Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

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PV Inverter Performance and Reliability: What is the Role of the Bus Capacitor?

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Postdoctoral Appointee

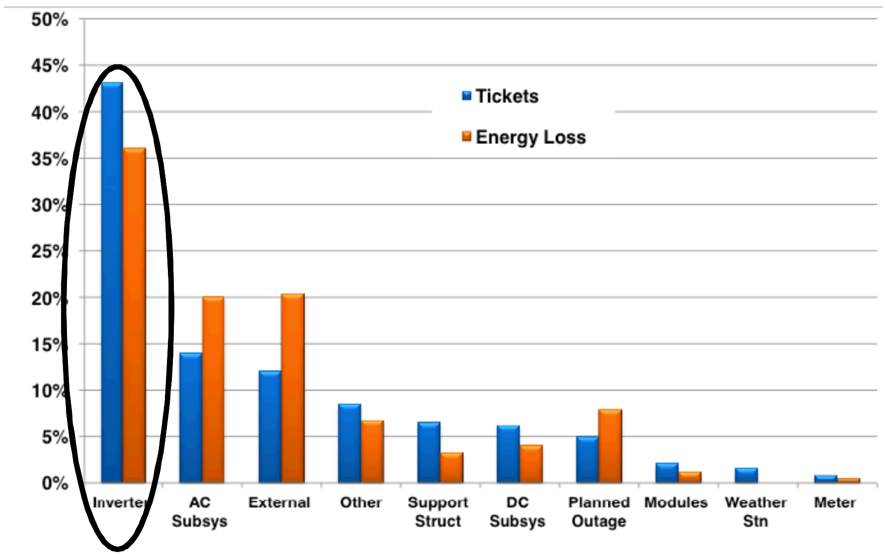
Wednesday, October 23, 2013

"Exceptional Service in the National Interest…"

Outline

- Bus Capacitors in PV Inverters
  - Why do we need a bus capacitor?
    - How does it affect PV array operation?
  - What types of capacitors are used?
    - Electrolytic
    - Metallized Thin Film
  - How are capacitors sized?
    - For capacitance
    - For ESR
    - For ringing
    - For lifetime
- Sandia's Experimental Test Setup
  - What factors affect capacitor lifetime?
  - How can we safely test large capacitors?
- Future Work
- Summary

Bus Capacitors in PV Inverters



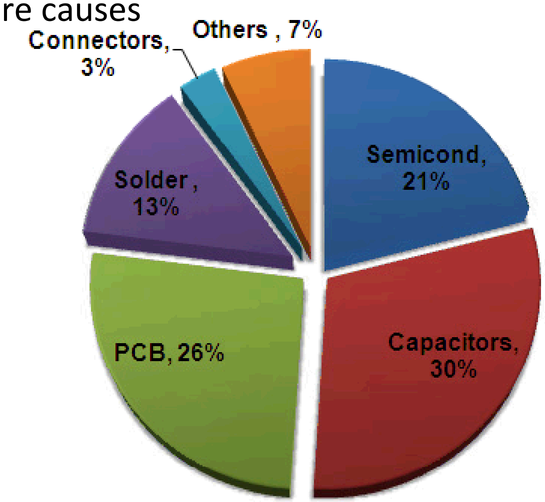
- Most research focuses on cost reductions in modules
  - BOS now 8-12% of lifetime PV cost ($0.25/W)
  - Well above DOE goal of $0.10/W by 2017

- One reason Reliability
  - Module lifetimes ~30 years with MTBF 500-7,000 years
  - Inverter lifetimes <<30 years with MTBF 1-16 years
  - Repair/replace multiple times over system lifetime
  - SunEdison says inverter 36% of energy losses from inverter

- Inverters are complicated machines
  - Power Conditioning
  - Grid Monitoring
  - Array reporting/monitoring
  - VAR management
  - Islanding protection, etc.

