In Search of Powerful Circuits: Developments in Very High Frequency Power Conversion

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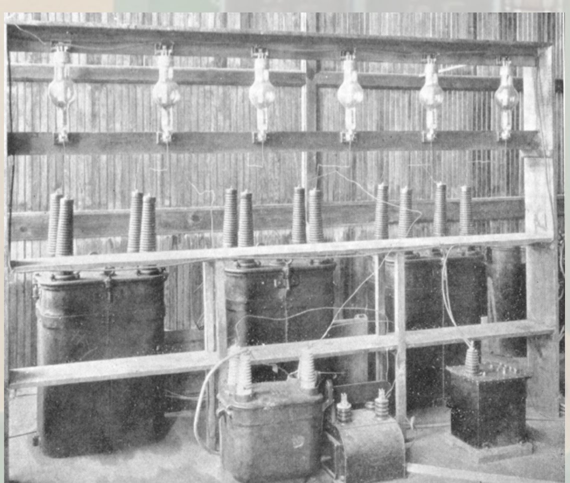
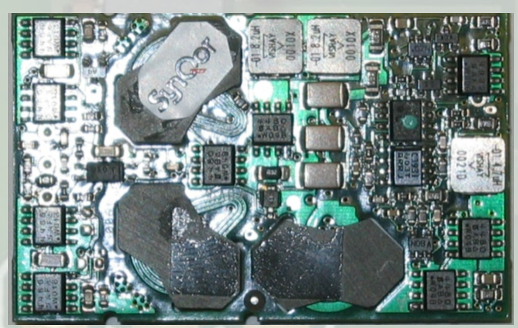
Princeton
April 28, 2014



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



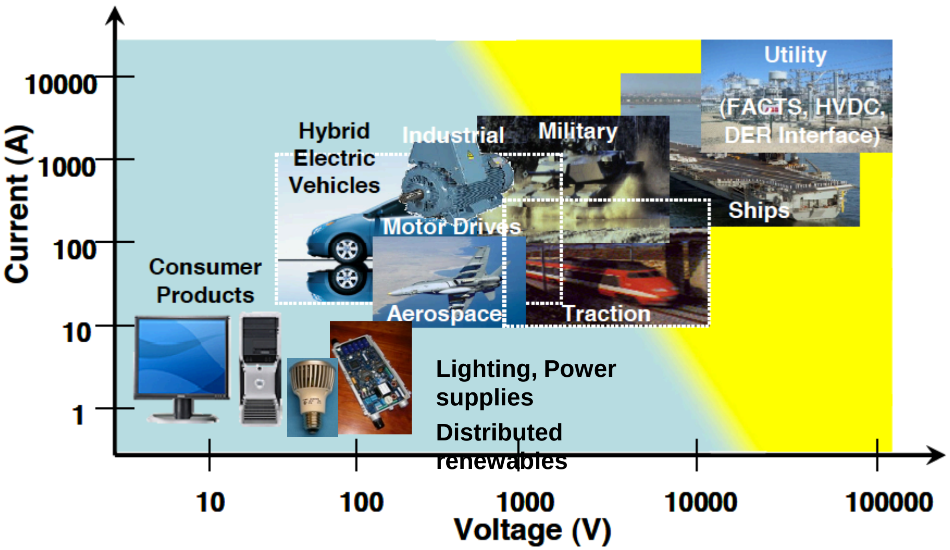
Server Power Supply, Circa 2006
(Manufactured by Synqor)

??

Circa 2016

Power Electronics

- The function of power electronic circuits is the processing and control of electrical energy
  - Modern electrical and electronic devices require power electronics
  - Lighting, computation and communication, electromechanical systems (e.g., motors), renewable generation,…
  - In 2005 ~ 30% of generated energy goes through power electronics; this is expected to be ~ 80% by 2030 (ORNL 2005)
- Power electronic circuitry is often a major factor determining system size, functionality, performance and efficiency



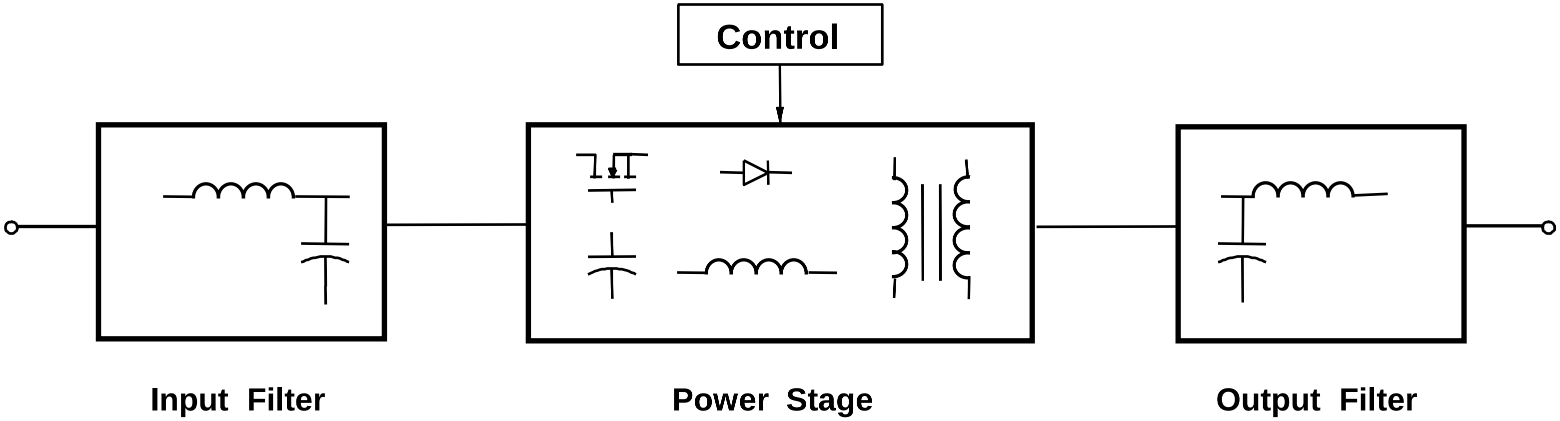
LED lightbulb and driver

Inverter for Prius HEV

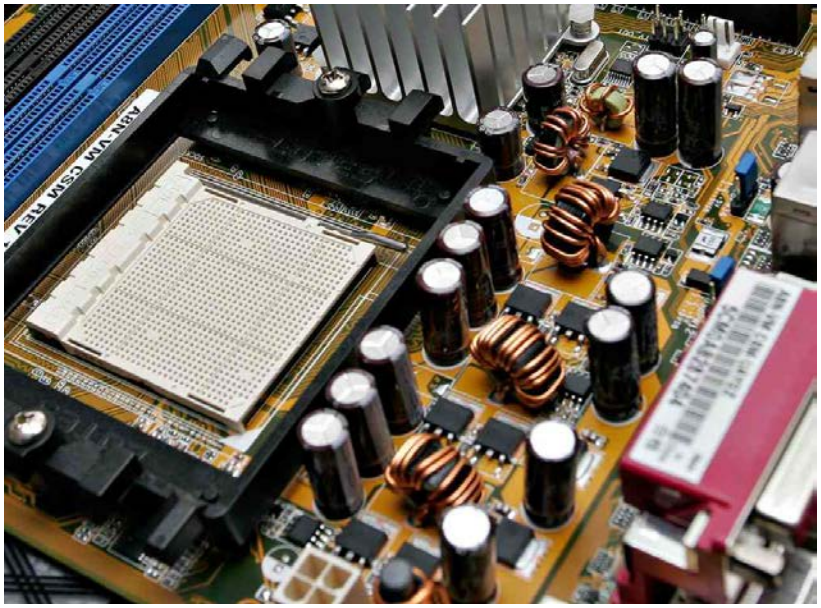
Microinverter for photovoltaic systems

(Modified from Tolbert et al, "Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications," ORNL 2005)

Structure of Power Electronic Systems



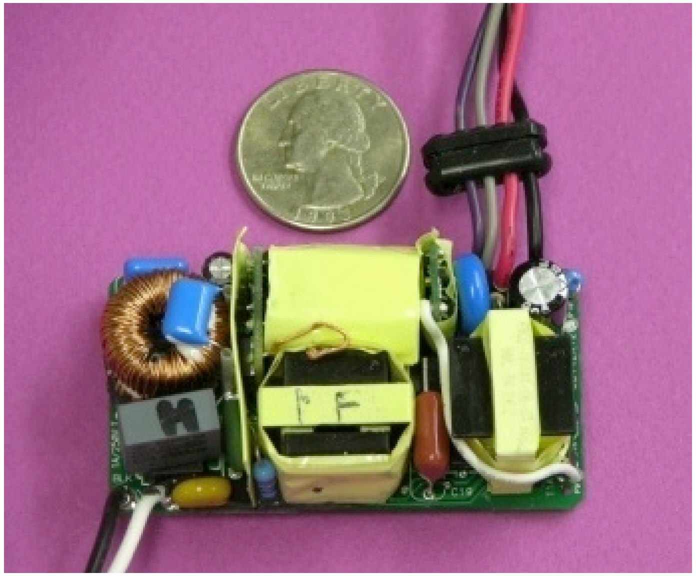
- **Power processing with (ideally) lossless components**
  - **Switches, inductors, capacitors, transformers,…**
- **Ancillary elements**
  - **Control, heat sinking, filtering…**
- **System operates cyclically**
  - **Draw some energy (switches)**
  - **Store in energy storage (L’s, C’s)**
  - **Transform**
  - **Transfer to output**
- **Often specified to operate over wide voltage, current and power ranges**



Passive Components Dominate

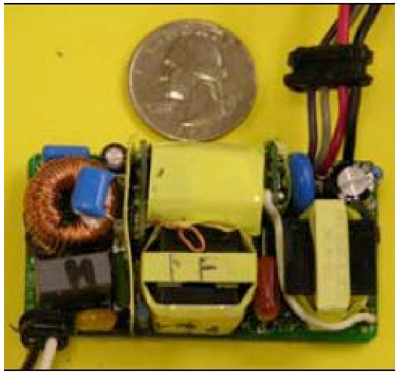
- **Passive components dominate the size of power electronics**
  - **Also limit cost, reliability, bandwidth,…**

A Voltage Regulator Module for a computer



A 25 W Line Connected LED Driver

Motivations for Frequency Increases



Commercial LED Driver
100 kHz
21 W
85% eff
4.8 W/in^3

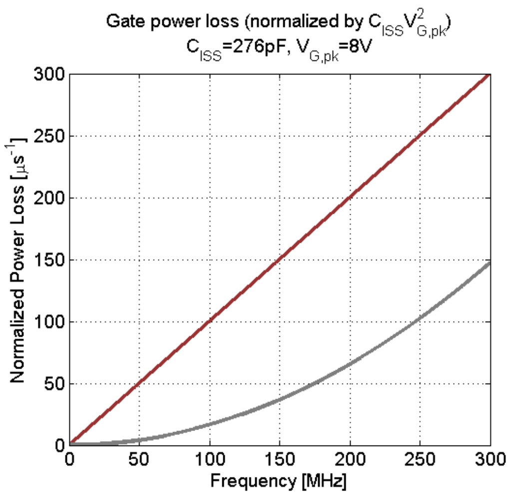
- **Goals**
  - **Miniaturization**
  - **Integration**
  - **Increased performance (bandwidth…)**
- **Passive energy storage components (especially magnetics) are the dominant constraint**
- ***Energy storage* requirements vary inversely with frequency: C,L proportional to f^{-1}**
- **Volume can be scaled down with frequency**
  - **But, often scales down *slowly* with frequency**
  - **Magnetic core materials especially impact frequency scaling**
- **Integration / batch fabrication of passives imposes further challenges**

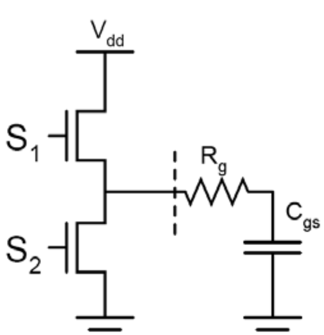
Perreault, et. al., "Opportunities and Challenges in Very High Frequency Power Conversion," APEC 2009

Switching Frequency Limitations

- **Loss mechanisms in power electronics limit switching frequencies**
  - **Relative importance of different losses depends on power, voltage**

Gating loss ($\propto f$)





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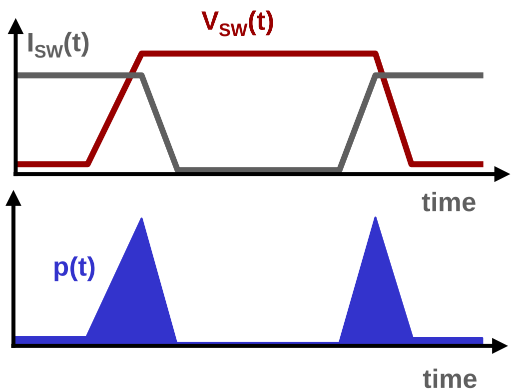
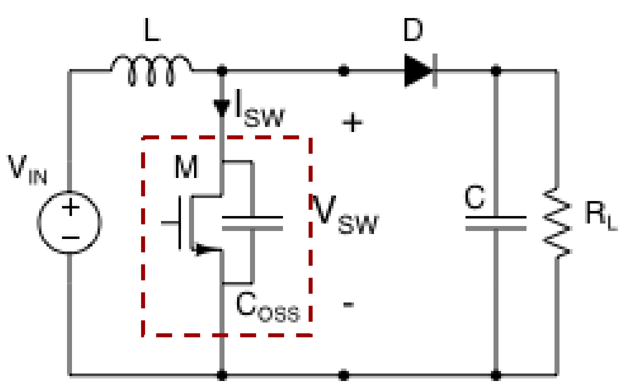
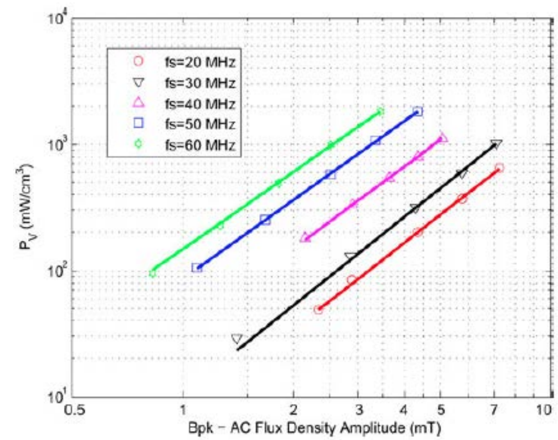
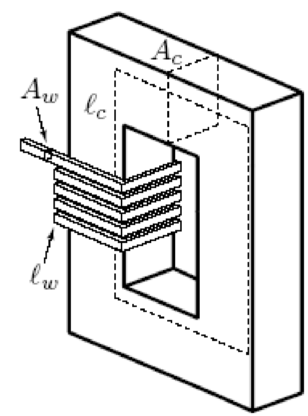




