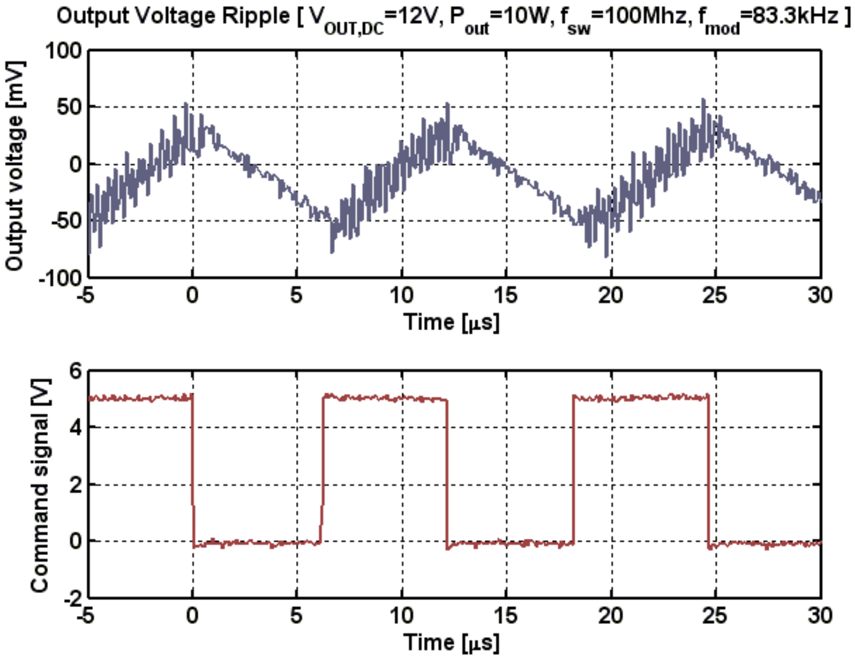
System Architecture and Control

- Develop system architectures and control strategies that are compatible with VHF conversion
  - ☐ Fixed/narrow duty ratio, frequency range
  - ☐ Maintain efficient operation across wide load range
- Achieved through partitioning of energy conversion and control functions

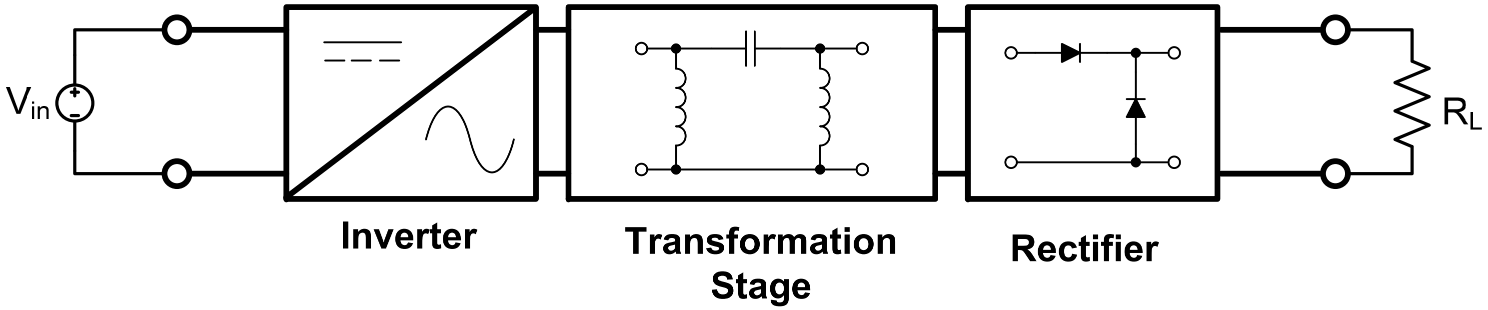
Cell Modulation / On-Off / Burst-Mode Control

- Converter cell “bursts” on and off to regulate output
  - Efficient across wide load range (no loss when cell is off)
  - Cells can operate at narrow load / operating range
    - Fixed frequency and duty ratio
    - Resonant gating, switching at VHF
- Power stage components sized for VHF switching frequency (small passives)
- Input and output filters work at lower modulation frequencies
  - Up to a few % of switching freq.
  - But sizing based only on ripple, not transient requirements





Desired Cell Topology Characteristics



- Efficient with ZVS switching, resonant gating at VHF
  - Switch control ports referenced to fixed potentials
  - Absorbs device and interconnect parasitics

- Compatible with On/Off control at fixed freq., duty ratio
  - Avoid bulk magnetic storage in power stage

- Operates well over wide input, output voltage ranges
  - Resonant inverter, rectifier characteristics often vary with voltage
  - Design must accommodate this

