High-Reliability Ceramic Capacitors to Enable Extreme Power Density Improvements

Jack Flicker, Co-PI, Power Electronics

Sandia National Laboratories

jdflick@sandia.gov

June 11, 2019

Project ID: elt222

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Overview

Timeline

- Start – FY19
- End – FY21
- 25% complete

Goals/Barriers

- Power Density = 100 kW/L
- Power target > 100 kW (~1.2kV/100 A)
- Cost target for drive system ($6/kW)
- Operational life of drive system = 300k miles

- Relative immaturity of new passive materials (performance/reliability)

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY18: $0
- Funding for FY19: $75K

Partners

- ORNL, NREL, Ames Lab
- Project lead: Sandia Labs
  - Greg Pickrell, Todd Monson, Jason Neely, Bob Kaplar

Oak Ridge National Laboratory | NREL National Renewable Energy Laboratory | Sandia National Laboratories

Relevance and Objectives

- Achieving power electronics density will require improvements in all aspects of drive train (switches, passives, etc.)

- Ceramic dielectric capacitors preferred to achieve high power density systems
  - High energy density and reliability
  - Achieving cost metric requires base metal electrodes (reliability issues)
    - Achieving high performance/long lifetime at high T has been elusive

- Instead of addressing performance/reliability through material composition
  - Develop innovative bipolar switching strategy
  - Periodically clear a build-up of oxygen vacancies at electrode surfaces
  - The dynamics of this strategy will be explored and optimized
- Survey current state-of-the-art ceramic capacitors and identify technology gaps

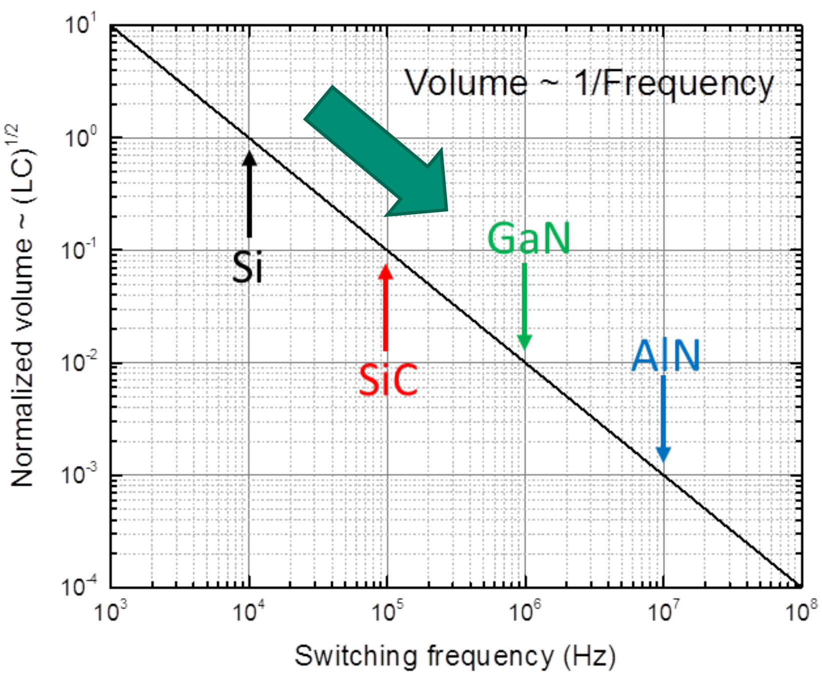
<u>Power Electronics and Drive Train Goals</u>

- Power Electronics Density = 100 kW/L
- Power Electronics target > 100 kW (~1.2kV/100 A)
- Power Density target for drive system = 33kW/L
- Cost target for drive system ($6/kW)
- Operational life of drive system = 300k miles

Approach: Capacitors for Power Electronics

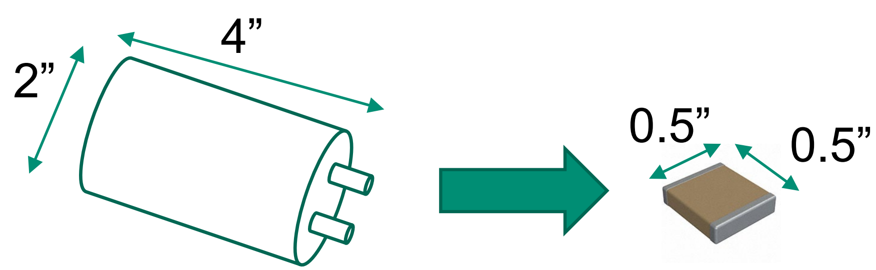
- Ceramic capacitors traditionally not used in high power electronics applications due to cost considerations
  - Scale significantly with size due to precious metal electrodes
  - Base metal electrodes can further reduce costs
    - Historically have reliability issues