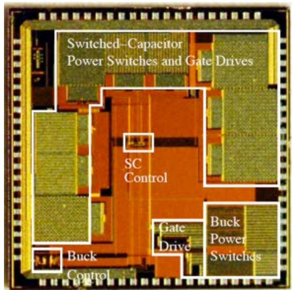
Magnetics loss ($\propto f^k$)

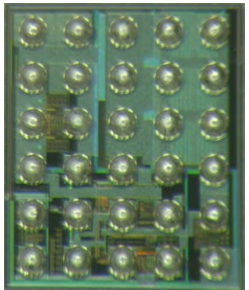




Design Requirements and Device Capabilities

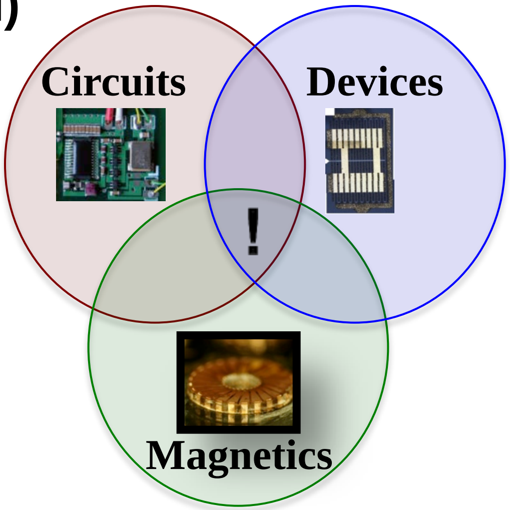
- **Application requirements also impose limits on miniaturization, integration and performance**
  - **e.g., line-frequency energy buffering requirement for single-phase grid interface imposes significant size constraints**
  - **Large conversion ratios, wide voltage or power ranges, isolation requirements, etc., impact achievable size**
- **Devices & characteristics available in different operating regimes also greatly impact performance**
  - **CMOS at low voltages (e.g., a few V) and power levels**
  - **Integrated LDMOS at moderate voltages (10's to 100's V) at low power**
  - **Discrete devices at high voltage and/or power levels**
    - **Vertical Si devices**
    - **GaN-on-Si devices**
    - **SiC devices**





Very High Frequency Power Conversion

- **Objective: develop technologies to enable miniaturized, integrated power electronics operating at HF and VHF (3 – 300 MHz)**
- **To achieve miniaturization and integration:**
  - **Circuit architectures, topologies and controls for HF/VHF**
    - **Develop approaches that overcome loss and best leverage devices and components available for a target space**
  - **Devices**
    - **Optimization of integrated power devices, design of RF power IC converters, application of new devices (e.g., GaN)**
  - **Passives**
    - **Synthesis of integrated passive structures incorporating isolation and energy storage**
    - **Investigation and application of VHF-compatible magnetic materials**
  - **Integration**
    - **Integration of complete systems**



System Examples

- Low-voltage, low-power
  - step-down conversion for battery-powered systems
  - CMOS devices
  - Hybrid capacitor/magnetic conversion

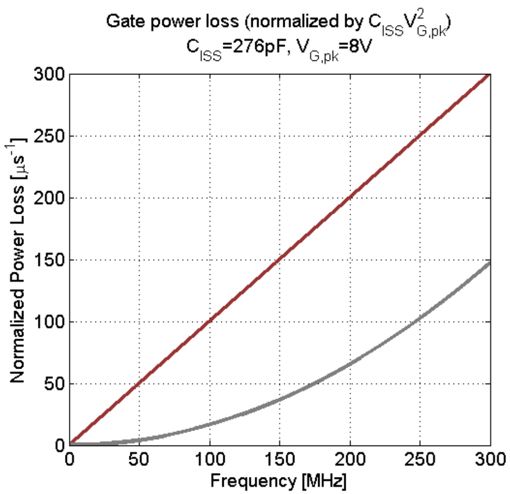
- **Moderate voltage, low power**
  - **Isolated dc-dc converter for power supply applications**
  - **Integrated LDMOS devices**
  - **PCB integrated magnetics**

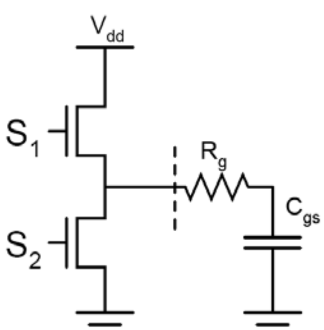
- **Grid voltage, moderate power**
  - **Grid-interface LED driver system**
    - **Line frequency energy buffering and power factor correction**
  - **Discrete GaN-on-Si devices**
  - **Hybrid capacitor/magnetic conversion**

Switching Frequency Limitations

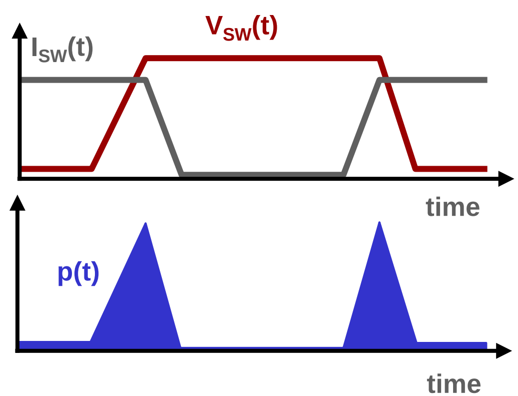
- **At moderate voltage levels, ALL of gating, switching and magnetics losses are important constraints on switching frequency**

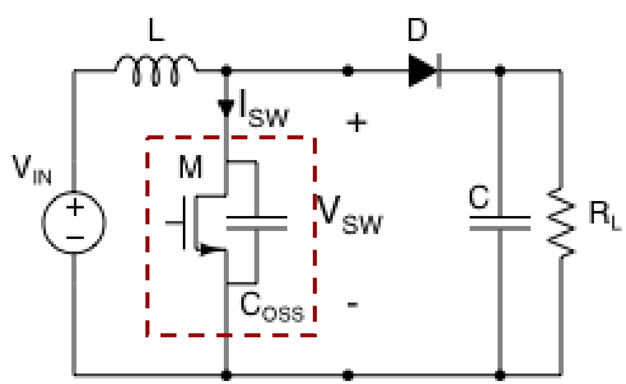
- **Gating loss ($\propto f$)**





- **Switching loss ($\propto f$)**





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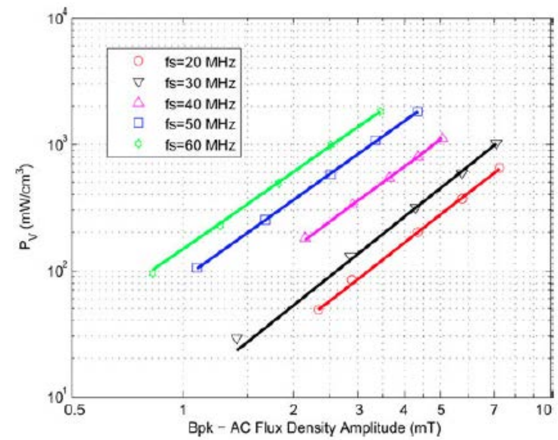
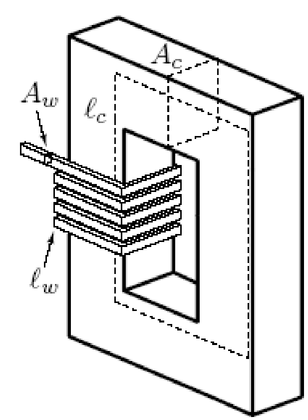
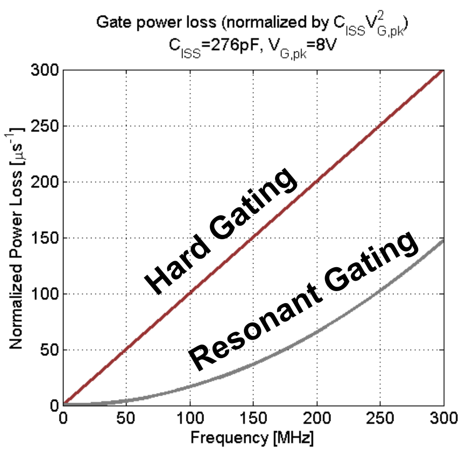


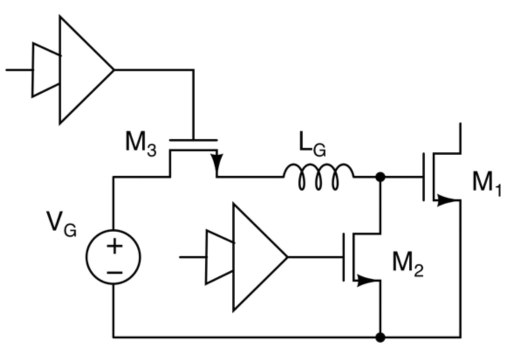


Switching Frequency Solutions

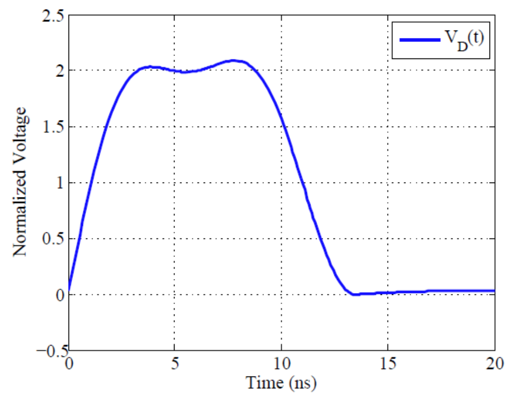
- **Minimize frequency dependent device loss, switch fast enough to eliminate/minimize magnetic materials, enable PCB integration**

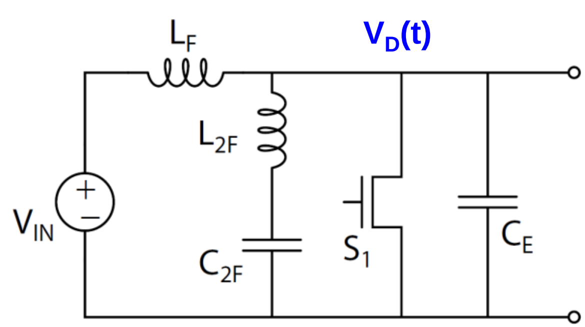
- **Resonant gating**





- **ZVS Soft switching**

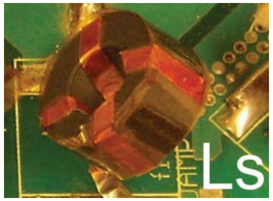




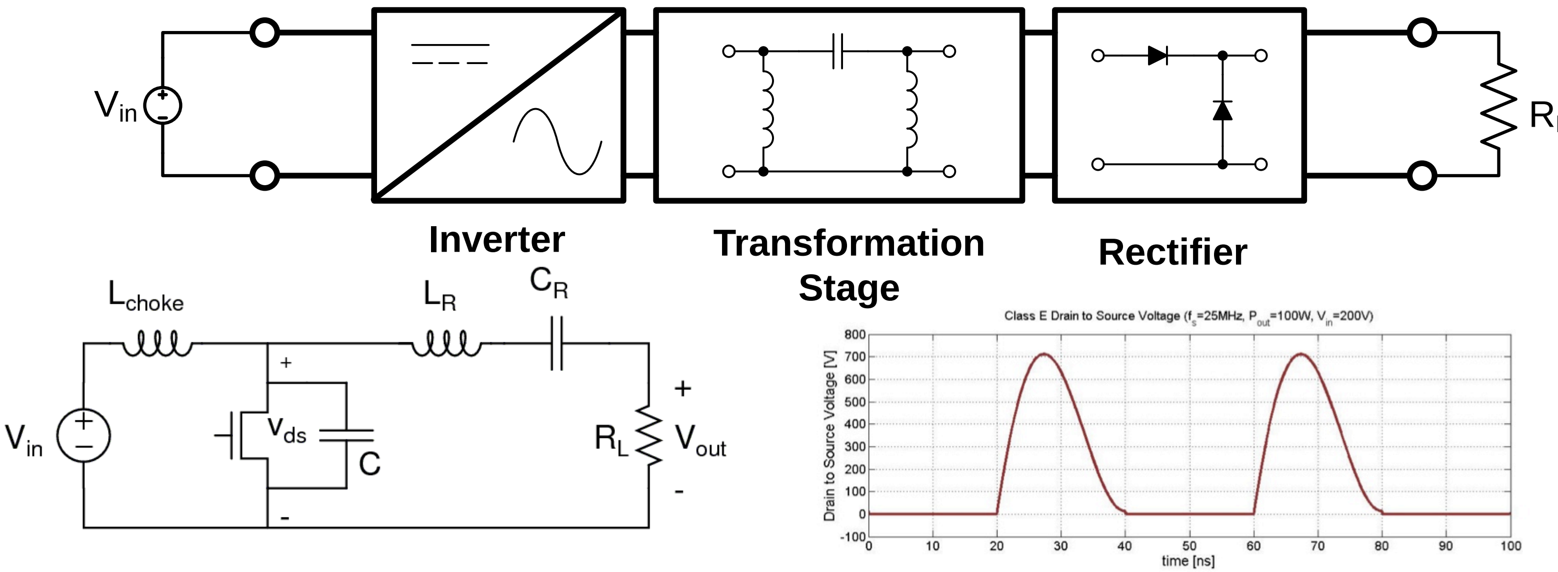
- **Coreless magnetics in package or substrate**