- Must endure harsh environments (humidity, corrosive) with large temperature cycles (ambient and power handling)

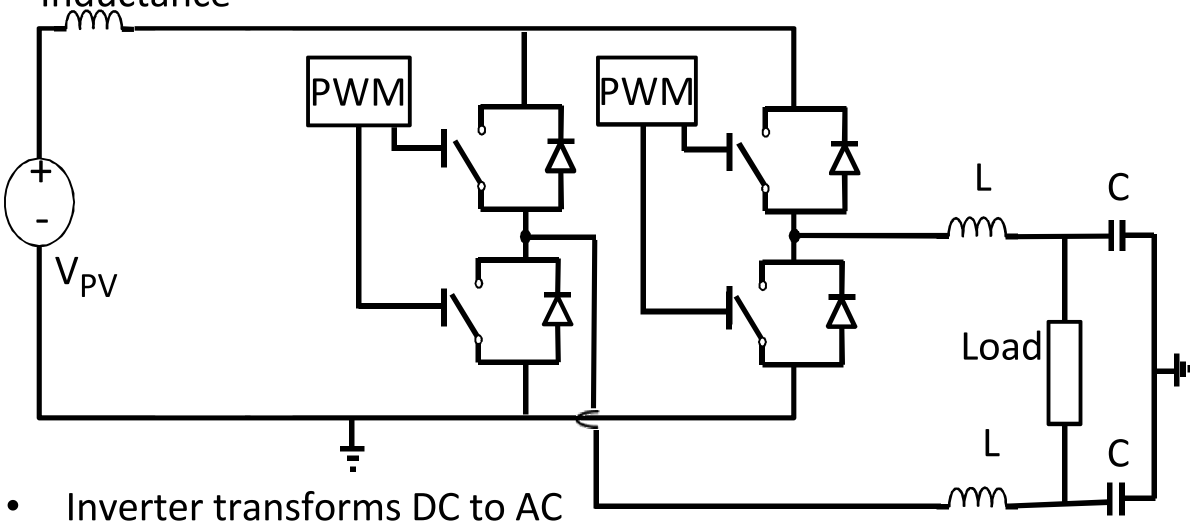
- Much disagreement about specific failure mechanisms, but capacitors generally agreed to be one of top three failure causes

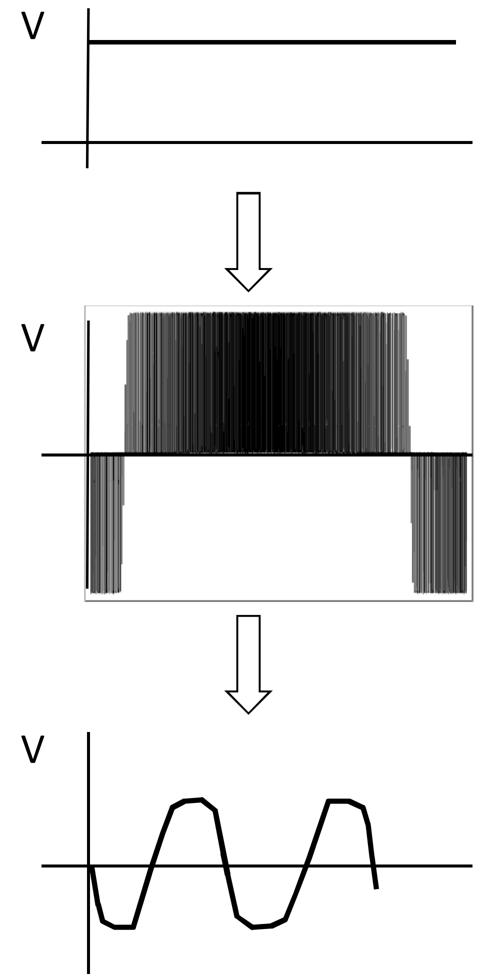


A. Golnas, "PV System Reliability: An Operator's Perspective," in 38th Photovoltaic Specialists Conference, Austin, TX, Jun. 2012, pp. 1–32.

U.S.Dept. of Defense, *Reliability Prediction of Electronic Equipment Military Handbook 217F, Feb. 28, 1995.*

Bus Capacitors in PV Inverters





- Inverter transforms DC to AC
- Simplest design is pulsed width modulation (PWM) unipolar inverter in H-bridge configuration ($V_{PV} \longrightarrow \pm V_{PV}$, 0)
- Switches: High power IGBT, but moving toward wide bandgap (SiC, GaN) materials
- PWM signal: Low frequency (50/60 Hz) carrier wave compared to high frequency (5-20 kHz) triangle wave
- Switch signal to AC with LC filters
- Source inductance interacts with switches to induce **voltage/current ripple on DC bus**

