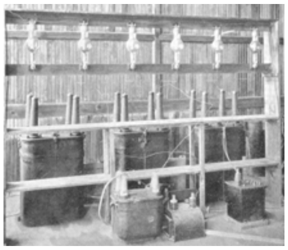
Massachusetts Institute of Technology

Power Electronics Research Group

Overview of the MIT Power Electronics Research Group

David Perreault



20 kW Kenotron Rectifier, Circa 1926

(From Prince and Vodges, 1927)

1 kW, 1 MHz 400-12V Converter, Circa 2021

(Mike Ranjram, MIT)

??

Circa 2036

Power Electronics Challenges

- **Many systems are limited by energy processing and control**

Efficient Lighting
(LED driver)

Computers
(Power Supply)

Transportation
(Tesla M.3 inverter)

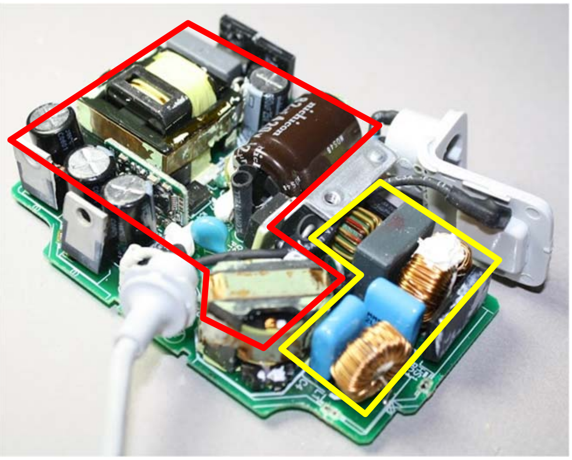
Renewable Energy
(Microinverter)

Mobile Devices
(Power management)

- **Advances in power electronics are needed**
  - ☐ **Miniaturization (smaller, lighter)**
  - ☐ **Higher efficiency (converters *and* systems)**
  - ☐ **Higher performance (better systems)**
  - ☐ **Applications (create entirely new *system* opportunities)**

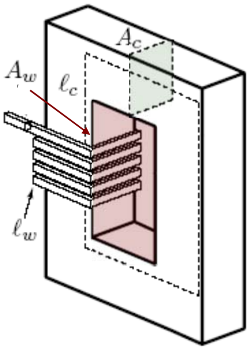
Passive Components Dominate

- **Passive components dominate size, weight and loss and limit performance**
  - ❑ **Both power stage and filters are important**
  - ❑ **Magnetics are especially challenging**



Miniaturizing Magnetics is *Fundamentally* Difficult

- **Scaling laws work *against* miniaturization of power magnetics**
  - ❑ **Simplified case: power handling (VA) of a fixed-frequency ac inductor**
    - **Flux density B_0 limited by core loss**
    - **Current density J_0 limited by winding loss**
- **Power handling $\propto$ (linear dimension)^4**
- **Volume $\propto$ (linear dimension)^3**
- **Power density (power/vol) $\propto$ (linear dimension)**
- **Magnetics get worse at smaller sizes!**



$$VA = V \cdot I \propto (N f B_0 A_C) \cdot \left(\frac{J_0 A_W}{N}\right) = f \cdot B_0 \cdot J_0 \cdot \boxed{(A_C A_W)}$$

Sullivan, et. al., "On Size and Magnetics: Why Small Efficient Power Inductors are Rare," *International Symposium on 3D Power Electronics Integration and Manufacturing*, June 2016

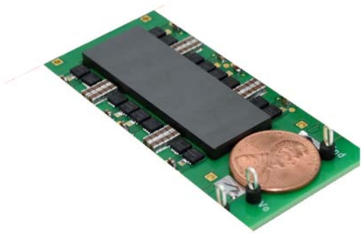
Opportunities for Advances

- **Improvements in design (passive components, circuits and systems), semiconductor devices, integrated circuits / controls, materials and packaging open the door to better power electronics**
- **Much *higher-frequency* converters now possible**
  - **(>10x higher than conventional designs)**
  - **Substantial reductions in energy storage / passives, faster response**
- **Improved passive components and integration**
  - **Better materials, designs, integrated construction**
  - **Alternative energy storage mechanisms (e.g., piezoelectrics)**
- **More *sophisticated* converter designs now possible**
  - **Increase complexity but greatly improve size, efficiency and performance**
- **Better power electronics to advance *applicationse***
  - **Advances enable new electronic functions**