Sagneri, MIT, 2011

- **Low-permeability RF magnetic materials**

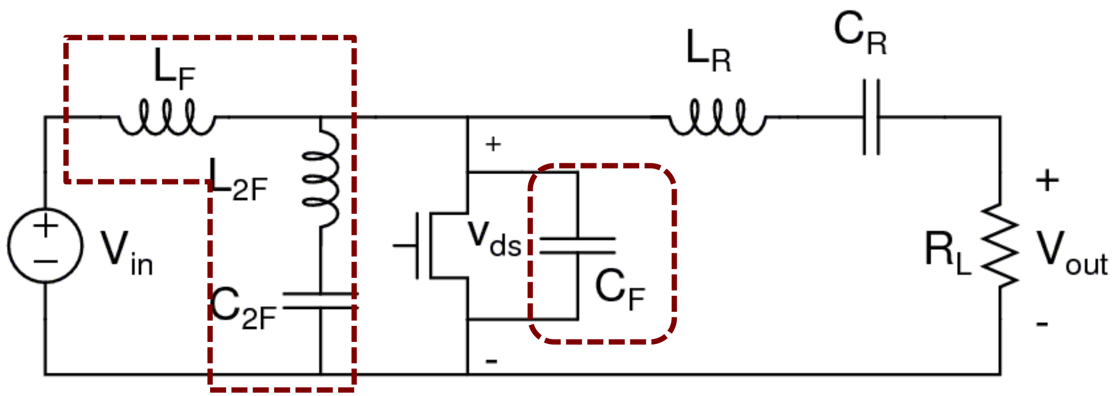


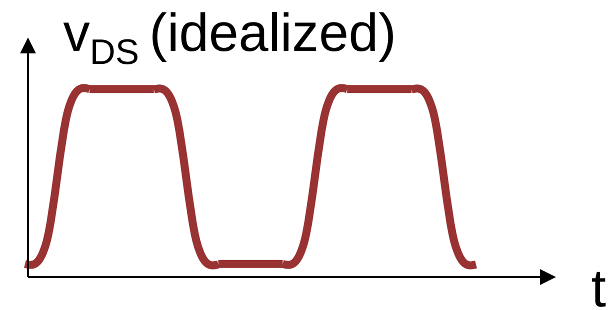
Topology Implications for VHF Conversion



- **Driving high-side "flying" switches becomes impractical**
- **Circuit operation *must* absorb parasitics**
  - **device capacitances, interconnect inductance, …**
- **Topology & device constraints impose limits**
  - **Topologies are often sensitive to operating conditions**
  - **Resonant gating, ZVS topologies limit control**
    - **Fixed frequency and duty ratio controls become preferable**

Inverter Topology: Φ_2 Inverter

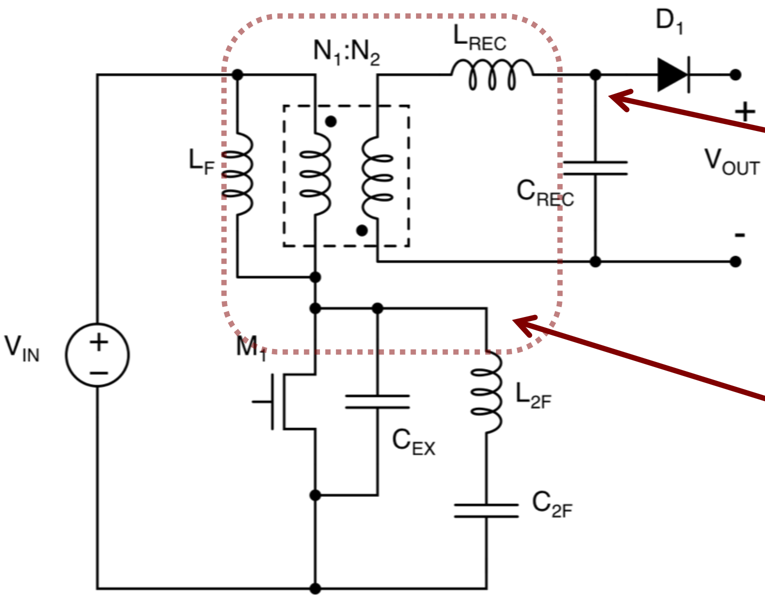




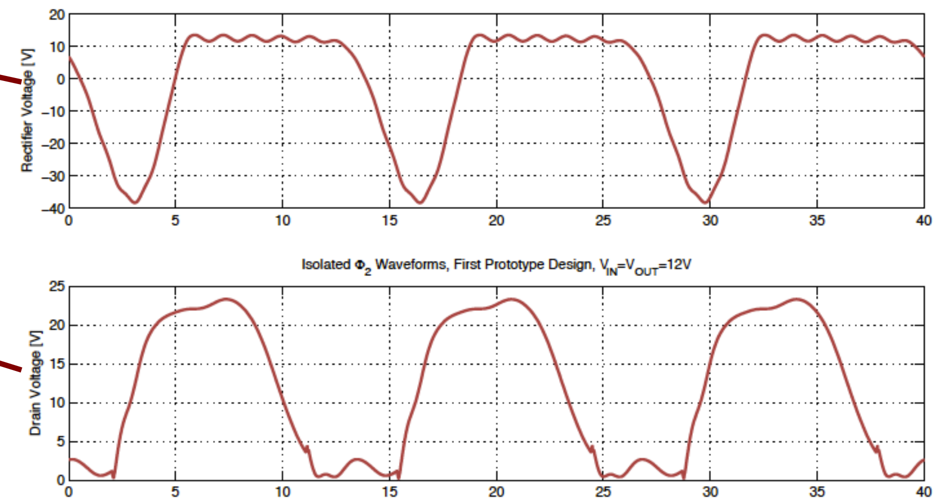
- **Multi-resonant network shapes the switch voltage to a quasi-square wave**
  - **Network nulls the second harmonic and presents high impedance near the fundamental and the third harmonic**
  - **Reduces peak voltage ~ 25-40% as compared to class E**
  - **Reduces sensitivity of ZVS switching to load characteristics**
- **No bulk inductance (all inductors are resonant)**
  - **Small inductor size**
  - **Fast transient performance for on-off control**
- **Absorbs device capacitance in a flexible manner**

Rivas, et. al., "A High-Frequency Resonant Inverter Topology with Low Voltage Stress," Trans. P.E., July 2008

Isolated VHF dc-dc Topology



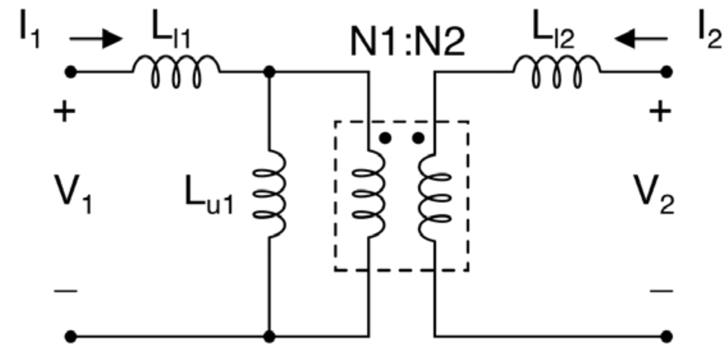
- **Isolated Φ_2 inverter, resonant rectifier**

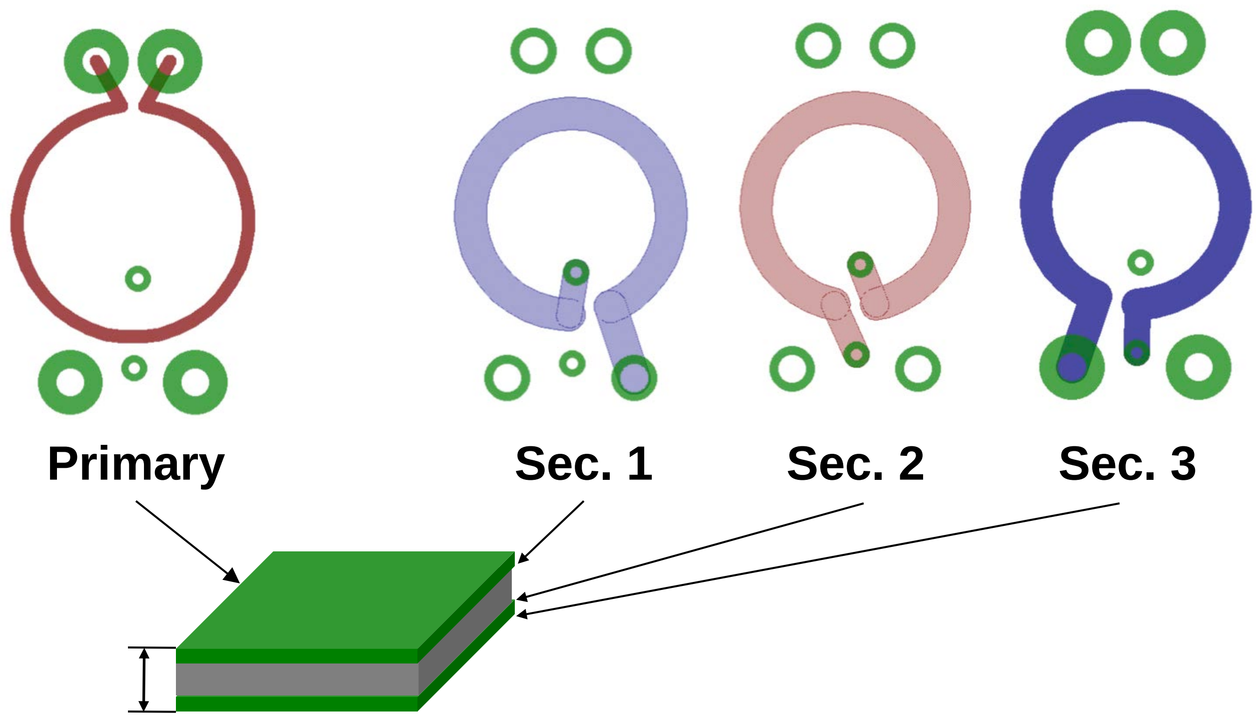


- **Single-switch resonant Inverter and resonant rectifier**
  - **ZVS switching waveforms with low voltage stress**
  - **Device, transformer parasitics fully absorbed**
    - **provide Φ_2 inverter and rectifier tuning**
- **Fixed frequency and duty ratio enables resonant gate drive of M_1**
  - **On-off control to regulate output**
- **Transformer design critical to obtain desired tuned operation**
  - **May be implemented as a planar PCB structure**

Planar PCB Transformer Implementation

- The transformer inductance matrix is fully constrained by converter design
- Implement in printed circuit board
  - Achieve characteristics by careful geometry selection
  - Select structure that best trades size and loss

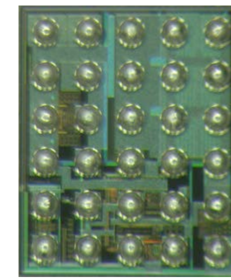




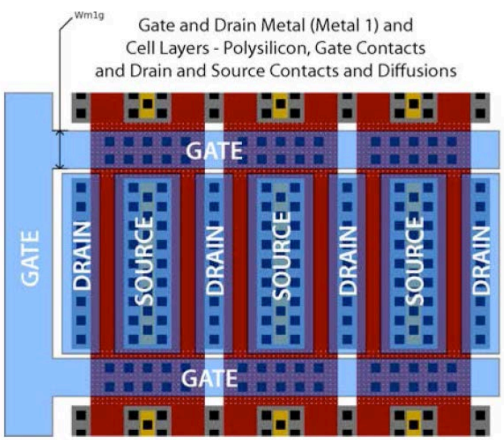
Sagneri, et. al., “Transformer Synthesis for VHF Converters,” *2010 International Power Electronics Conference, June 2010*