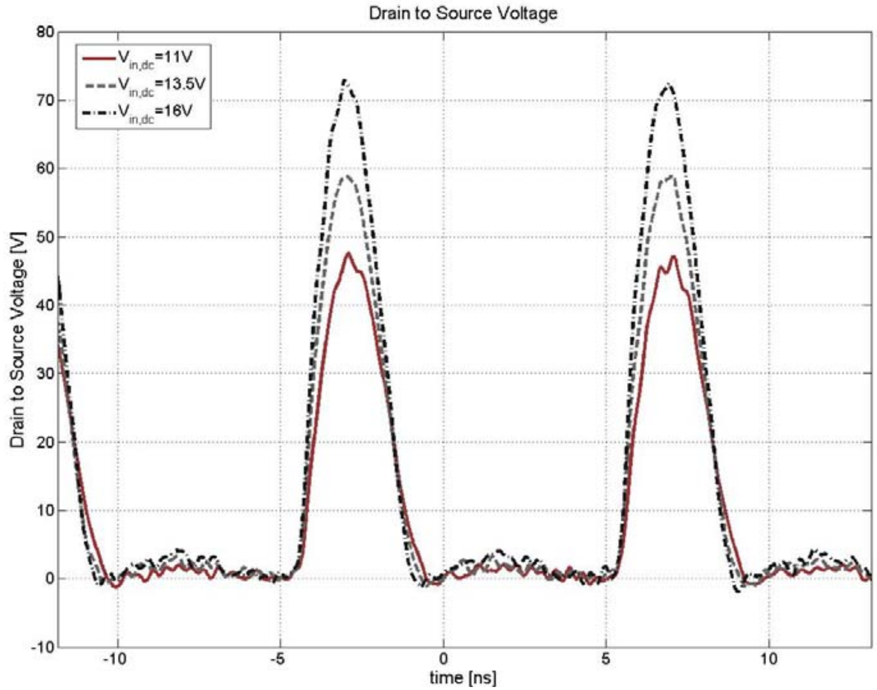
Limitations of Traditional Class E Inverter

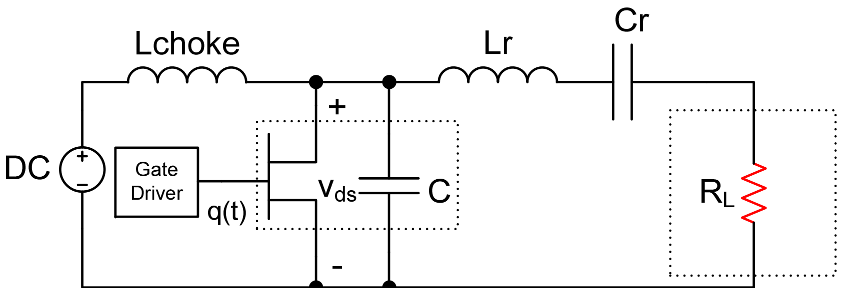
- High device stresses
  - $V_{ds,pk} \approx 3.6 \cdot V_{IN}$ for Class-E
- Tight link between output power, device capacitance, loss, and frequency

$$P_{out} \propto C_{oss} \cdot f \cdot V_{DC}^2$$

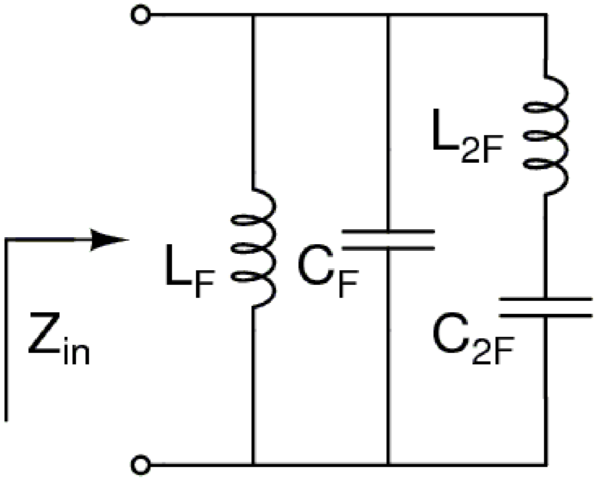
$$\%P_{cond} \propto R_{ds-on} \cdot C_{oss} \cdot f$$

- A maximum frequency thus exists for a specified efficiency
  - $R_{ds-on} \cdot C_{oss}$ is an important device metric
- Uses a large "choke" inductor
  - Reduces performance under on/off control
- Inverter performance sensitive to load resistance