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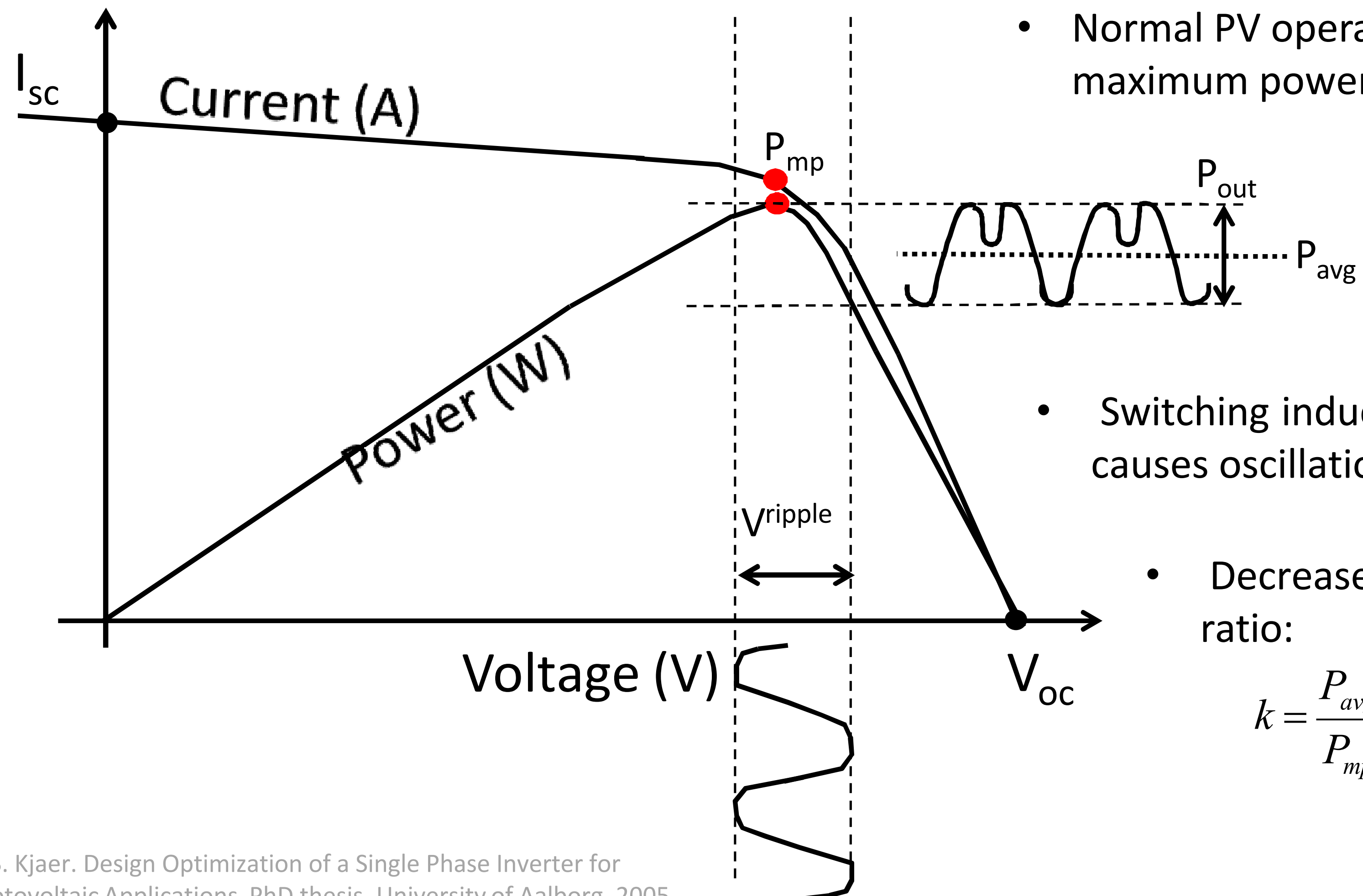
Effects of Bus Capacitors Degradation