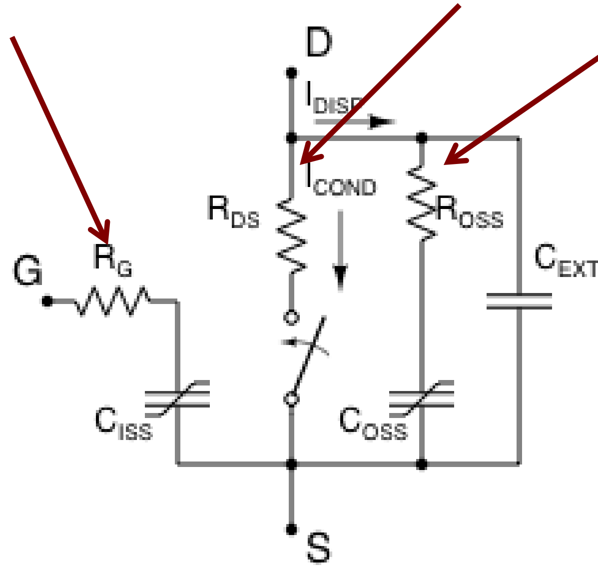
Integrated Switch and Controls

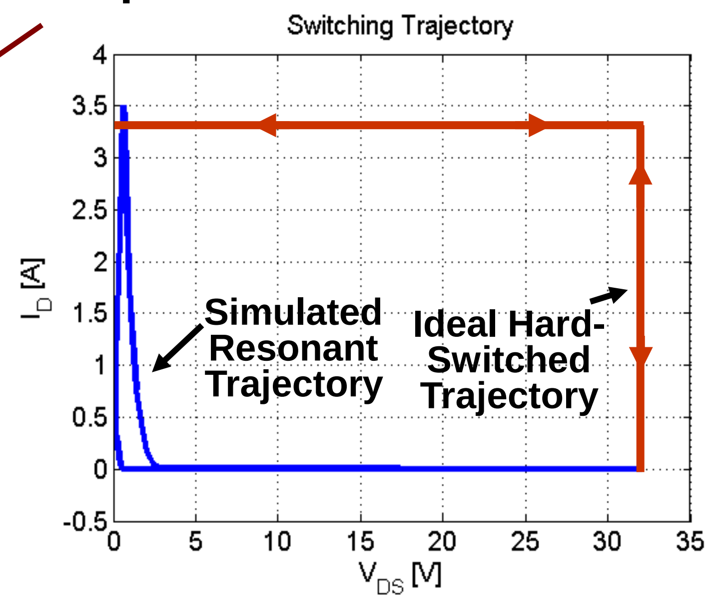
- Power applications often require *integrated switches and controls* in *low-cost processes* (e.g., LDMOS devices in a BCD process)
- With device layout optimization one can achieve VHF operation (30-300 MHz) with conventional (low-cost) power processes
  - Circuit/Device co-optimization: Optimize device layout for *specific* circuit waveforms
  - Take advantage of soft switching trajectory in device design
  - >55% loss reduction demonstrated through this method



$$P_{TOT} = \underbrace{K_1 \cdot R_G \cdot C_{ISS}^2}_{\text{Gating}} + \underbrace{K_2 \cdot R_{DS-ON}}_{\text{Conduction}} + \underbrace{K_3 \cdot R_{OSS} \cdot C_{OSS}^2}_{\text{Displacement}}$$

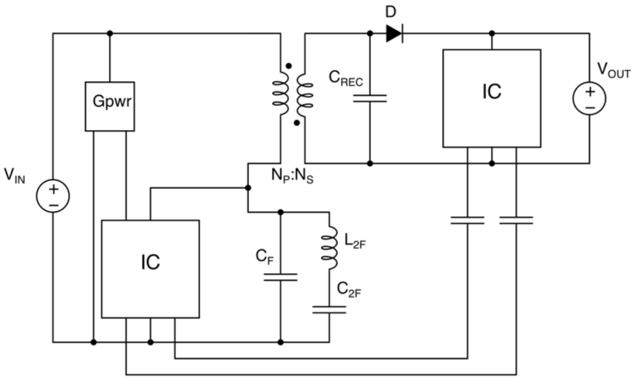




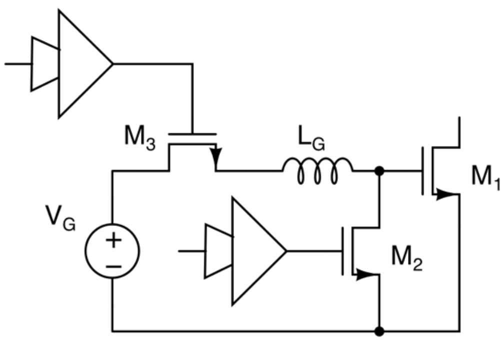


Sagneri, et. al., "Optimization of Integrated Transistors for Very High Frequency dc-dc Converters," Trans. P.E (July 2013)

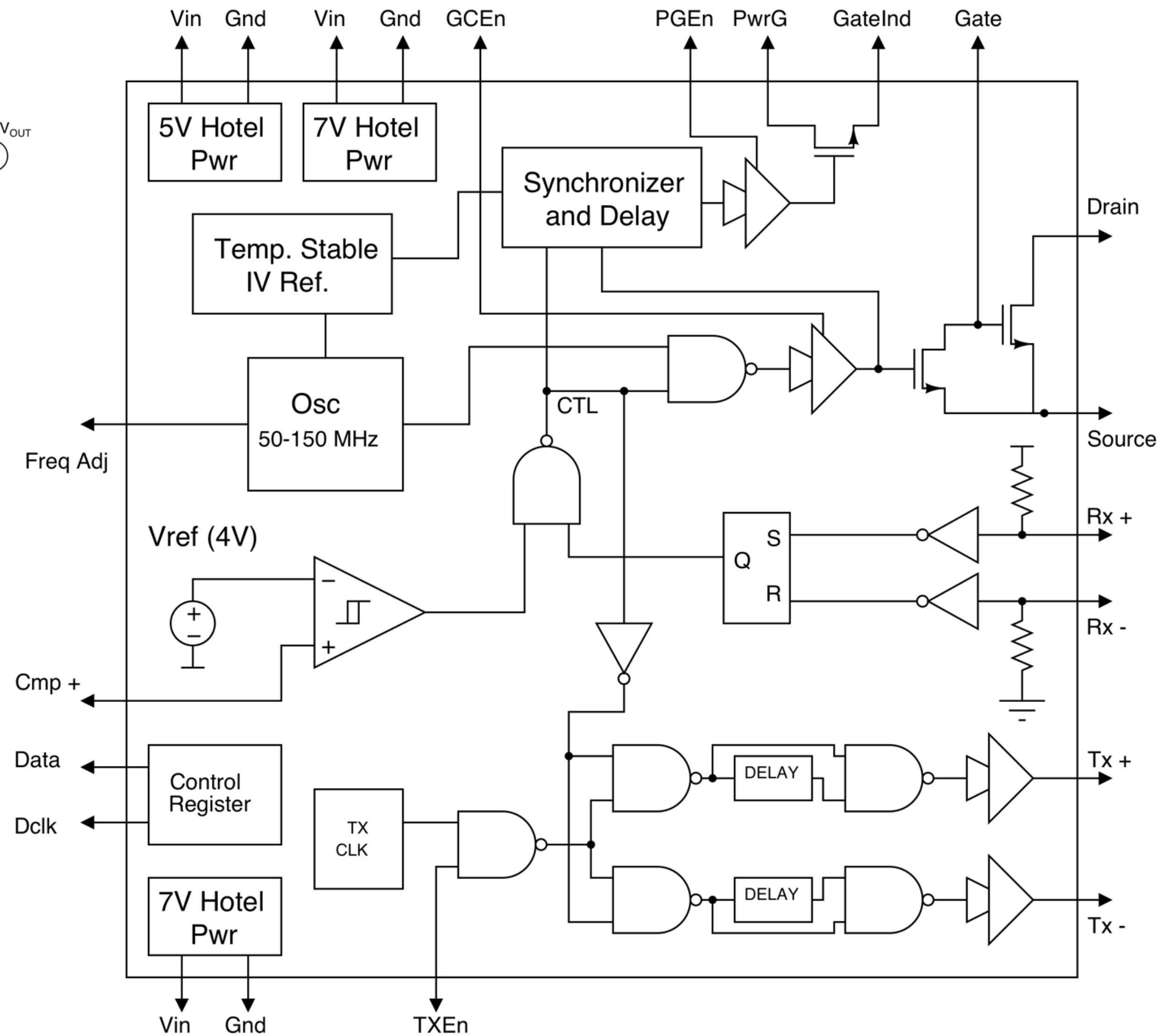
Integrated VHF Converter in BCD Process



Isolated converter

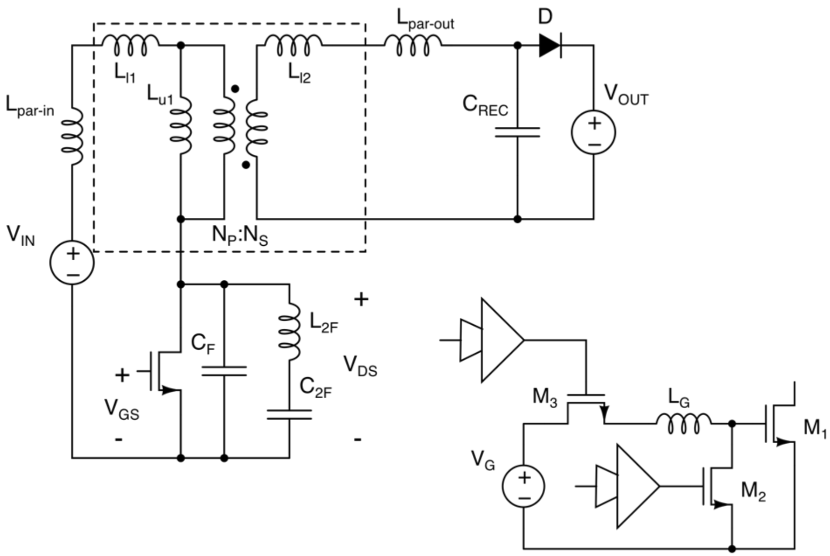


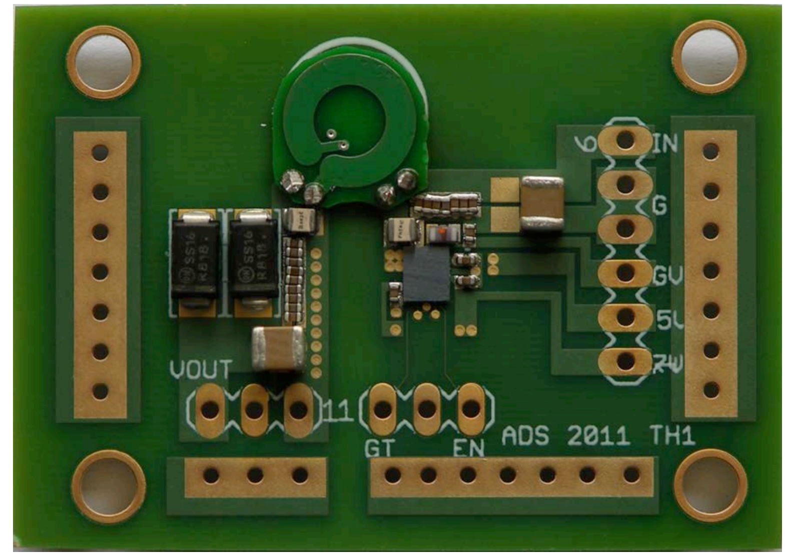
Half-sine resonant gate drive



Integrated controls and power devices

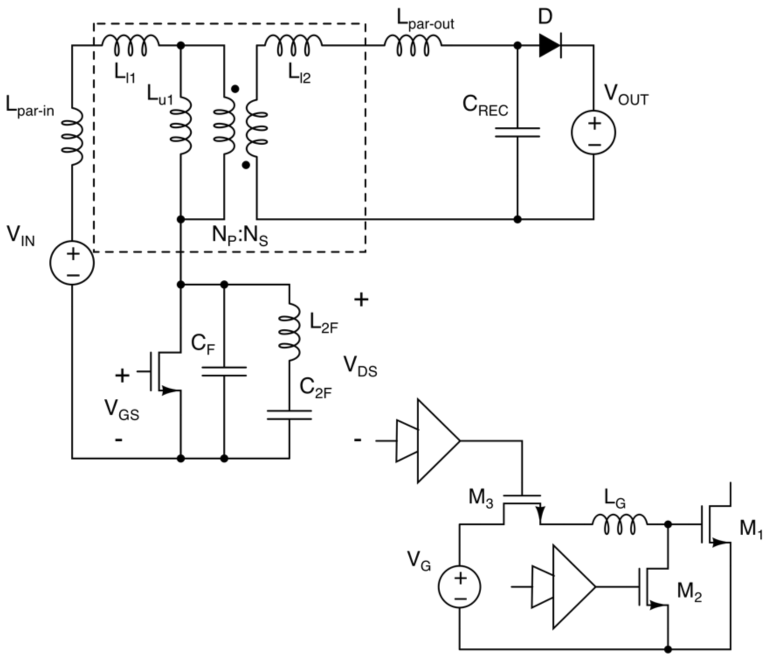
Prototype Isolated Φ_2 Converter

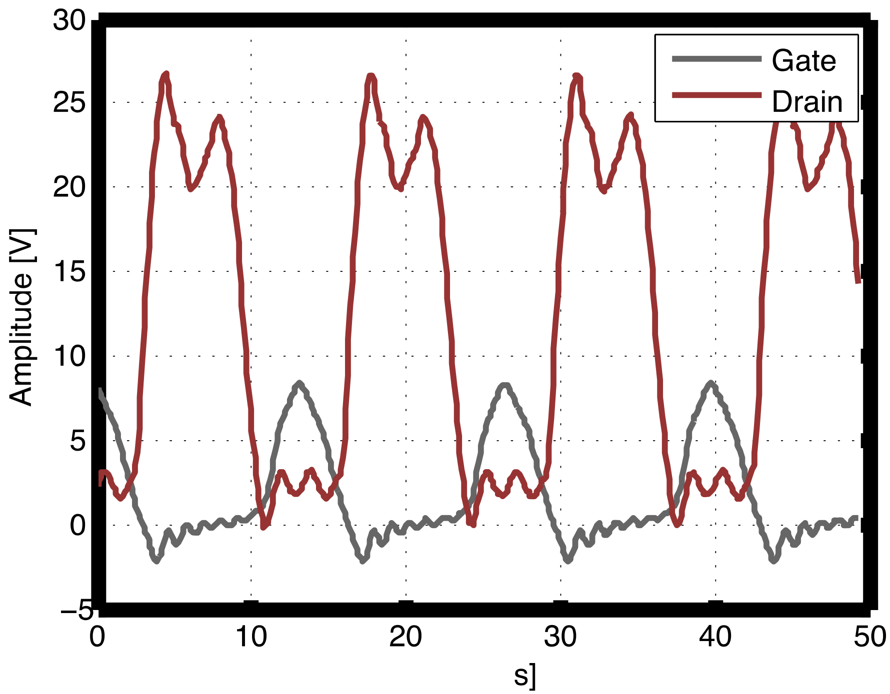




- **6 W, 75 MHz isolated converter**
  - **8-12 V input, 12 V output**
  - **On-off control to regulate output**
  - **ZVS switching, resonant gating to achieve VHF**
- **Printed-circuit-board transformer**
- **Integrated switch, resonant driver and controls**
  - **ABCD5 process**