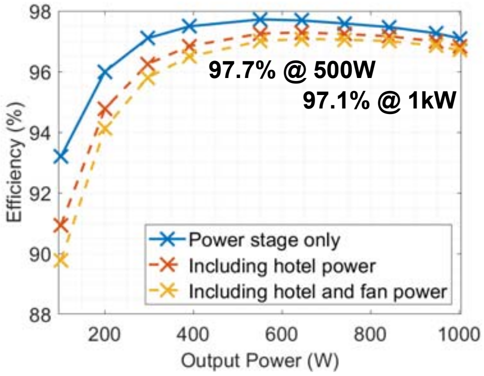
Advancing Frequency

- **Current technology supports power electronics at the kW scale operating at low MHz frequencies**
  - **Example: Datacenter converter, 380 V to 12 V @ 1 kW, η > 97%, f_{sw} ~1 MHz**

High Power Density



High efficiency



M. Ranjram et al, "A 380-12V, 1kW, 1 MHz Converter Using a Miniaturized Split-Phase Fractional Turn Planar Transformer," *TPEL* Feb. 2022.

Advancing Frequency

- Current technology supports power electronics at the kW scale operating at low MHz frequencies
- We are seeking to advance power converter designs to operate at *still much higher* frequencies
  - ❑ e.g., 10+ MHz
  - ❑ in the "High-Frequency" (HF, 3-30 MHz) range

Goals for Frequency Increases

- Goals
  - ❑ Miniaturization (smaller, lighter)
  - ❑ Increased performance (bandwidth,…)
  - ❑ Improved construction / integration
  - ❑ Enable new applications
  - ❑ Reduced cost (eventually…)
- Energy storage requirements vary inversely with frequency: C, L proportional to 1/f

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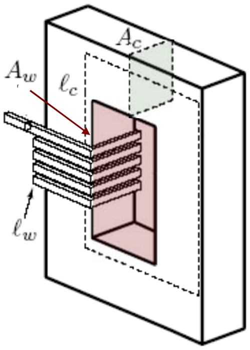

- **Power handling ∝ (linear dimension)^4**
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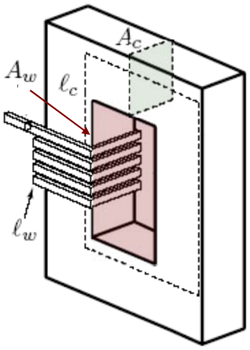

- **In principle, higher frequency can enable greater power handling**
  (or smaller size at constant power)

$$VA = V \cdot I \propto (N f B_0 A_C) \cdot \left(\frac{J_0 A_W}{N}\right) = \boxed{f} \cdot B_0 \cdot J_0 \cdot (A_C A_W)$$

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Frequency Challenges

- **Factors in increasing switching frequency**
  - ❑ **Magnetic component design**
  - ❑ **Power devices**
  - ❑ **Sensing and control circuitry**
  - ❑ **Parasitics and packaging**
  - ❑ **Circuit design**

High-Frequency Magnetics Design

- ***Design of improved high-frequency power magnetics remains a high-impact research challenge***
  - ❑ **Leverage high-frequency magnetic materials (e.g., at low μ)**
  - ❑ **Address skin and proximity effects, especially at high current**
    - **Cu skin depth ~21 μm at 10 MHz, 25˚C**
    - **Litz wire presently less useful above several MHz**
      - ❑ **50 AWG wire diameter is ~25 μm**

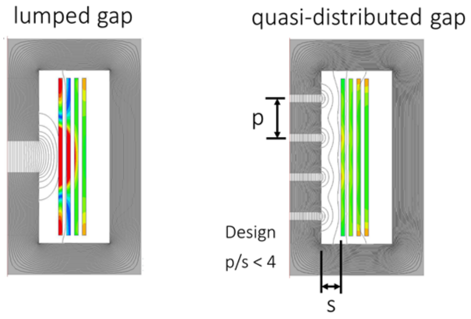
- **High performance designs in the HF range are achievable**

HF Magnetics

- **Must address key challenges that dominate at HF**

Challenge 1: Fringing field loss

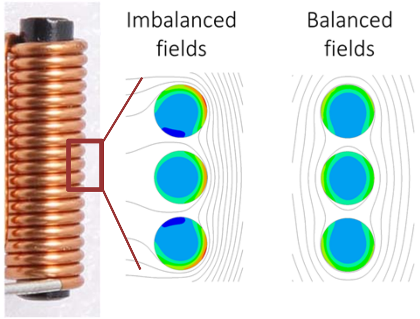
- Fringing fields at energy storage gap lead to eddy current losses (proximity effect)



Solution 1: Use quasi-distributed gaps that do not impose HF fringing fields at conductor

Challenge 2: Current distribution (skin effect)

- Conventional designs have imbalanced H fields that give poor winding utilization