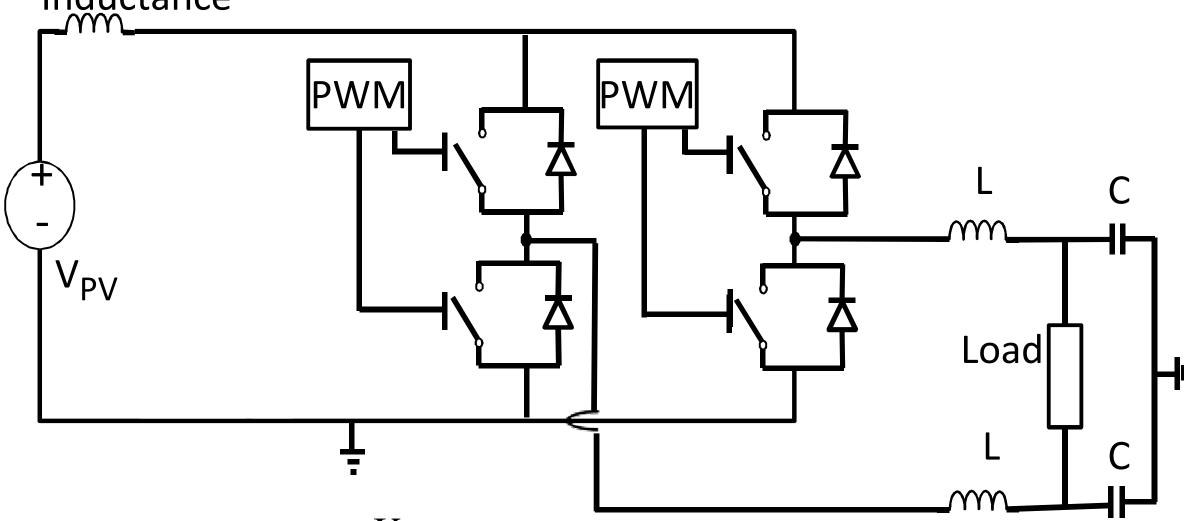


- Normal PV operation is on maximum power point (P_{mp})
- Switching induced voltage ripple causes oscillation around P_{mp}
- Decrease in utilization ratio:

$$k = \frac{P_{avg}}{P_{mp}} << 1$$

S. B. Kjaer. Design Optimization of a Single Phase Inverter for Photovoltaic Applications. PhD thesis, University of Aalborg, 2005.

Simulation Setup



$$V_{p-p}^{ripple} = \frac{V_{PV}}{32 \cdot C_{bus} \cdot L \cdot f_{PWM}^2}$$

where:

V_{PV} is the solar panel DC voltage,
C_{bus} is the capacitance of the bus capacitor,
L is the inductance of the filter inductors,
f_{PWM} is the switching frequency.

M. Salcone and J. Bond. IEEE International Electric Machines and Drives Conference (IEMDC), pp 1692–1699, 2009.

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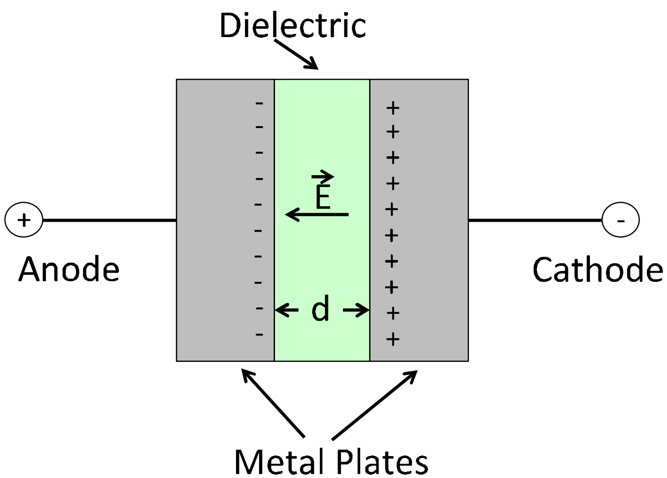
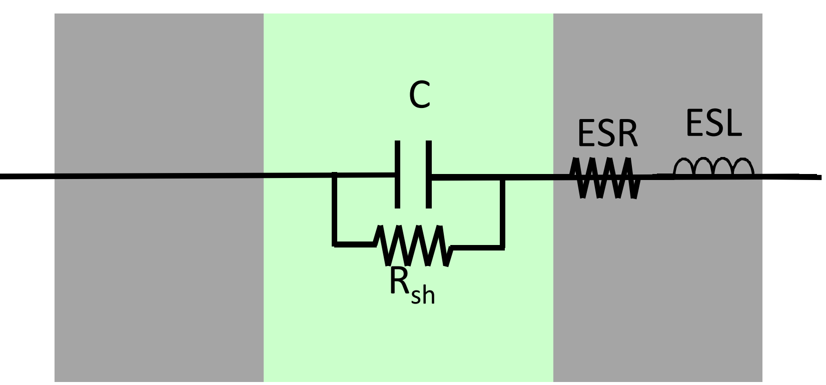
Bus Capacitors in PV Inverters