Prototype Isolated Φ_2 Converter Results

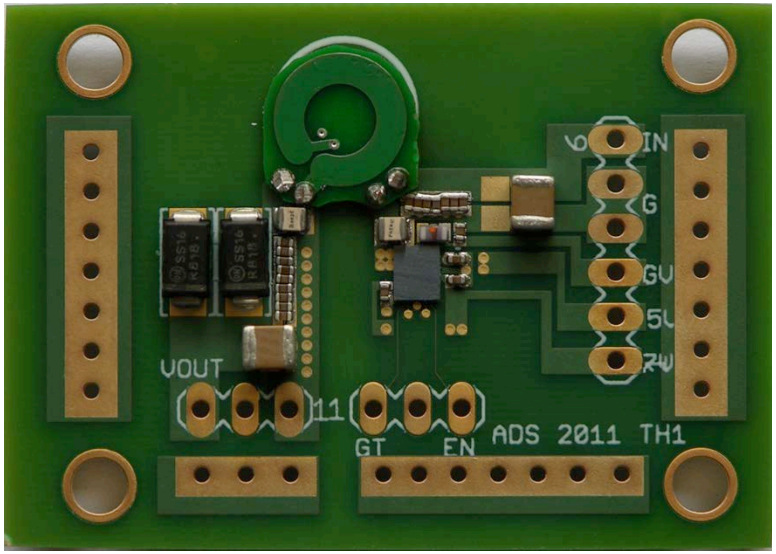
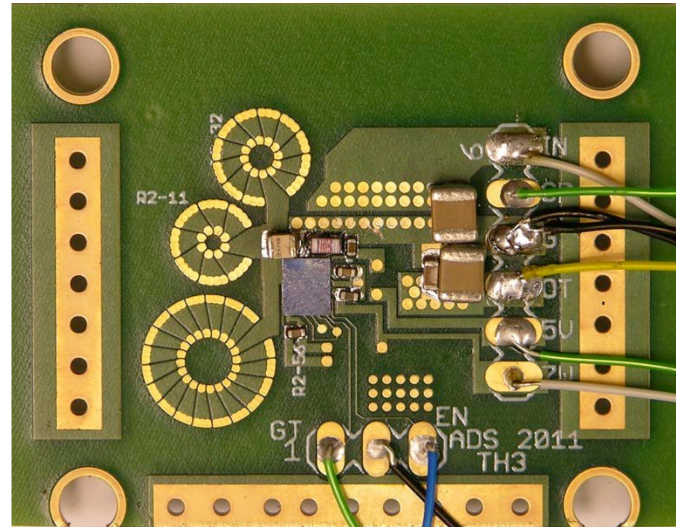




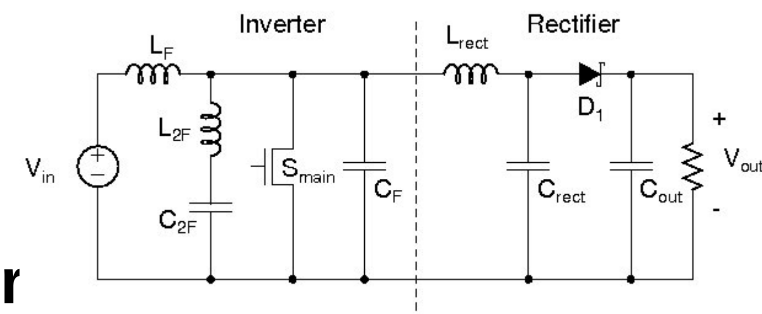
- ZVS Resonant waveforms over operating range
- Efficiency 66%-76% across voltage, load range
- Half-sine resonant gate driver

Pgate ~ 110 mW @ 75 MHz, ~ 3x improvement over hard gating

Prototype 75 MHz Integrated Converters

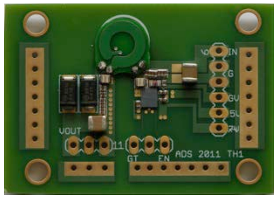
Isolated Φ_2 Converter	Φ_2 Boost Converter
	
6W, 73% efficiency	14W, 85% efficiency

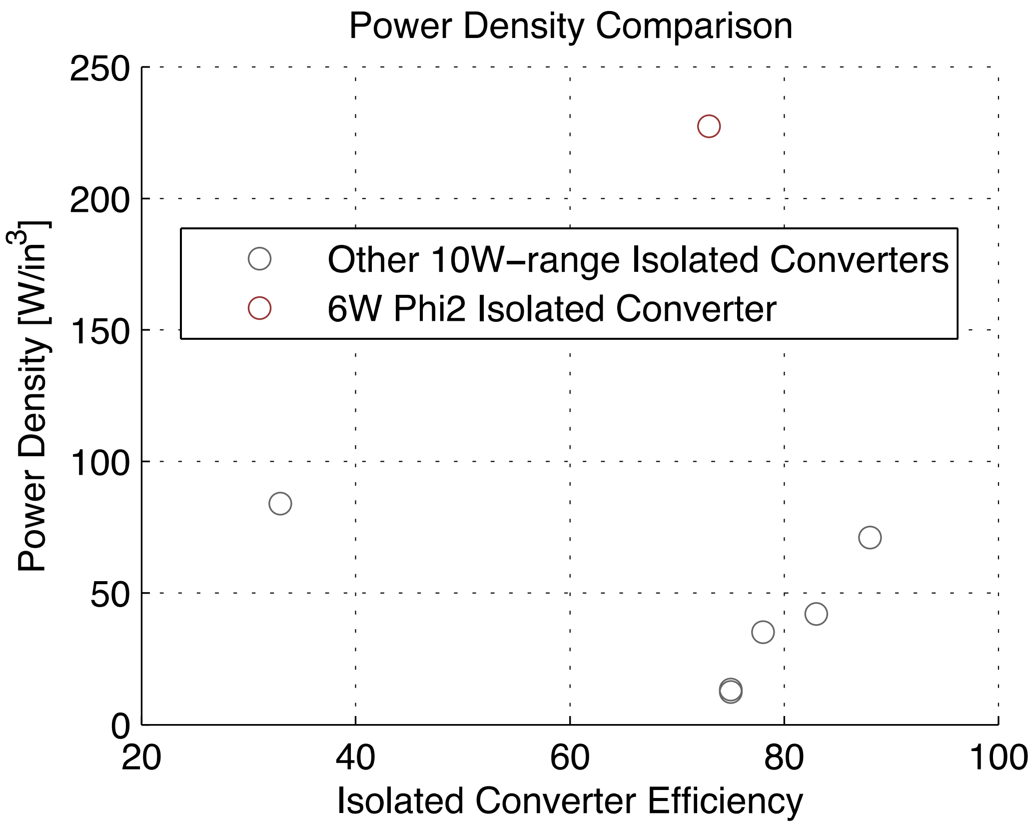
- Non-isolated (boost) variant with PCB-integrated magnetics also demonstrated
- Non-isolated version yields higher power, efficiency, power density
  - Many related topology variants



Pilawa-Podgurski, et. al., “Very High-Frequency Resonant Boost Converters,” Trans. P.E. June 2009

Power Density, Efficiency, Integration





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  - step-down conversion for battery-powered systems
  - CMOS devices
  - Hybrid capacitor/magnetic conversion
- **Moderate voltage, low power**
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  - **Integrated LDMOS devices**
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    - **Line frequency energy buffering and power factor correction**
  - **Discrete GaN-on-Si devices**
  - **Hybrid capacitor/magnetic conversion**

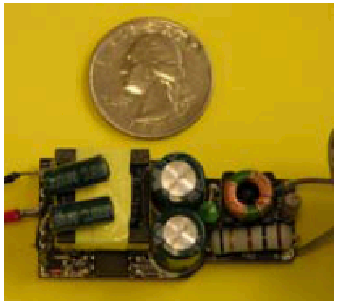
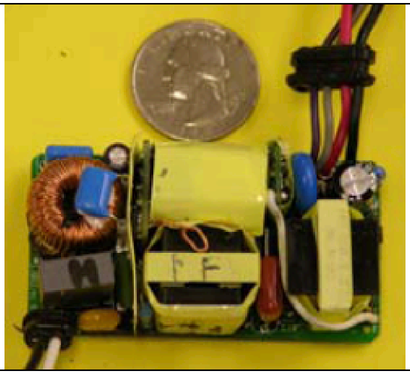
High Voltage, Moderate Power

- **Many electronic systems operate at 100’s of Volts and 10’s – 100’s of Watts**
  - **Conventional designs typically operate at 50 kHz – 500 kHz**

- **Application requirements:**
  - **Discrete power devices and passives can be used**
  - **Integration of passives desired but not presently typical**
  - **Single-phase grid interface requires twice-line frequency energy buffering**
    - **Higher switching frequency does not help with this**

- **To increase switching frequency, must address:**
  - **Switching loss (ZVS soft switching)**
  - **Circuit parasitics (capacitance and inductance limits)**

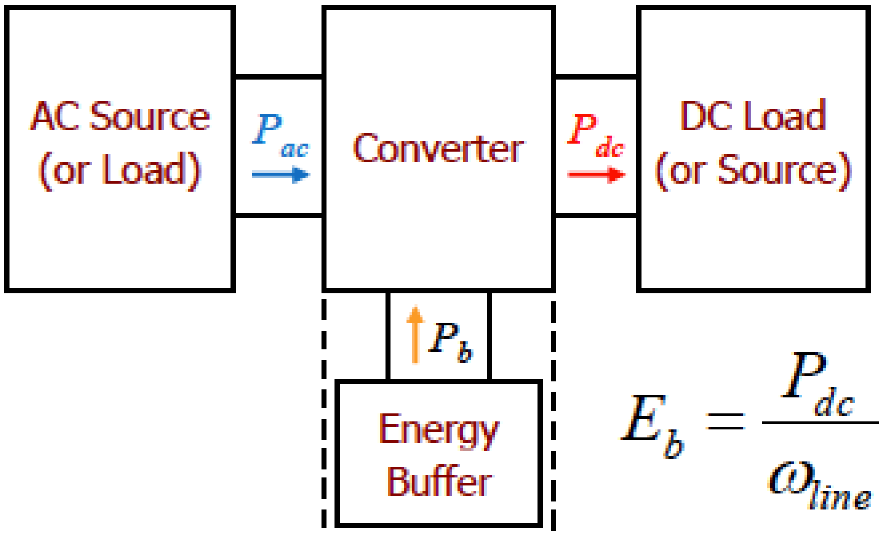
Example: Solid-State Lighting Drivers

Model	Polar-ray 6W		Cooper 1200 Series 24.8 W	
Output power	4.0 W		21.1 W	
Sw. Frequency	57 kHz		100 kHz	
Efficiency	64%		85%	
Converter Volume	1.27 in^3		4.76 in^3	

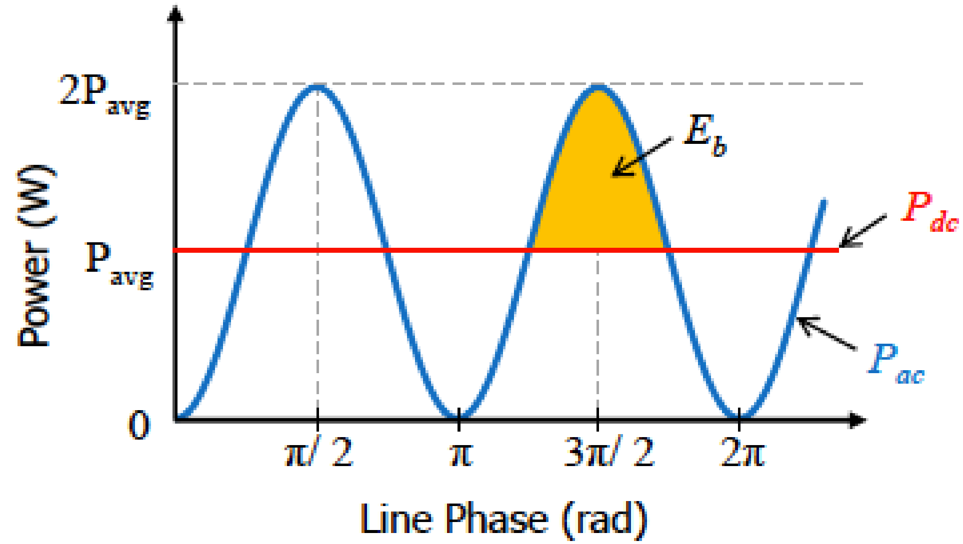
- **Today: η ~ 60-90%**
- **Power density of commercial designs < 5 W/in^3**
  - **Largest components are typically magnetic elements (inductors, transformers)**
  - **Second largest are usually electrolytic capacitors for line-frequency energy storage**
  - **Switching frequencies typically ~ 100 kHz**
- **Power factor / line-frequency energy buffering is also an important consideration**
  - **PF of 0.7 (residential) or 0.9 (commercial) is desired but often NOT achieved**

Twice-line-frequency energy buffering

- **Interface between (continuous) dc and single-phase ac requires buffering of twice-line-frequency energy**
  - **Energy storage requirement is independent of switching frequency**



$$E_b = \frac{P_{dc}}{\omega_{line}}$$



- **Electrolytic capacitors are energy dense but have temperature and lifetime limits**