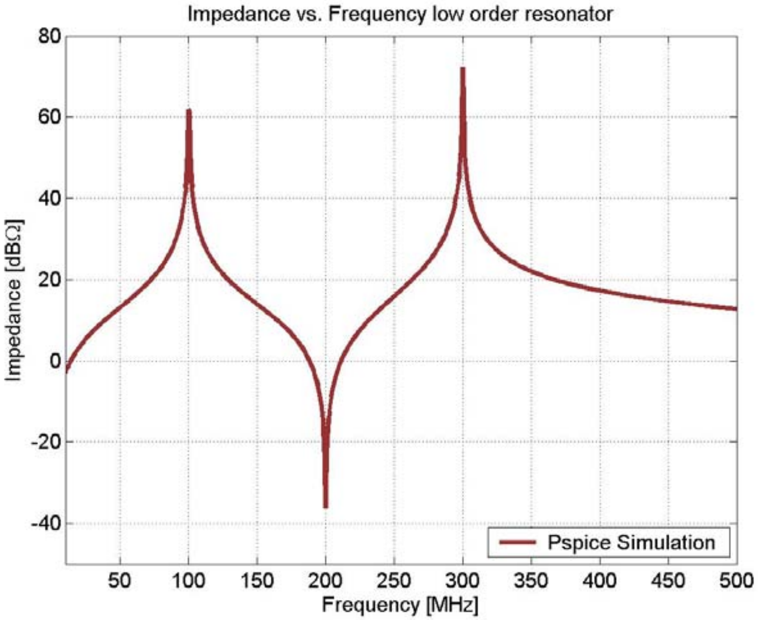
Impedance-Based Waveform Shaping



$$L_f = \frac{1}{9(\pi \cdot f_s)^2 C_f}$$

$$C_{2f} = \frac{15}{16} C_f$$

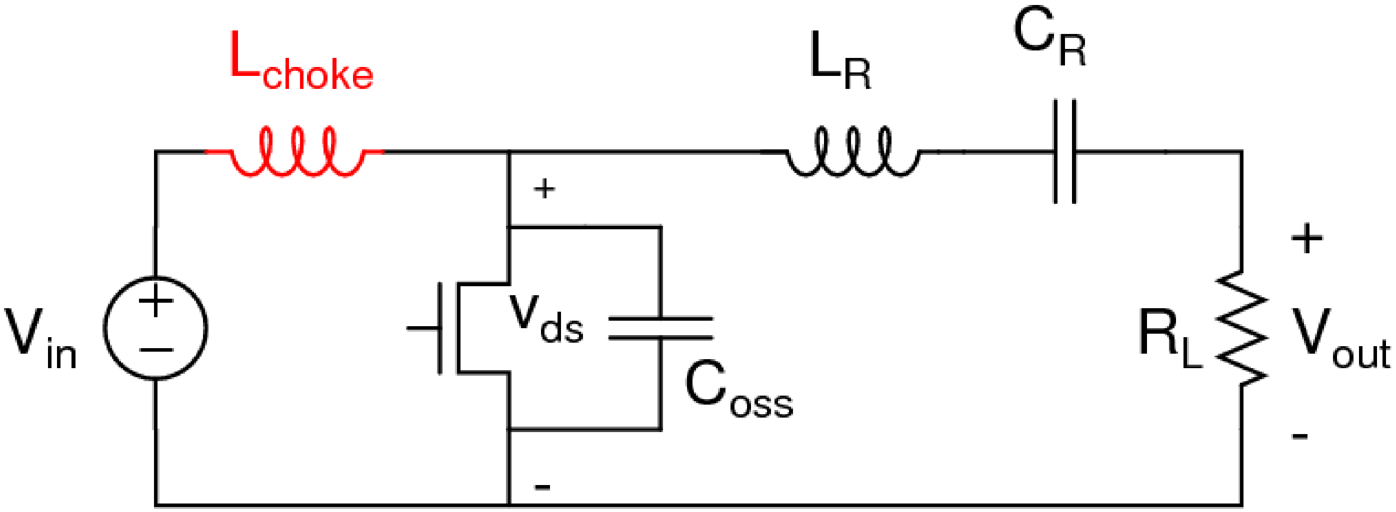
$$L_{2f} = \frac{1}{15(\pi \cdot f_s)^2 C_f}$$



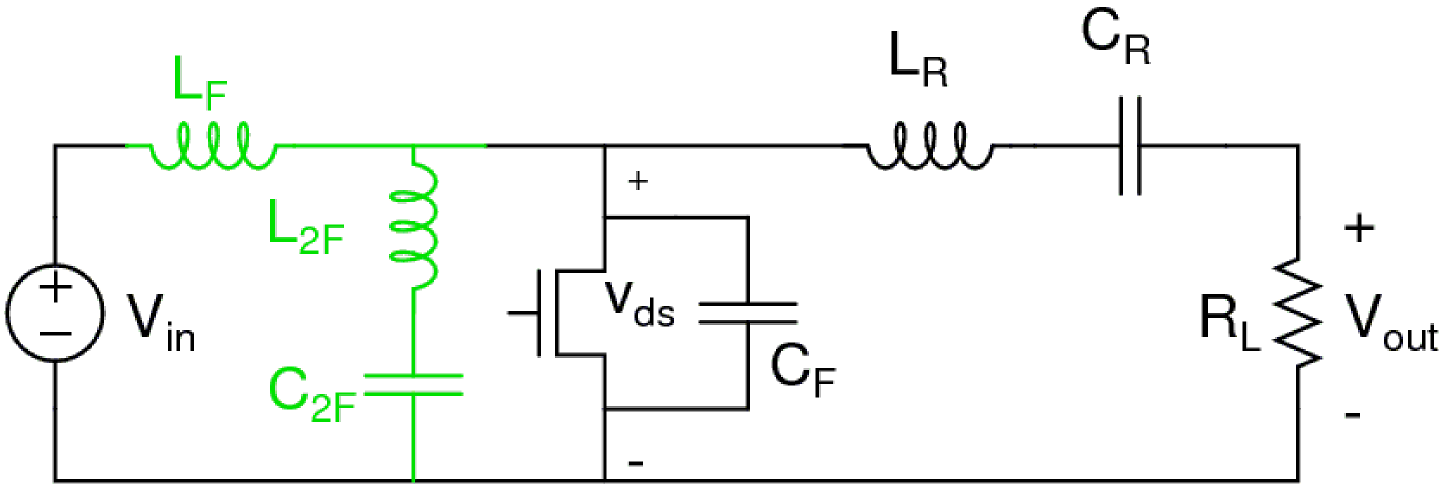
- By controlling the impedance seen at the transistor output, we can shape the voltage waveform
- A simple network can null the second harmonic and present a high impedance at the fundamental and the third harmonic
  - Impose odd-harmonic symmetry in voltage waveform
- This network can be used in an inverter to “shape” the switch voltage to approximate a trapezoidal wave

