Power Electronics Challenges

- All kinds of systems are limited by energy and how it is controlled and processed

Needs

- Miniaturization (smaller, lighter)
- Higher efficiency (converters and systems)
- Higher performance (better systems)
- Applications (create entirely new system opportunities)

Develop and apply technologies for improved power conversion
Passive Components Dominate

- Passive components dominate size, weight and loss
  - Both power stage and filters are important
  - Magnetics especially challenging
Miniaturizing Magnetics is Difficult

- Scaling laws work against miniaturization of power magnetics
  - Simplified case: power handling (VA) of a fixed-frequency inductor
    - Flux density $B_0$ limited by core loss
    - Current density $J_0$ limited by winding loss

- If we scale dimensions by factor $\varepsilon$
  - Areas scale as $\varepsilon^2$
  - Volumes scale as $\varepsilon^3$
  - Power handling as $\varepsilon^4$, faster than volume

- Power density scales as $\varepsilon$
  - Gets worse at smaller size!

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

Opportunities for Advances

- Improvements in semiconductor devices, integrated circuits / controls, magnetic materials and packaging open the door to better power electronics

- More sophisticated converter designs now possible
  - Increase complexity but greatly improve size, efficiency and performance

- Much higher-frequency converters now possible
  - (10-100x higher than conventional approaches)
  - Substantial reductions in energy storage / passives

- Improved passive components and integration
  - Better materials, designs, integrated construction
  - Alternative energy storage mechanisms (e.g., piezoelectrics)

- New power electronics applications now possible
  - Advances enable new electronic functions
Frequency Increases

- **Objective:** develop technologies to enable miniaturized, integrated power electronics operating at HF (3 – 30 MHz) and above

- **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 magnetic materials at HF & VHF
  - Integration
    - Integration of complete systems
HF Magnetics Example: Low-loss inductors

- Leverage quasi-distributed gaps and field balancing for reduced conductor loss

| Experimental Q | 980 |
| Simulated Q    | 1000 |

16.6 uH, 2 A, 3 MHz 5/9/10/48 performance (litz)

Twice the Q of conventional inductors with the same magnetic materials (Yang, TPEL’21)

High-Power HF Self-Shielded Inductor

- 500 nH, 13.56 MHz Inductor @ 80 $A_{ac}$ / 3400 $V_{ac}$

- Cored inductor for use in high-power rf applications (PAs, TMNs)
- Smaller, more efficient than coreless solenoids, and shielded!
- Prototype demonstrated with $Q\sim 850+$ up to 80 A, 13.56 MHz

Mansi Joisher, MIT 2023
High Efficiency 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, Linearity, Bandwidth, Load Range
- We apply switched-mode techniques for efficient RF power conversion with linear control
  - Outphasing control for linear power amplification
  - Design of switched-mode RF inverters / power amplifiers
- Target wide power and load impedance ranges at high efficiency

5 kW, 13.56 MHz Wide-Range Inverter

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

- **Piezoelectric-based power converters**: 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

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Power density vs. efficiency FOMs for 50 hard PZT materials

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Experiment for $V_{in} = 100$ V, $V_{out} = 40$ V, $P_{out} = 6$ W, $\eta = 97.1\%$

$$FOM_M = \left( \frac{P_{loss}}{P_{out}} \right)^{-1} = 4k_{33}^2Q_m \pi + \frac{\pi^2 \gamma_0}{\pi^2 \gamma_0^2}$$

$$FOM_{APD} = \left( \frac{P_{out}}{A} \right)_{max} = \frac{l_{L_{max}}^2}{4\pi^2 \varepsilon_i}$$

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High-Performance Design Example

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

\[ V_{in} = 275 \text{ V}, \quad V_{out} = 150 \text{ V}, \quad P_{out} = 12 \text{ W}, \quad 493 \text{ kHz} \]

Piezo Power Density: 1.01 kW/cm³
Temperature: <36 °C

A high-performance design example

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Today’s talk by Amanda Jackson is an example of this research direction

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- Temperature: <36 °C

**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

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

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