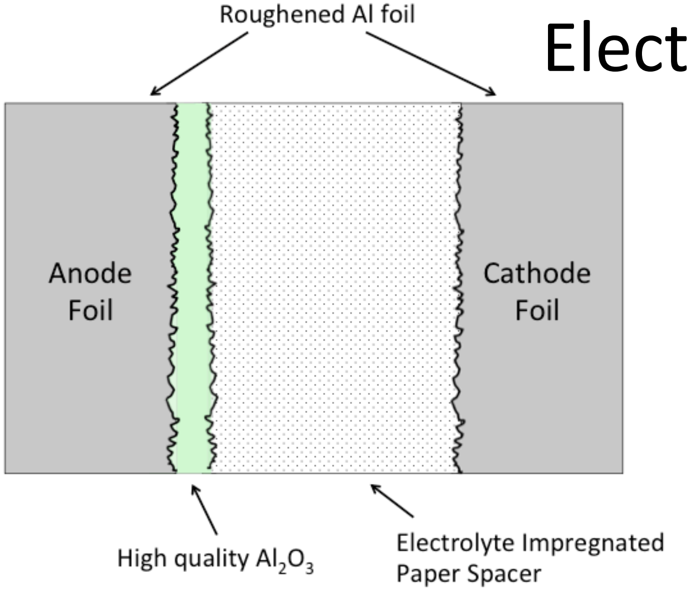




- Alters current flow to keep applied voltage constant
- Ideal capacitor prevents charge from flowing during charging
- All energy is stored in the electric field
- Capacitor discharges with no resistance
- Dielectric does not prevent all current flow during charging
- Leaky dielectric has finite shunt resistance (R_{sh})
- Bypasses the dielectric capacitance
- During discharge current flow, pins, tabs, electrolyte (if present), prongs, etc. have nonzero resistance in series with capacitance
- Equivalent series resistance (ESR)
- Capacitor does store some energy in magnetic field
- Equivalent series inductance (ESL)
- Small (~5nH) so usually ignored in circuit analysis

Types of Capacitors

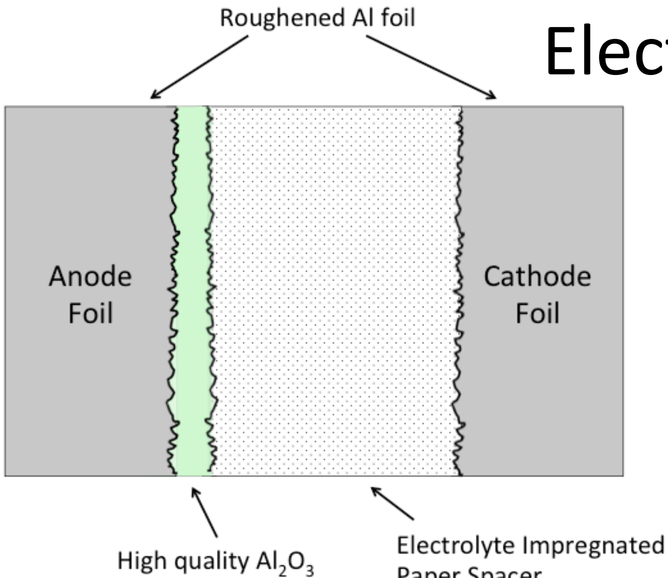
Electrolytics - Construction

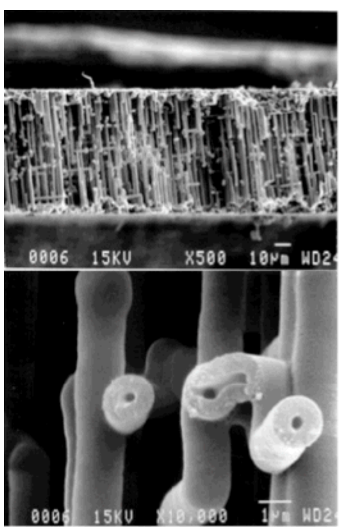


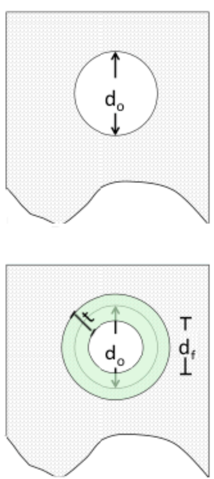
- Electrolyte impregnated paper layer sandwiched between two highly roughened metal foils
- Thin, very high quality oxide grown directly onto the anode foil
  - acts as the dielectric
  - formed via anodization of Al foil
  - interface with excellent adhesion and few defects
- An electrolyte/foil system acts as the cathode
  - electrolyte used to:
    - maintain integrity of dielectric via ion current
    - provide good contact to fragile oxide surface