Class E --> Φ2 Inverter

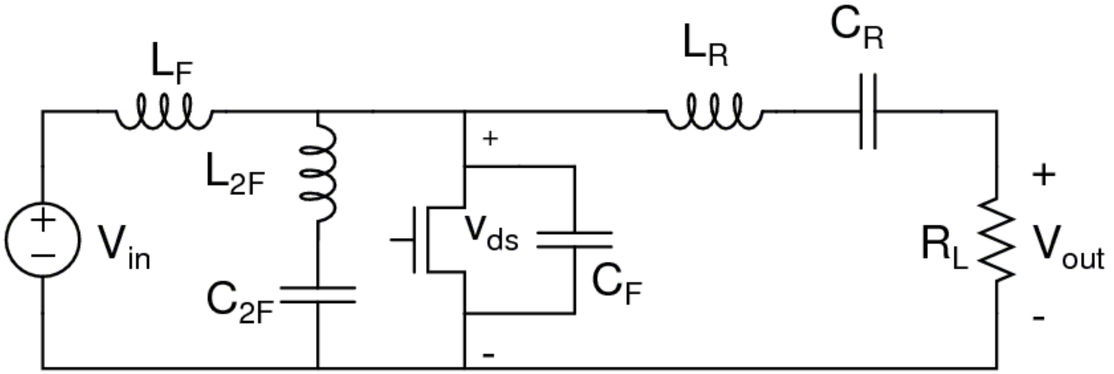
- **Class E Inverter**

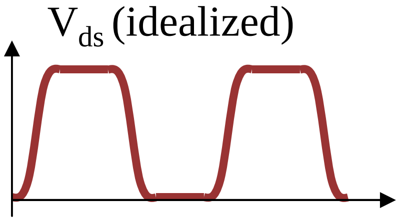


- **Φ2 Inverter**



Φ2 Inverter

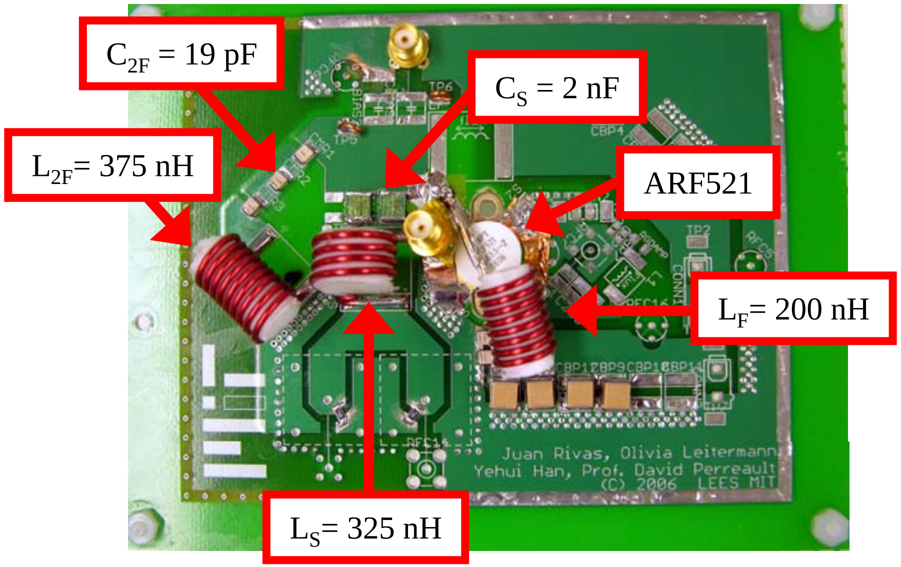


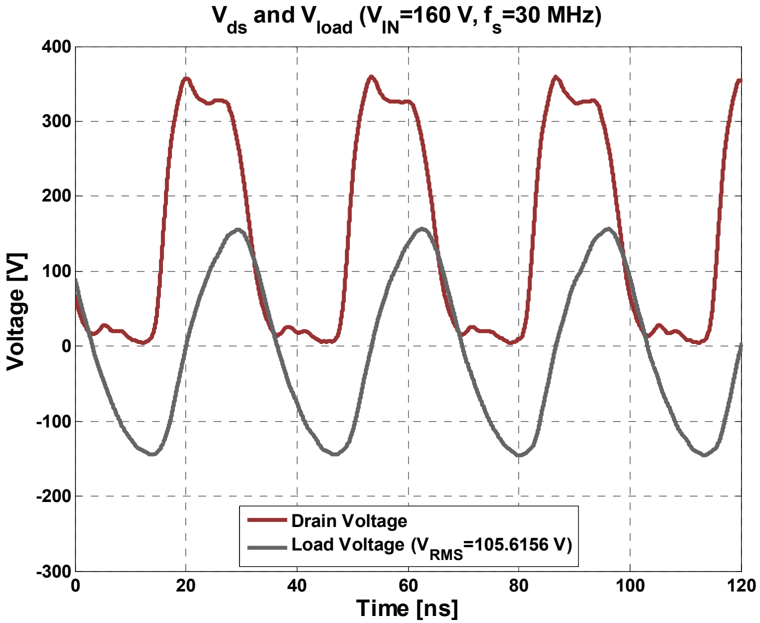


- Replace dc choke with simple multi-resonant network
  - ☐ Network nulls the second harmonic and presents high impedance near the fundamental and the third harmonic
  - ☐ Shapes drain-source voltage to reduce peak voltage (25-40%)
  - ☐ Reduces sensitivity of ZVS switching to load resistance
- Eliminates bulk inductance
  - Small inductor size
  - Fast transient performance
- C_F is selected as part of the multi-resonant network design
  - Eliminates the tie between device capacitance and power that exists in the class E inverter

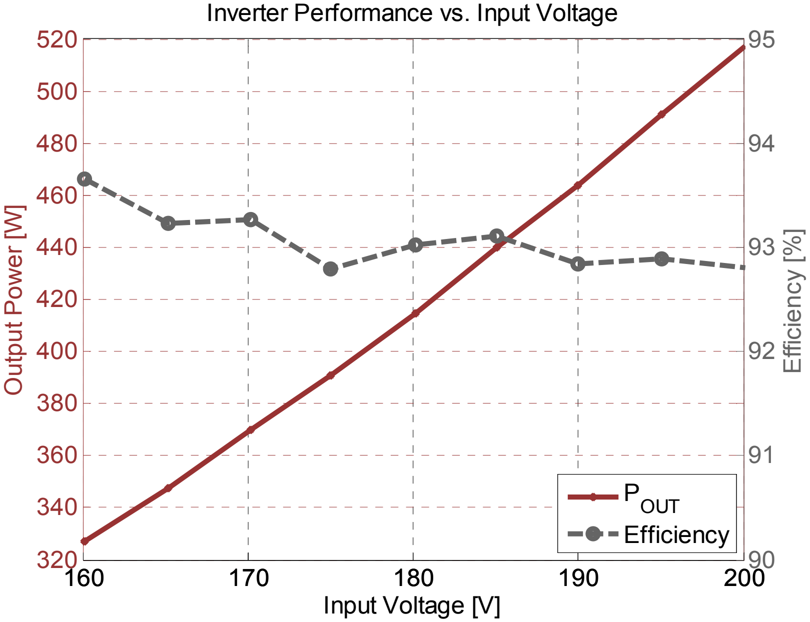
Rivas, et. al., "A High-Frequency Resonant Inverter Topology with Low Voltage Stress," PESC 2007