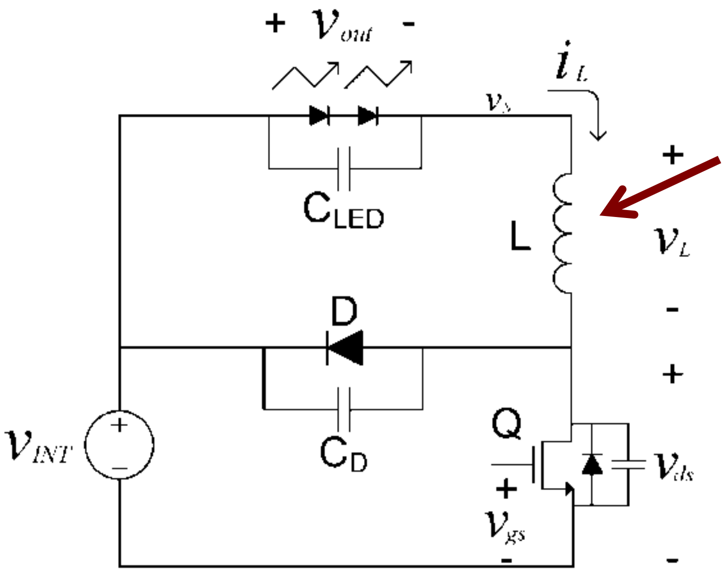
Added Goal: Achieve energy buffering (for high pf and continuous output) at high power density without electrolytics

Application Background

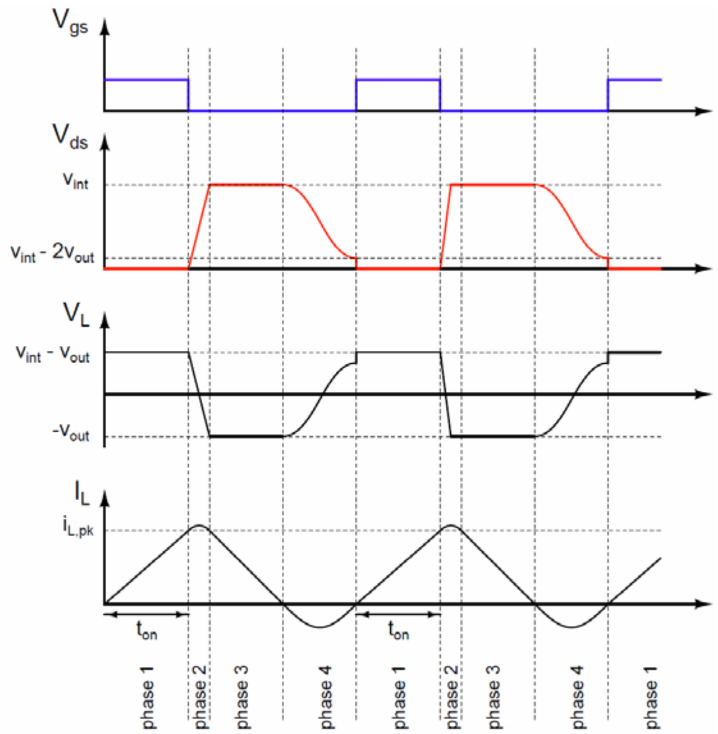
- Operation from ac-line-voltage inputs (to 200 V peak) to moderate outputs (~30 V) at low powers (~10-50 W)
- Resonant circuits at high voltage and low current lead to very small capacitance limits and large inductor values
  - Challenging to achieve with integrated magnetic components
- Increase in frequency reduces *both* L's, C's
  - Minimum practical capacitances can limit frequency
- Design approach selected to enable minimal magnetics and improved integration possibilities
  - Stacked architectures to reduce subsystem operation voltage
  - Multi-stage/merged conversion techniques
  - Topologies selected for small magnetics size

HF dc-dc Power Stage

- High-frequency dc-dc conversion block (50-100 V in, ~25-40 V out)

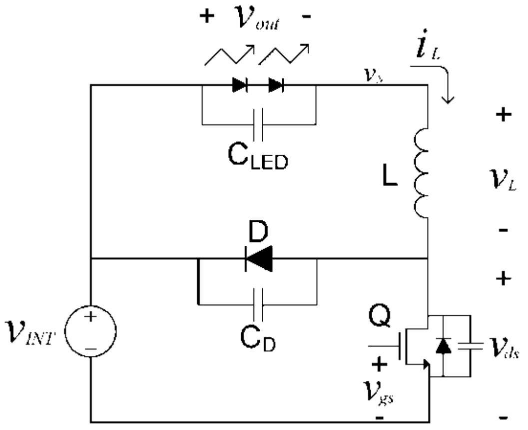


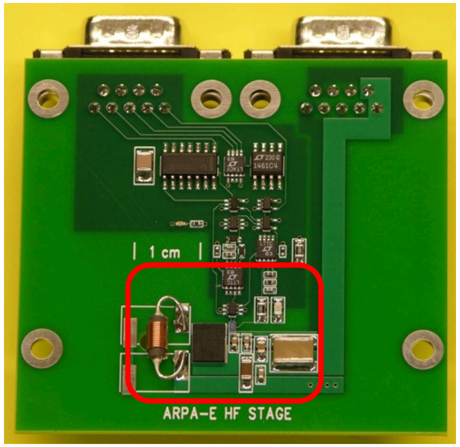
Enables small Inductance and possible Integration!



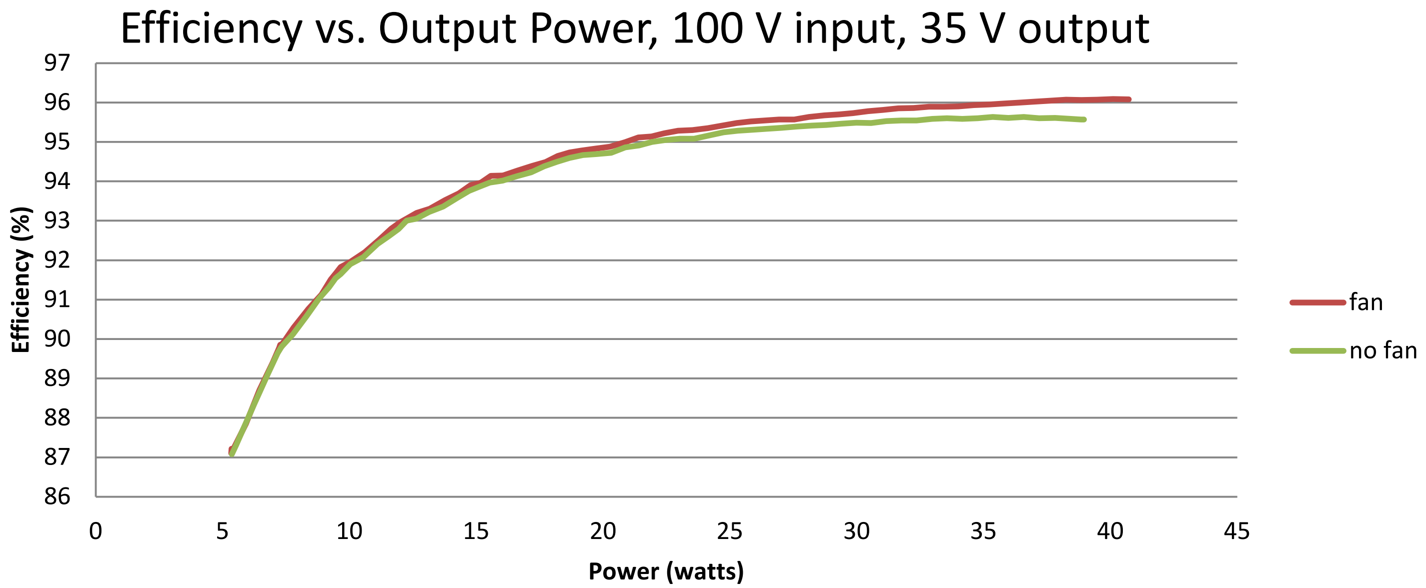
- **Resonant transition inverted buck circuit at edge of DCM**
- **Low voltage stress enables operation with significant device capacitance**
- **Small magnetics (700-1000 nH inductor for 100 V input)**
- **ZVS / near ZVS with PWM control of output power**
- **ground referenced switch for HF switching operation (~5-10 MHz)**
- **PWM “on-time” control for 50-100 V input range at ~25-50 V output**

HF dc-dc Power Stage

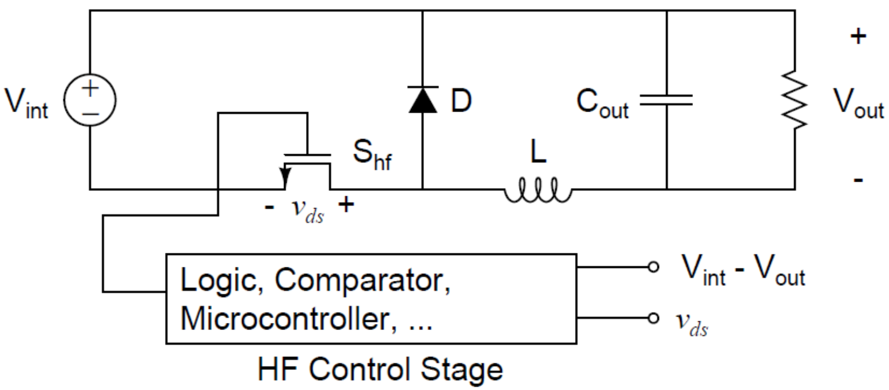


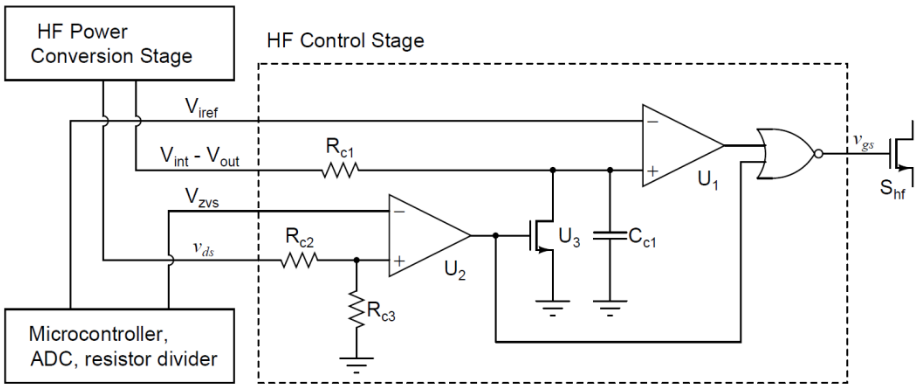


Discrete Prototype V_{in}=100 V, V_{out} = 35 V, f_{sw} ~ 7.8 MHz



HF Inverted Buck Converter Control



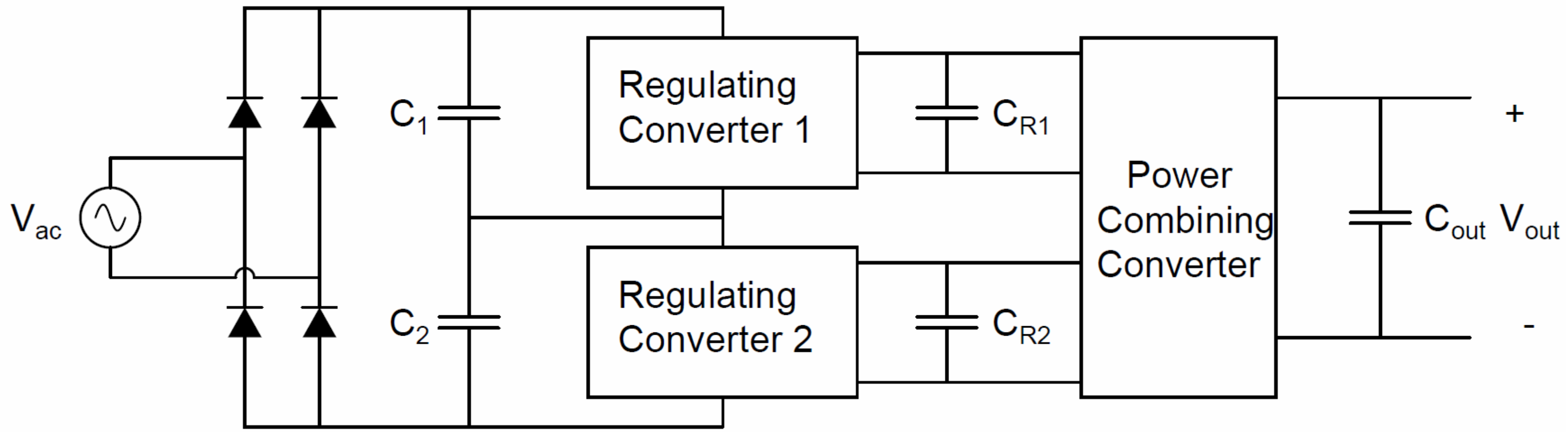


- **peak inductor current is controlled by changing switch on-time**
  - **Enables continuous modulation of power at high frequency**
- **turn on at ZVS / near ZVS voltage**

Architectural Strategy

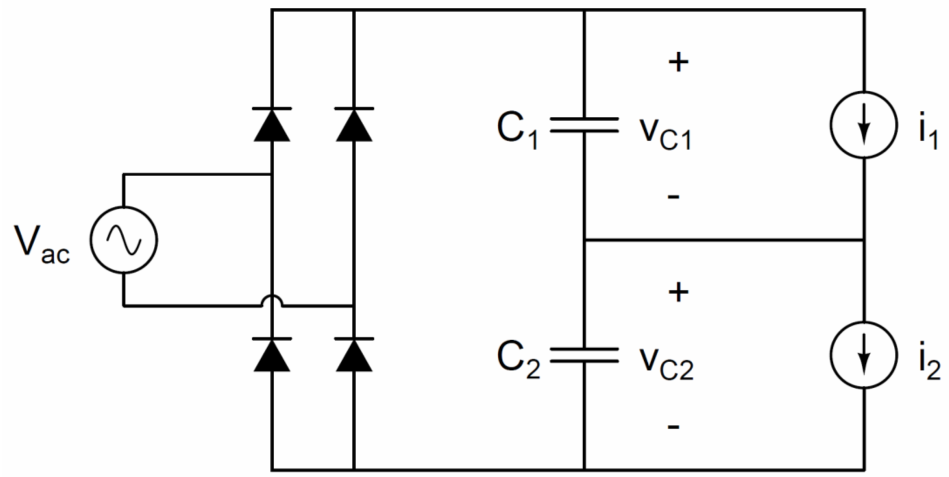
- **Use a "stacked" circuit architecture to enable processing of high input voltage with lower-voltage blocks**
  - **Enables "resonant-transition inverted buck" conversion blocks to be used for energy processing at high frequency**
- **Buffer line-frequency energy at relatively high voltage with large voltage swing to minimize capacitor size**
  - **Can use film or ceramic capacitors, eliminating electrolytic capacitors while maintiaining high power density**
  - **This is important because energy buffering depends upon line frequency, and not upon switching frequency**