- High frequency switching system reduces electrical size of capacitors



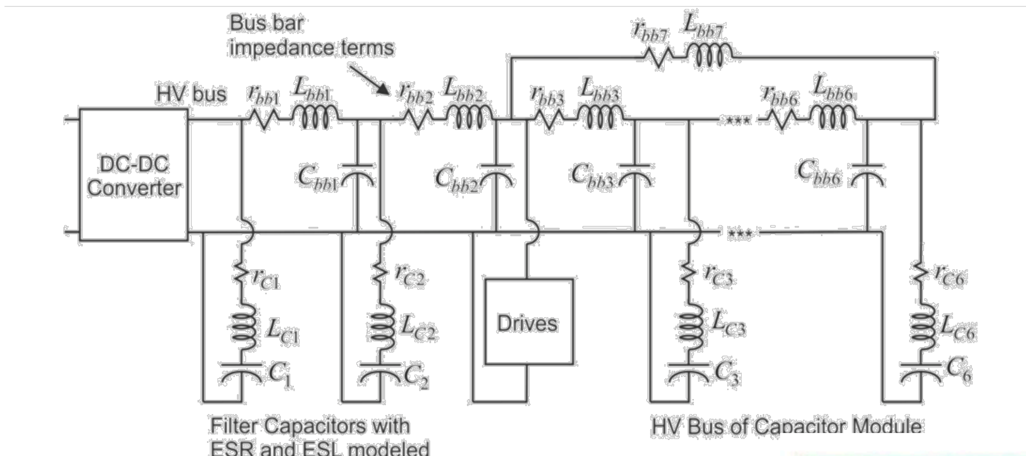
For a unipolar inverter:

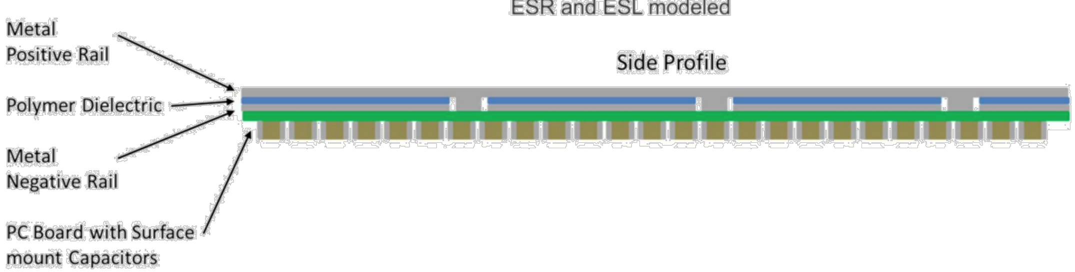
$$V_{pk}^{ripple} = \frac{V_{bus}}{32 \cdot L \cdot C \cdot f^2}$$

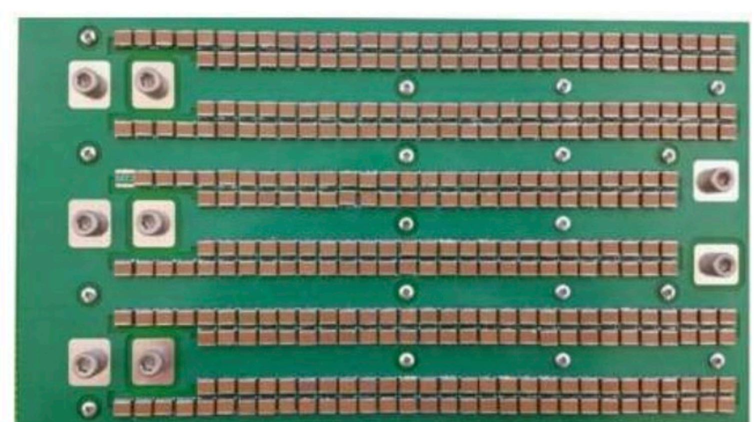


Approach: Capacitors for Power Electronics

- High frequency switching system reduces electrical size of capacitors
  - Use of distributed, small capacitors on DC bus enable use of ceramic capacitors at reasonable cost
  - Increase in power density through elimination of large capacitors