Example Φ2 Inverter Design

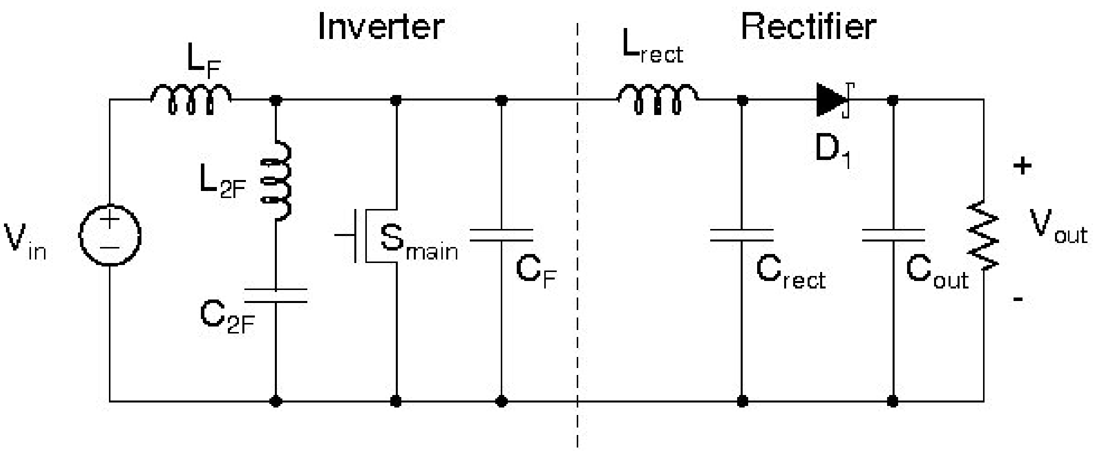


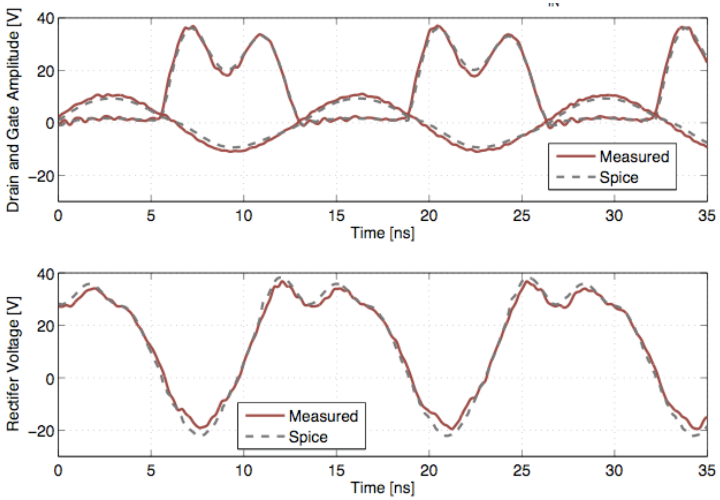


- 30 MHz class Φ2 inverter
  - ☐ V_{in} = 160 – 200 V
  - ☐ P_{out} > 320 W @ η_D~ 93%
- Breaks class E frequency limit
- Low device stress
  - ☐ $V_{ds,pk} < 2.3\ V_{in}$
- Small passive components
  - ☐ Fast transient response



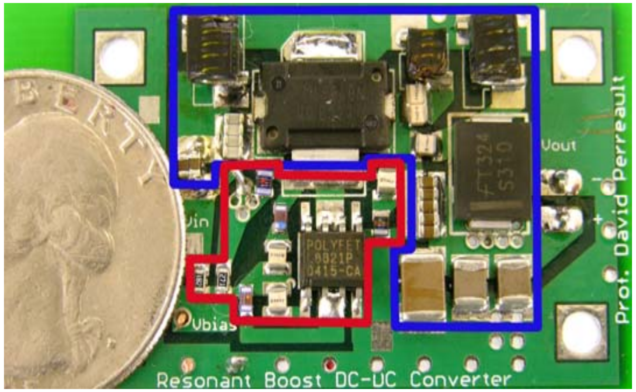
Resonant Φ_2 Boost Converter





- Replace inverter load network with resonant rectifier
  - ❑ Rectifier tuned to replace load network at fundamental
- Low peak stress, ground-reference switch
- Fully resonant with small component size
- Ideally suited for constant frequency/duty ratio operation
- Low energy storage - good candidate for on/off modulation control