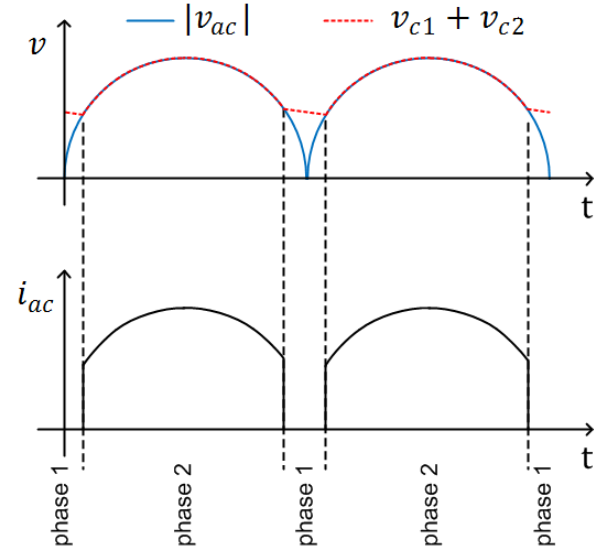
HF AC-DC Architecture



- **Two stacked "regulating" converters operating at HF**
  - **Generate regulated voltages across C_{R1}, C_{R2}**
- **Capacitor C_2 buffers twice-line-frequency energy (with high voltage fluctuation over the ac line cycle)**
- **Capacitor C_1 enables capacitor stack voltage to track line voltage**

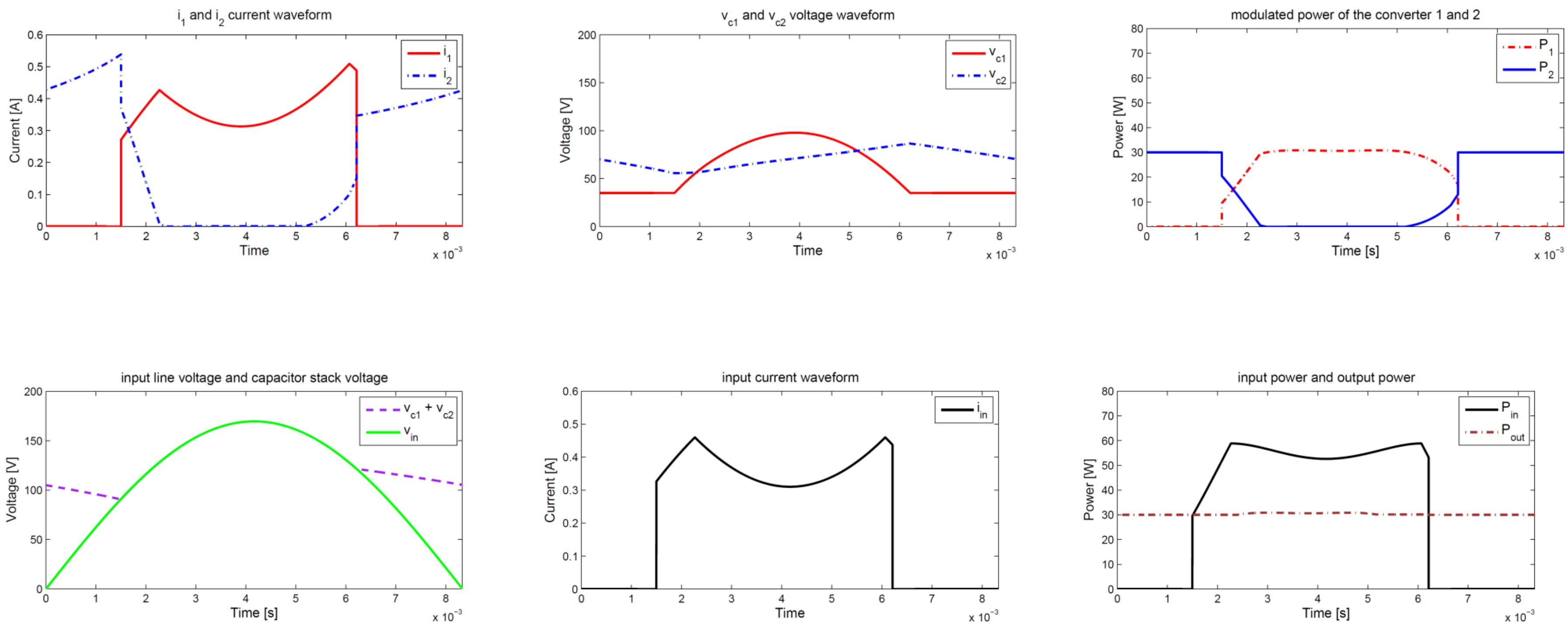
HF AC-DC Architecture – front end





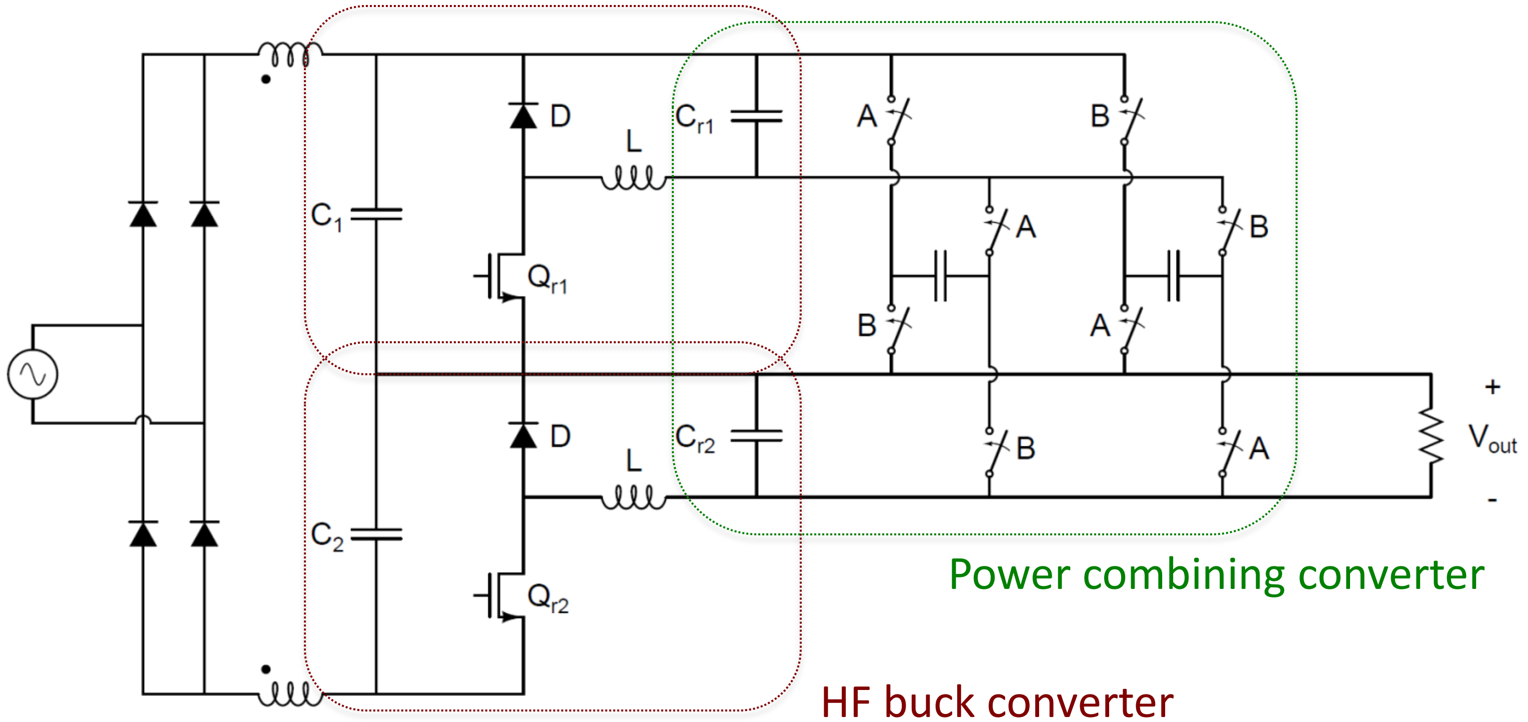
- **0.95 power factor can be achieved for a clipped-sine input current (sine current flows when input voltage is above 100 V (120 Vac case)**
- **At a given input current with a certain power factor, there are currents i_1 and i_2 satisfying steady state conditions for v_{c1}, v_{c2} over the ac line cycle**

Stacked Converter Model Simulation



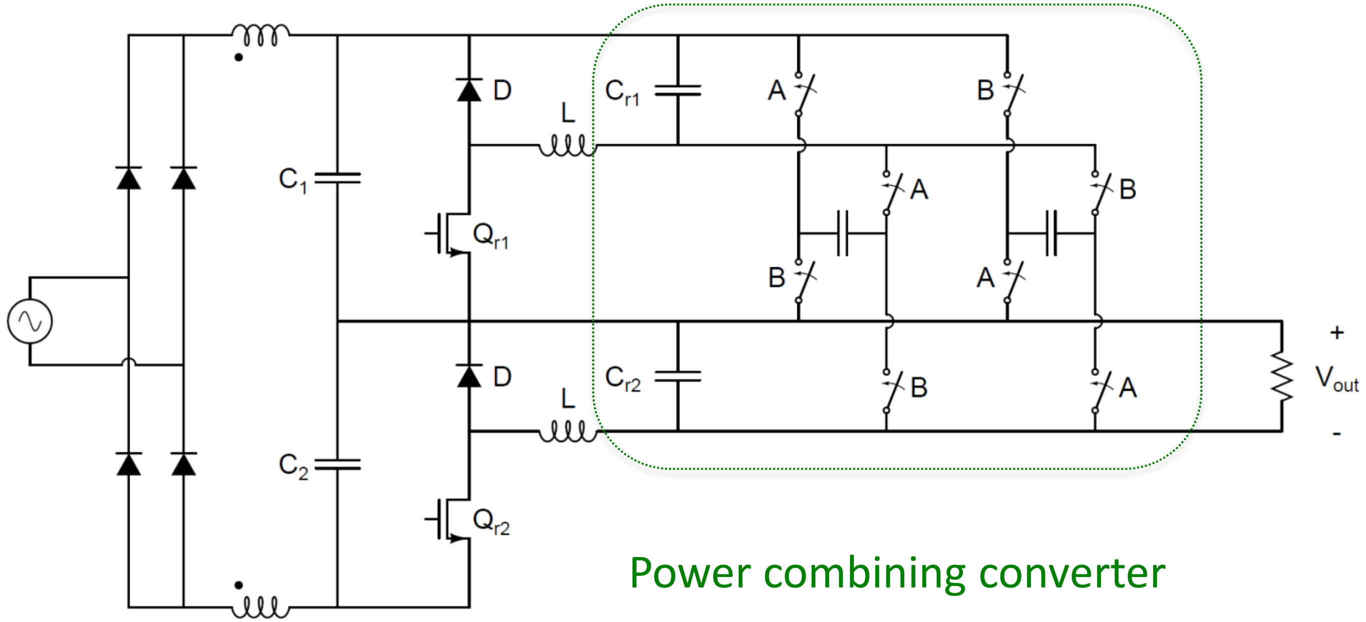
- **Example current and voltage waveforms**
- **For desired input power, calculate i_1 and i_2 currents over the ac line cycle (command for the individual dc-dc conversion blocks)**
- **Constant output power supplied to load**

Prototype Converter

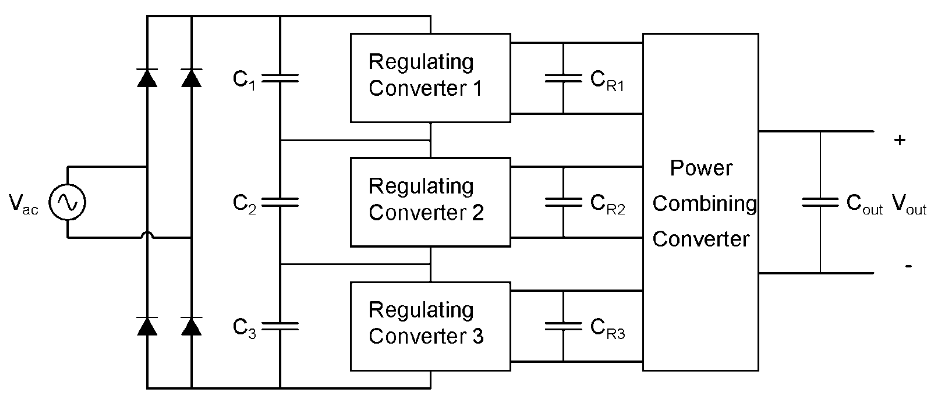


- Two stacked HF buck converters modulate input power across the ac line cycle, causing desired input current waveform and providing energy buffering in C_2
- SC circuit combines the power from converters to supply the load