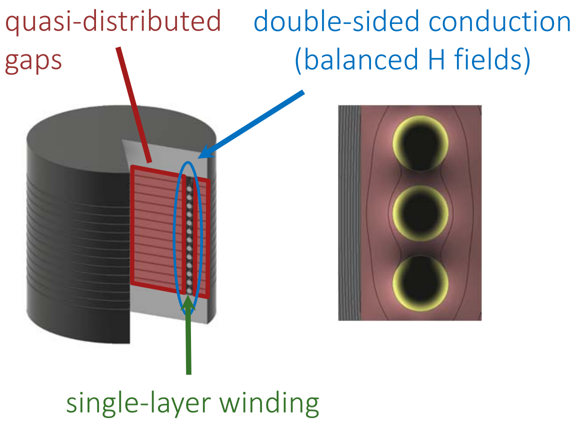


Solution 2: Design a magnetic structure that balances the fields around the windings, enabling better conductor utilization

R. Yang et. al. "A Low-Loss Inductor Structure and Design Guidelines for High-Frequency Applications," *IEEE Transactions on Power Electronics*, 2019.

Example: Low-Loss HF Inductors

- **Leverage quasi-distributed gaps and field balancing for reduced conductor loss**
  - ❑ **Twice the Q of conventional inductors using the same magnetic material**



16.6 uH, 2 A, 3 MHz performance	5/9/10/48 (litz)
Experimental Q	**980**
Simulated Q	1000

R. Yang et. al. "A Low-Loss Inductor Structure and Design Guidelines for High-Frequency Applications," *IEEE Transactions on Power Electronics*, 2019.

Approach scalable to a wide range of applications

R. Yang et. al. "Design Flexibility of a Modular Low-Loss High-Frequency Inductor Structure," *IEEE Transactions on Power Electronics*, 2021.

Example: High-Power High-Frequency Inductor

- **570 nH, 13.56 MHz inductor , Q = 1150 @ 80 $A_{pk,\ ac}$ / 3.9 $kV_{pk,ac}$**
  - ☐ **155 kVA @ 13.56 MHz**
  - ☐ **Fully self-shielded**
  - ☐ **Smaller, more efficient than conventional designs (Q=1150 @ vol = 1.6 l)**
  - ☐ **Designed for use in high-power RF applications (power amplifiers, matching networks)**


Outer core and Inner core


Winding


Inner core + outer core top view

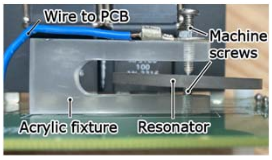

Endcaps

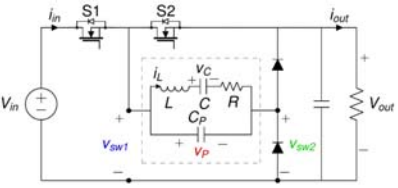

Inductor with Shield

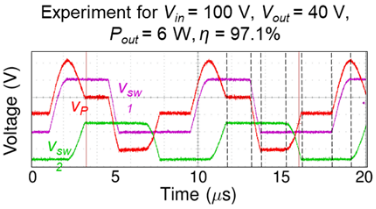
M. Joisher et. al. “High-Performance High-Power Inductor Design for High-Frequency Applications,” *APEC 2024*.

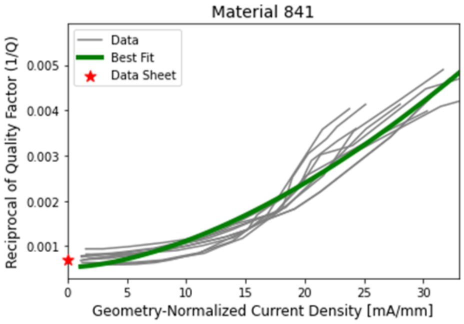
Piezoelectric Power Conversion

- **Store energy mechanically rather than magnetically**
  - ☐ **Potential for very high power density, better scaling to small size**
- **Topologies, operating sequences, controls**
- **Investigation of materials and devices**
- **Packaging, integration and high-power-density designs**





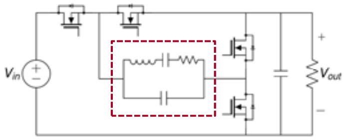




J. D. Boles, et. al. “Enumeration and Analysis of DC-DC Converter Implementations Based on Piezoelectric Resonators," *IEEE Transactions on Power Electronics*, Jan. 2021.
A.K. Jackson , et. al. “Large-Signal Characterization of Piezoelectric Resonators for Power Conversion," *IEEE APEC*, Feb. 2024.