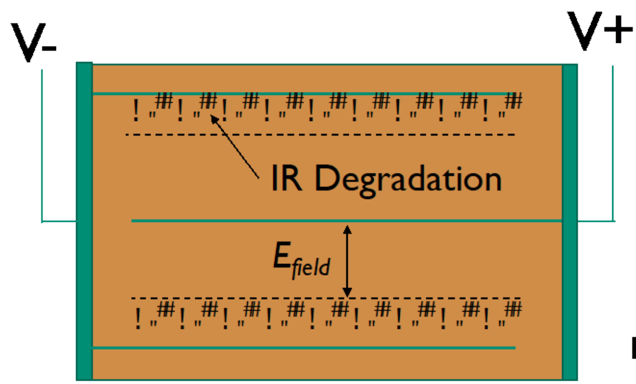


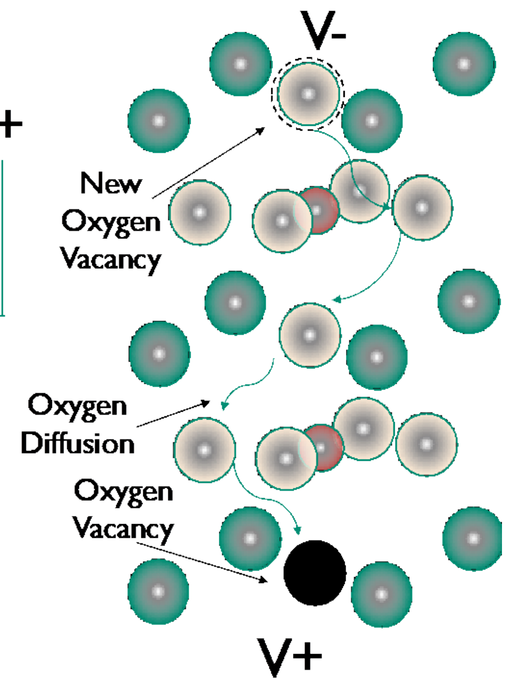




J. Stewart, J. Neely, J. Delhotal, and J. Flicker, "DC link bus design for high frequency, high temperature converters," in *2017 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2017, pp. 809-815: IEEE.

Approach: Capacitors for Power Electronics

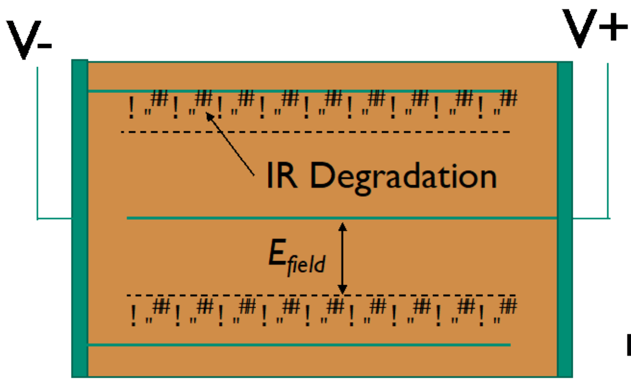


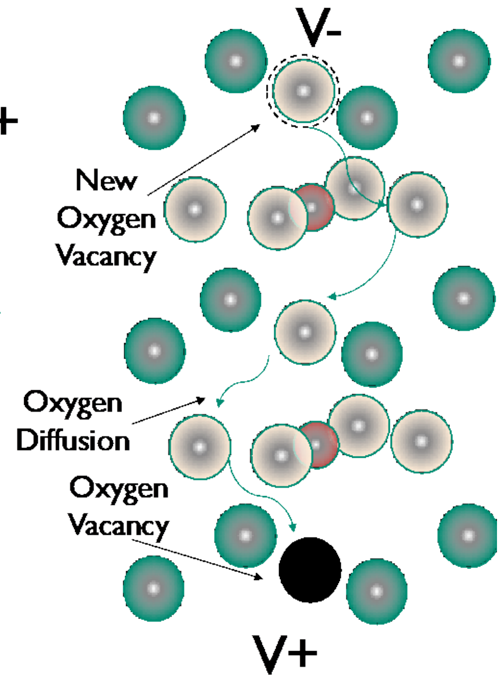


- Base metal electrodes (Ni) require reducing environment during sintering to avoid oxidation
  - → oxygen vacancies are created in the ceramic