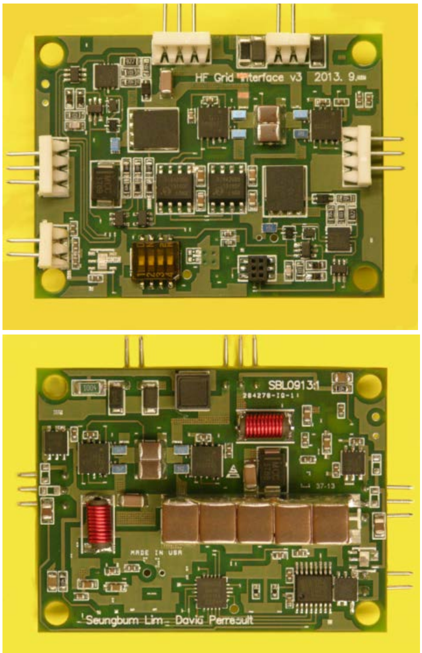
SC Power Combining Converter

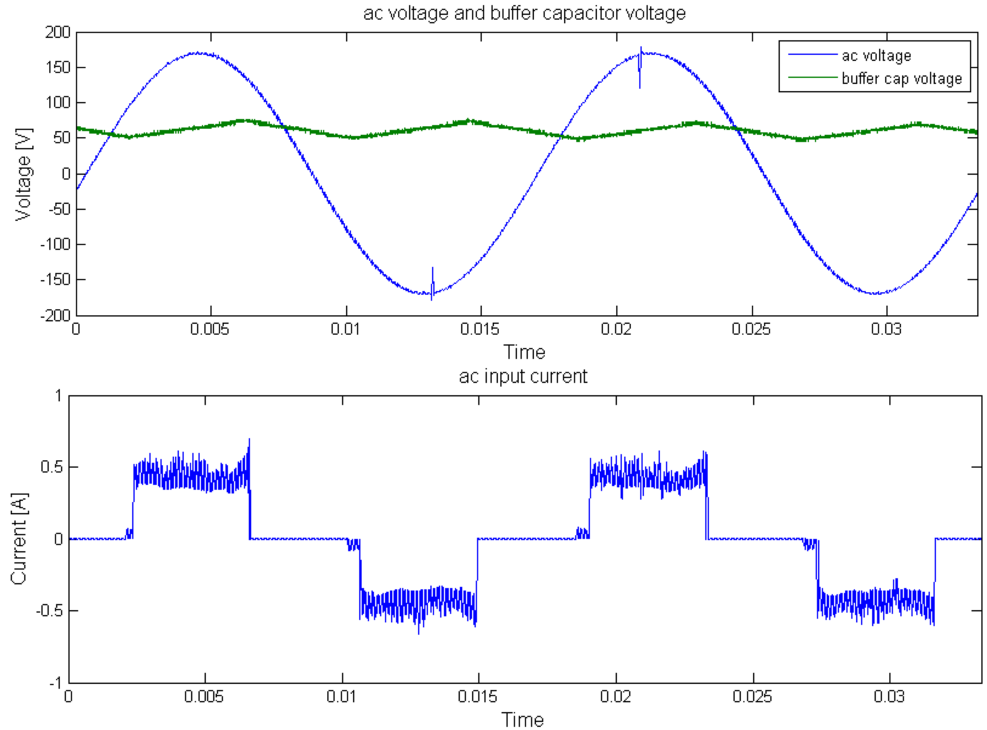


- Interleaved switched capacitor charge transfer circuit
- Delivers power from C_{r1} to C_{r2} (output port)
- Operates at ~30kHz with 50% duty ratio
  - High efficiency operation
- May be expanded:
  - Isolated power combining converters are also possible
  - Universal-input power converters



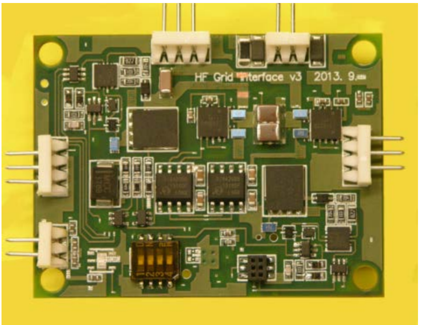
Experimental Results

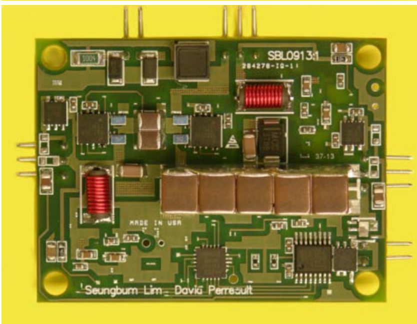


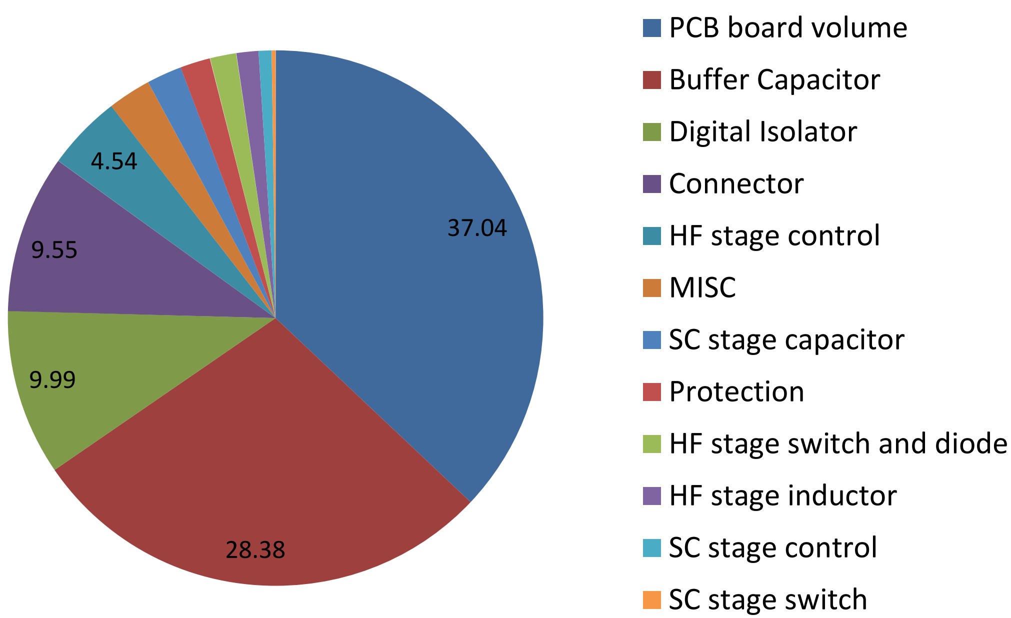


- **15uF x 15 = 225 uF MLCC ac energy buffer capacitor (works as 50 uF at 70V): eliminates electrolytic capacitors at modest size**
- **Buck converters each use a miniature ~800 nH inductor**
- **Overall 93.3% efficiency at 30W output power**
- **0.89 power factor (higher performance appears possible)**

Prototype Power Density



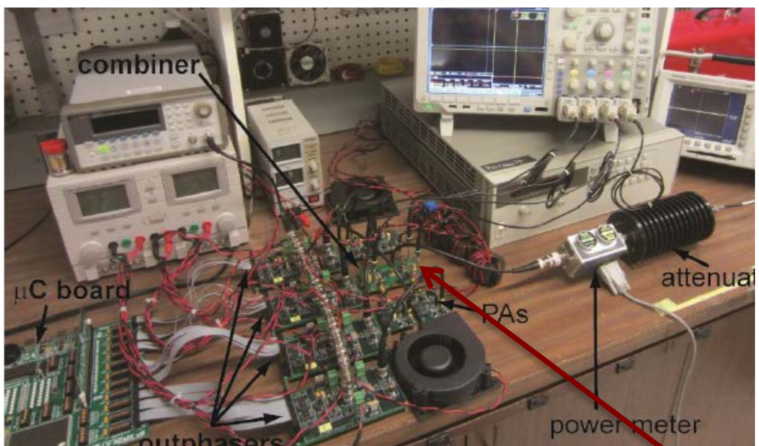


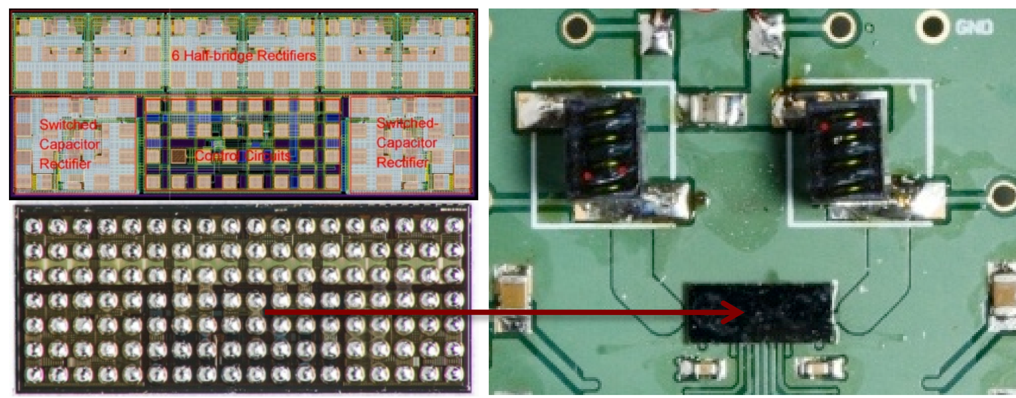


- **1.9 x 1.4 x 0.45 inch, 25 W/in^3 "box" power density**
- **Displacement volume: 0.23 in^3 , Power density: 130.55 W/in^3**
- **Digital isolator, Connector, HF stage control volume, pcb volume and layout can be further optimized**

Many Opportunities for Advances!

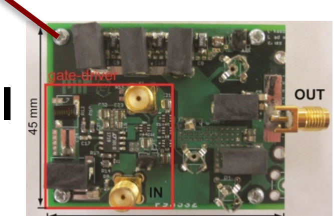
- **Improved architectures, topologies and control methods**
  - **Phase-shift control / outphasing at VHF offers large performance gains (e.g., load modulation control of VHF power converters)**
  - **Synchronous rectification (for higher efficiency at low voltages) is feasible at VHF (especially with CMOS rectifiers)**
    - **Hybrid GaN / Si Converters for large voltage step down**





Integrated 50 MHz CMOS step-down rectifier

27.12 MHz 100 W RF Inverter System with Outphasing Control of 4 inverters

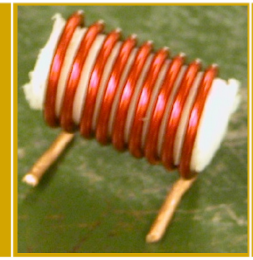


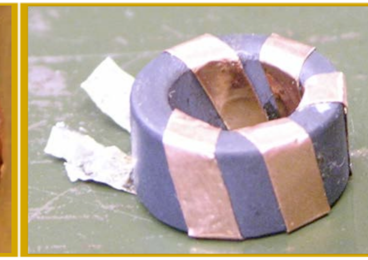
27.12 MHz 25 W GaN Class E Inverter optimized for load modulation and outphasing

A.S. Jurkov, et al, "Lossless Multi-Way Power Combining and Outphasing for High-Frequency Resonant Inverters," ***IPEMC 2012***
W. Li et al, "Switched-Capacitor Rectifier for Low-Voltage Power Conversion," ***APEC 2013***

Many Opportunities for Advances!

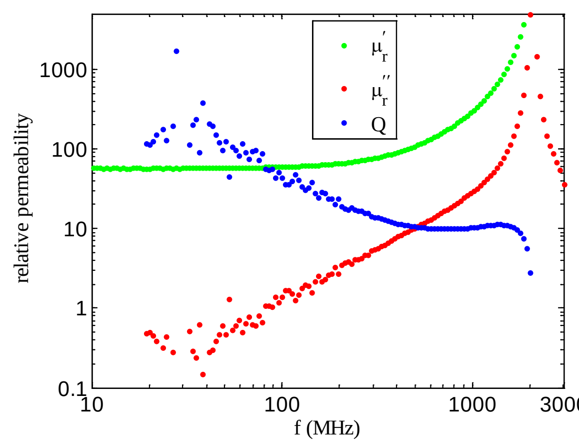
- **Bulk Low-μ RF magnetic materials are advantageous to beyond 60 MHz**
  - **e.g., 30 MHz, 1 A, 200 nH inductors**
  - **Smaller size, higher Q**

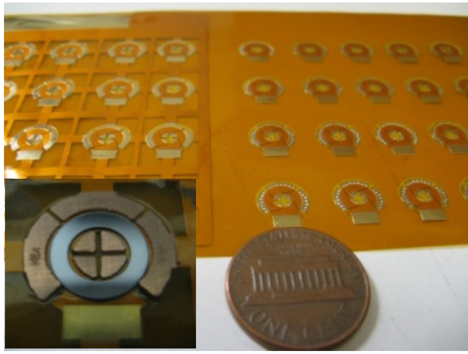




Type	Solenoid coreless	Toroid Coreless	Toroid Magnetic core
Inductance	200 nH	217.6 nH	190 nH
Volume	1.0 cm^3	1.2 cm^3	0.5 cm^3
Q_L	88	98	120

- **New integrated thin-film magnetic designs provide ultra-high density at up to 100 MHz**
  - **Sullivan, Dartmouth**





Charles Sullivan, Dartmouth

We can still leverage cored magnetics at frequencies to ~ 100 MHz

Han, et. al., "Evaluation of magnetic materials for very high frequency power applications," Trans. P.E, Jan. 2012

Araghchini, et. al., "A Technology Overview of the PowerChip Development Program," Trans. P.E., Sept. 2013

Summary

- **Higher frequency offers the potential for miniaturization, integration, bandwidth**
  - **Must overcome device and magnetics losses and manage parasitics**
- **Appropriate system design methods enable operation at HF and VHF frequencies**
  - **Correct strategy depends upon operating regime (voltage / power) , device characteristics, integration requirements**
- **Example strategies shown for two operating regimes**
  - **Low voltage, low power: CMOS devices, mixed SC/magnetic, hybrid fabrication**
  - **Mid voltage, low power: integrated LDMOS, pcb magnetics**
  - **High voltage, mid power: discrete GaN, mixed SC/magnetic**
- **Feasibility and advantage of these approaches have been demonstrated**
  - **Outperform more conventional implementations**
  - **The potential for further improvements is large**