Types of Capacitors

Electrolytics - Construction



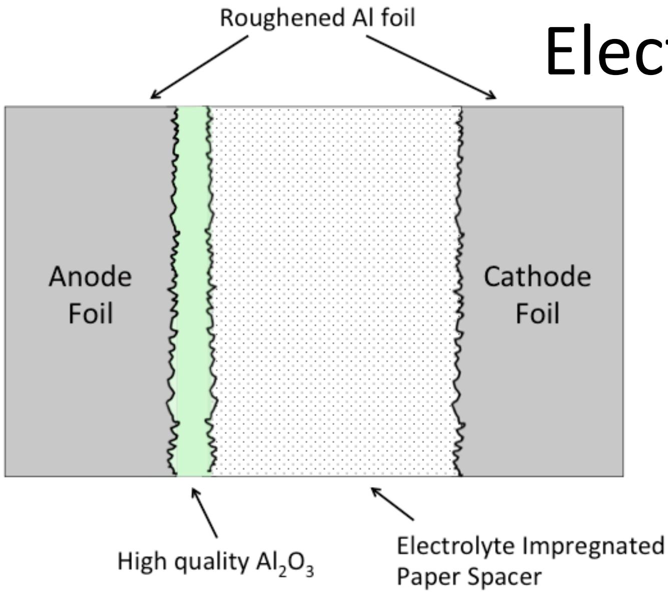




- Foils roughened via etching
  - forms parallel tunnels perpendicular to surface
  - increases area of foil by ~100x
  - large increase in capacitance/volume
- Low voltage applications have small, dense tunnels with thin oxide
- High voltage application foils have larger tunnels with thick oxide
- Tunnel diameter optimized for the needed oxide thickness
  - too narrow, oxide clogs tunnel, does not add to capacitance
  - too large, oxide doesn't fill tunnel, capacitance not maximized
- Oxide layer present on one of the electrode foils
  - operational polarity
  - voltage reversal reduces Al_2O_3 back to Al
  - capacitor will short circuit, heats capacitor
  - can will vent due to electrolyte vapor pressure
  - reversed voltage of only 1-1.5V for ~1s

Types of Capacitors

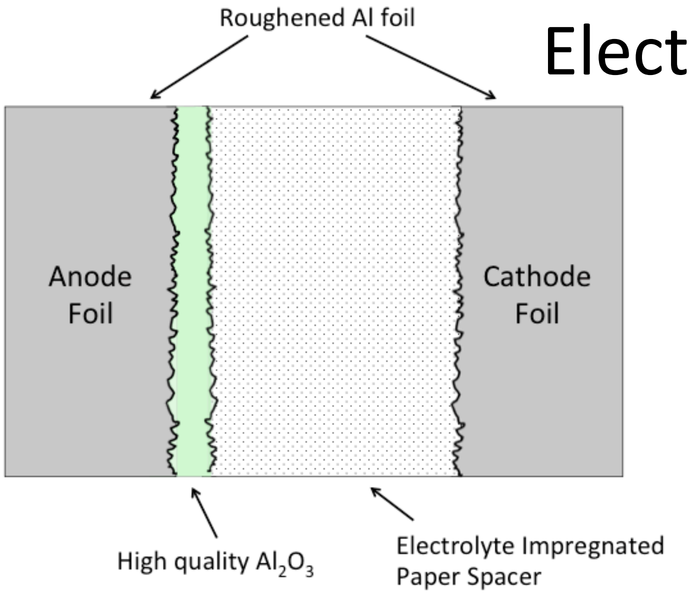
Electrolytics - Construction



- Electrolyte formulation/quality controls capacitor lifetime
  - majority of ESR due to the electrolyte solution
  - proprietary formulations are closely guarded secrets
  - major reason for premature failure → capacitor plague
- Two Types of electrolyte
  - Aqeous and non-aqueous
- Non-aqueous electrolytes
  - Small percentage of water content
  - Usually contains weak acid, salt of weak acid, and solvent
- Aqueous electrolytes
  - larger percentage water content (~75-85%)
  - also ionic conductor, sugars, solvents, evaporation retarders, thickning agents, buffers, and gas preventers (gatters)
  - preferred due to cost and oxide reformation potential