- Under applied voltage, at temperature oxygen vacancies migrate and preferentially getter at electrode/dielectric interface
  - Results in loss of insulation resistance (IR) → high DC leakage
  - Increased leakage raises operational temperature, creating more vacancies
  - Accelerating failure mechanism

Approach: Capacitors for Power Electronics



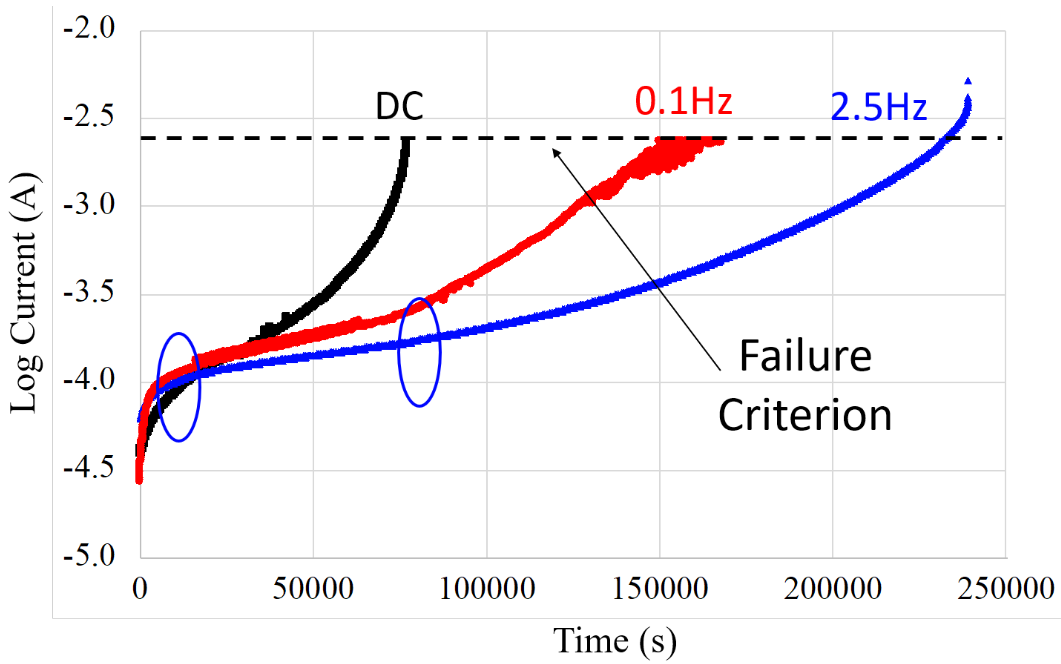


- Instead of altering fabrication or materials properties
  - Targeting oxygen vacancy transport to electrodes
  - By altering the electric field from a DC field to an AC field, we can periodically "flush" oxygen vacancies at electrodes

- Exploring the development of a bipolar switching technique to periodically alter direction of oxygen vacancy travel
  - Testing to identify possible gains in ceramic capacitor reliability
  - Evaluating possible usage in electric drive

Technical Accomplishments and Progress-Passives

- Carried out preliminary bipolar switching testing
  - Tested capacitor degradation at DC bias, and bipolar switching of 0.1 and 2.5 Hz
  - Applied ~10x V_{rated} at 125°C **above** T_{rated}
- Preliminary results show bipolar switching can significantly increase time to failure
  - Demonstrated ~4x lifetime increase with a 2.5 Hz bipolar switching scheme compared to DC



Collaboration

NREL- Novel high density integration and thermal management

Oak Ridge – Implementation into traction drive

Proposed Future Research

- Survey current state-of-the-art ceramic capacitors and identify technology gaps

- Perform further experiments on bipolar switching
  - Longer term testing (less acceleration)
  - Larger capacitors appropriate for power devices

- Evaluate bipolar switching scheme compatibility with drive train technologies

Any proposed future work is subject to change based on funding levels

Summary

- Carried out preliminary bipolar switching testing on ceramic capacitors

- Demonstrated ~4x lifetime increase with a 2.5 Hz bipolar switching scheme compared to DC