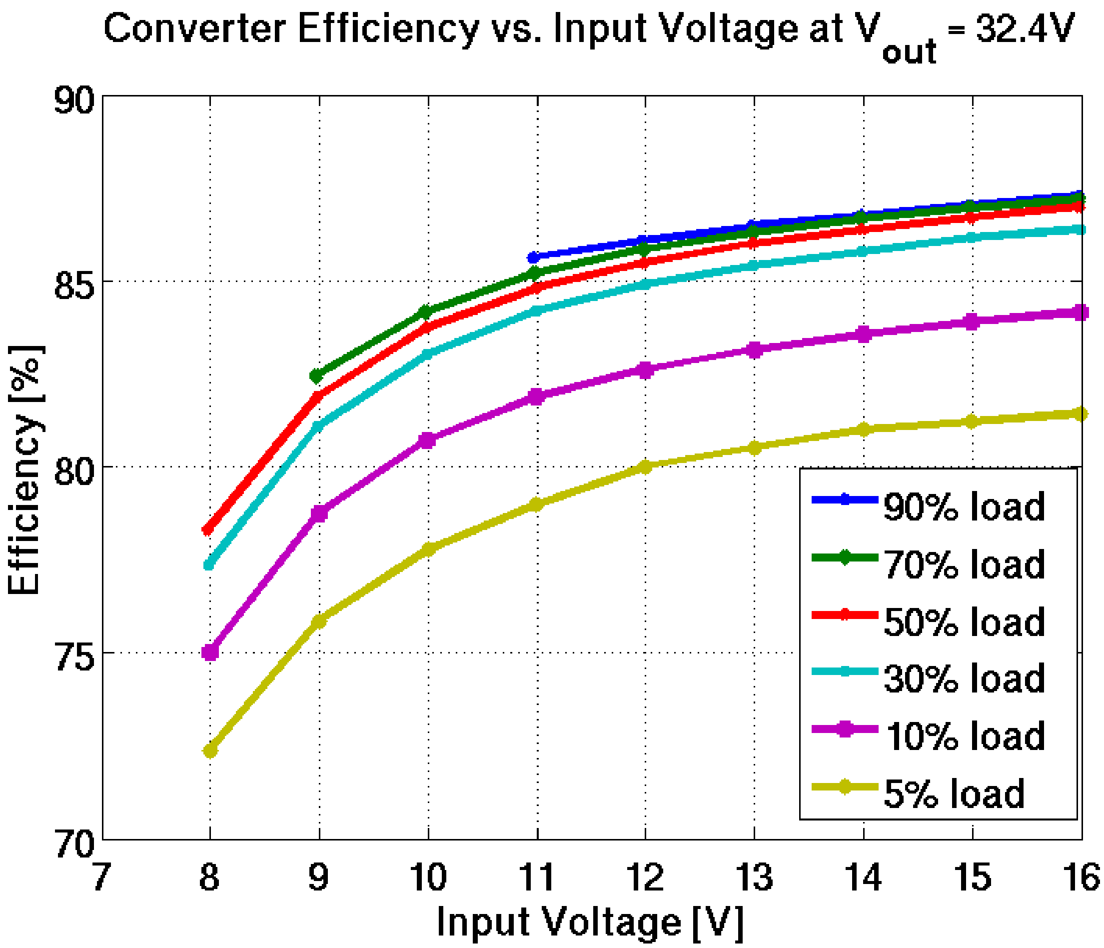
Φ_2 Boost – Discrete Implementation



- **Φ_2 Boost converter based on a commercial LDMOSFET**
  - **Switching Frequency: 110 MHz**
  - **Input voltage range: 8V – 18V**
  - **Output voltage range: 22 – 34V**
  - **Output power 23 W nominal**
  - **87% efficiency**
  - **Small inductors, potential for integration or self-shielding design**

Power Stage Component	Value
L_f	33 nH
L_{rec}	22 nH
L_{2f}	12.5 nH
C_{2f}	35 pF
C_{rec}	10 pF
LDMOS SWITCH	FREESCALE MRF6S9060
SCHOTTKY DIODE	FAIRCHILD S310

Closed Loop Efficiency Map