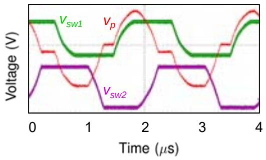
Example Piezoelectric Power Converter

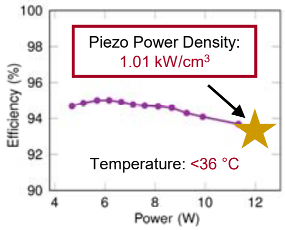
- **Achieves high performance with high power density**
  - ❑ Step-down dc/dc converter at ~ 500 kHz
  - ❑ PR power handling > 1 kW/cm³ at low ΔT




Piezo

V_{in} = 275 V, V_{out} = 150 V, P_{out} = 12 W, 493 kHz





- **We are currently pursuing techniques to achieve still much higher performance**

J. D. Boles et al., "Towards High Power Density with Piezoelectric-Resonator-Based DC-DC Converters," *IEEE Trans. Power Electronics*, March 2023.

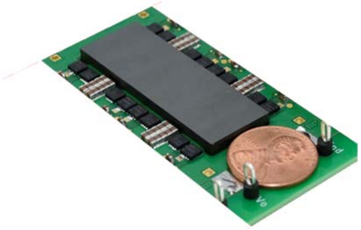
More Sophisticated Designs: "Managed Complexity"

- **Power electronics design has historically sought to maximize simplicity**
- **Advances in semiconductor devices, integrated circuits, controls and passive integration techniques favor adoption of more sophisticated power conversion approaches**
- ***Judiciously* utilize higher complexity to leverage technology advances ("managed complexity")**
  - ❑ Smaller, more efficient and higher-performance solutions
- **We can accomplish this by leveraging:**
  - ❑ Designs that reduce size/loss/impact of magnetic components
  - ❑ Designs / Controls enabling very wide operating ranges at low device and component stress (e.g., via multiple levels, reconfigurability or mode changes)

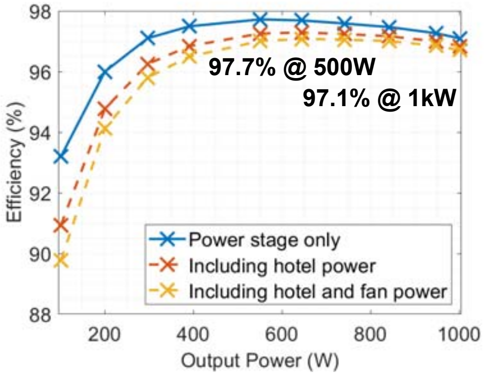
Example: Variable Inverter Rectifier Transformer (VIRT)

- Leverages hybrid magnetic/device hybrid structure to provide a "fractional-turn" transformer for large voltage step-down
  - ❑ Higher efficiency, smaller size than conventional designs
  - ❑ Datacenter converter, 380 V to 12 V @ 1 kW, $\eta > 97\%$, f_{sw} ~1 MHz

High Power Density



High efficiency



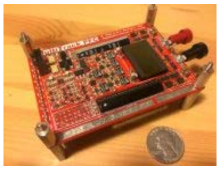
M. Ranjram et al, "A 380-12V, 1kW, 1 MHz Converter Using a Miniaturized Split-Phase Fractional Turn Planar Transformer," *TPEL* Feb. 2022.

Applications

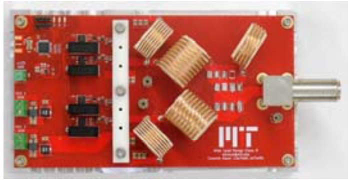
- Power electronics technology to benefit specific applications
  - ❑ Design, manufacturing, control
- Target major system-level improvements
  - ❑ Efficiency, performance, functionality
- Many application areas
  - ❑ Electrified transportation
  - ❑ Computation and communications
  - ❑ Renewables
  - ❑ RF systems

Hybrid magnetic switched-capacitor converter for low-voltage power delivery

HF PFC power supply, 5-10 MHz, 50 W/in^3



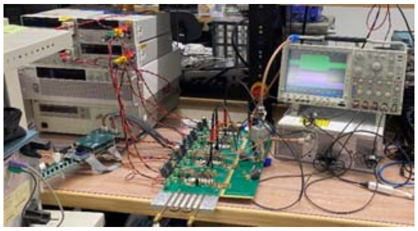
Multitrack HF PFC power supply, 50 W/in^3



13.56 MHz 1 kW High-Frequency Variable Load Inverter (HFVLI)

High-Efficiency Switched-Mode RF Power Systems

- Radio-frequency (RF) power amplifiers / inverters find use in a diverse range of applications
- A need is to better achieve (simultaneously)
  - ☐ Efficiency, speed, power range, load impedance range
- We apply switched-mode techniques for efficient RF power conversion with linear control



5 kW, 13.56 MHz Wide-Range Inverter

Switched-mode rf matching network (1.5 kW @ 13.56 MHz)

A. Bastami et al, “A 1.5 kW Radio-Frequency Tunable Matching Network Based on Phase-Switched Impedance Modulation,” *OJPE*, 2020.
H. Zhang, “Techniques for Efficient Wide-Range Radio-Frequency Power Generation,” MIT PhD Thesis, 2022.