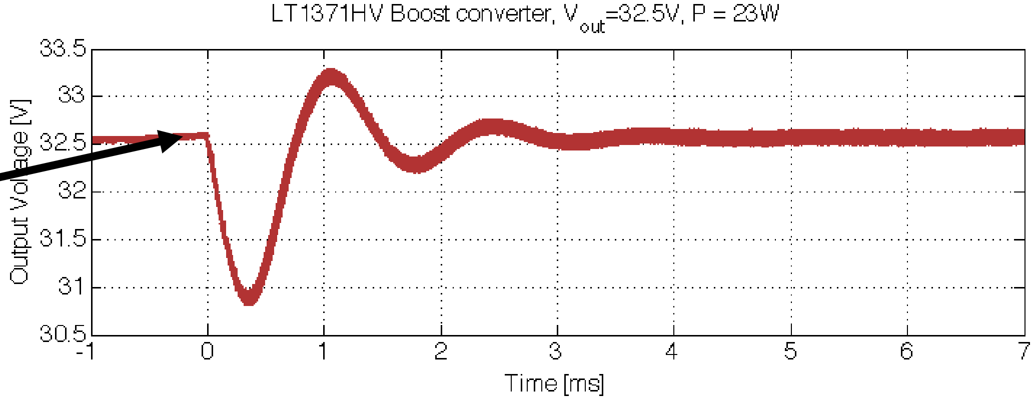


- Efficiency ranges from 82% to 87%+ over 5% to 90% load
- 2:1 input voltage range, 1.5:1 output voltage range
- Topology and control contribute to achievable range

Transient Response, 10% to 90% Load

Hard-switched Boost

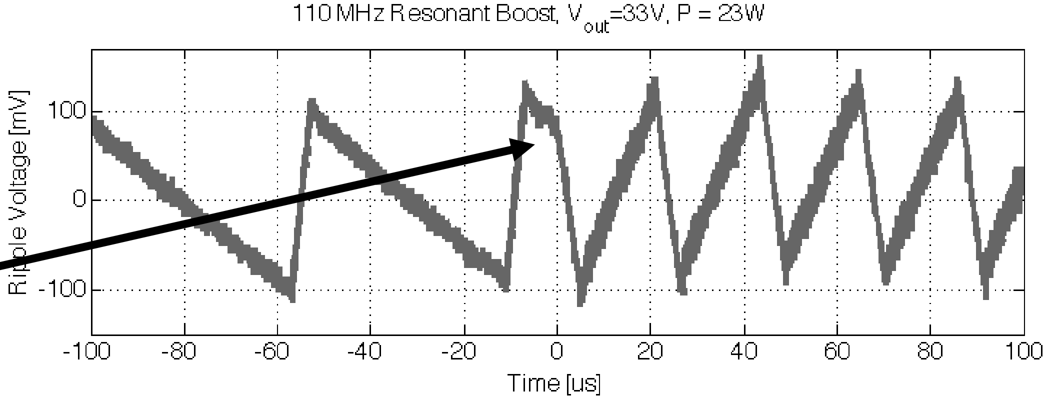
2.4V, 3ms transient



LT1371HV Boost converter, V_{out}=32.5V, P = 23W

Resonant VHF Boost

200 mV, 1us transient



110 MHz Resonant Boost, V_{out}=33V, P = 23W

- **VHF converter transient response excels when compared to equivalent hard-switched boost converter**

Summary

- Higher frequency offers the potential for Minaturization, Integration, Bandwidth
  - Switching, gating, and magnetic losses limit the practical operating frequency of conventional designs
- Appropriate system design methods enable operation at VHF frequencies
  - Resonant gating and switching
  - Architecture and control
    - Separate energy conversion, regulation
  - Improved topologies
  - *Improved devices and passive designs also have a big impact*
- Feasibility of this approach has been demonstrated
  - Example converters at 30-110 MHz at 10’s-100’s of watts, volts
- Work in this area is ongoing

Acknowledgments

Students

Anthony Sagneri, Yehui Han, Robert Pilawa, Jackie Hu, Olivia Leitermann, David Jackson, James Warren, Riad Wahby, Juan Rivas, Joshua Phinney,…

Sponsors

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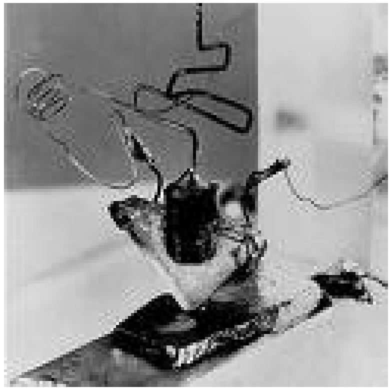
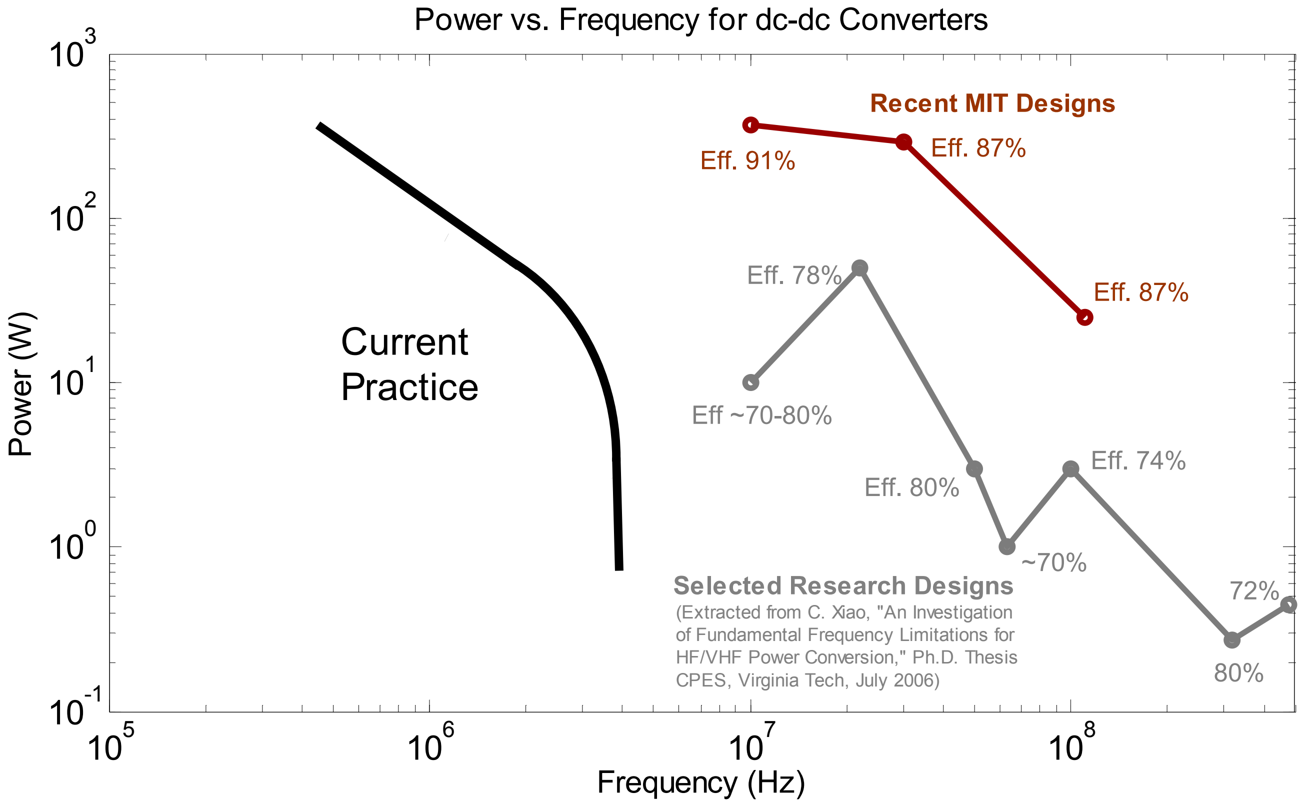


Research Design Comparison

Power vs. Frequency for dc-dc Converters



(Extracted from C. Xiao, "An Investigation of Fundamental Frequency Limitations for HF/VHF Power Conversion," Ph.D. Thesis CPES, Virginia Tech, July 2006)

- **This general approach appears promising**
  - **Increasingly viable across a range of power levels and applications**