Types of Capacitors

Electrolytics - Construction



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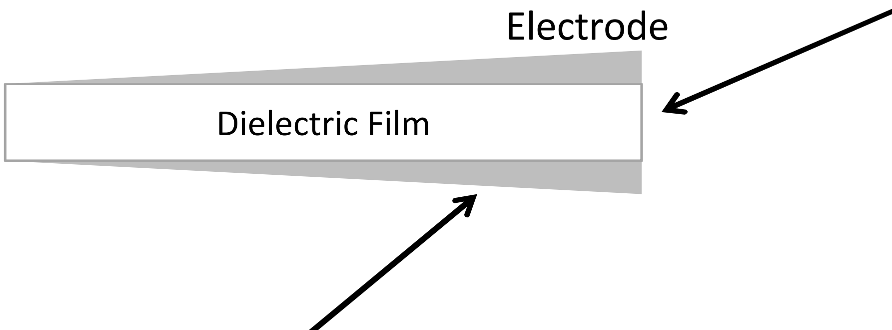
- Water key to oxide reformation
  - leakage current drives H_2O/Al reaction to reform compromised Al_2O_3
  - consumes H_2O while producing H_2 → Leads to increased ESR
  - production of H_2 eventually lead to failure (can designed to vent at ~7atm)

- Overall, presence of H_2O can yield:
  - higher quality dielectric layer
  - better electrical performance
  - at the expense of high temperature performance and decreased lifetime

Types of Capacitors

Metallized Thin Film - Construction



- Metallized on both sides to form electrodes
  - Al or Zn metal (or alloy)
  - deposited via evaporation or PVD
  - thickness of ~20-100nm, graded to reduce ESR
  - electrical connections by end spraying (schooping) metal to the exposed edges

- Metallization layer is symmetrical on both sides of the dielectric
  - nonpolar
  - overvoltage and voltage reversals are typically accepted without affecting lifetime

- Dielectric plastic film 10-100µm in thickness
  - future work in thinner (~5µm) dielectrics
  - two layers of film a wound tightly together

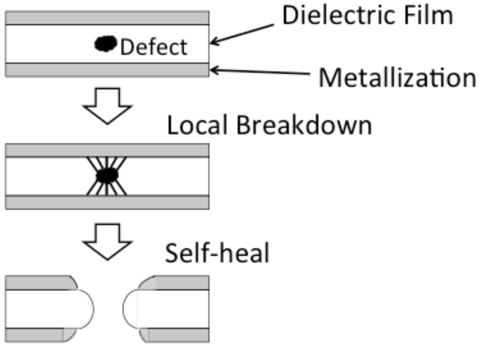
- Variety of plastic film dielectrics
  - polyester (PET), polystyrene, mylar, polyimide, polycarbonate, and teflon

- Majority of high performance capacitors utilize biaxially oriented polypropylene
  - low cost, low resistance and highly consistent

- Impregnated with oil or epoxy
  - non-swelling, low viscosity, low surface tension, highly oxygenated liquid
  - increases breakdown strength, HV behavior, and lifetime

Types of Capacitors

Metallized Thin Film - Failure



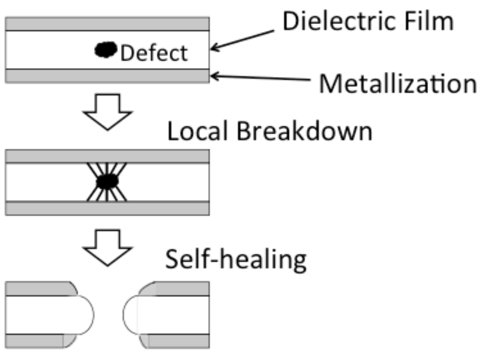
- Originally, poor lifetime characteristics due to local imhomogeneities in dielectric
  - leads to local, then global, failure
  - lifetime improved by thinning metal electrodes to nm
  - allows for local failure without global failure
    process known as **self-healing or clearing**

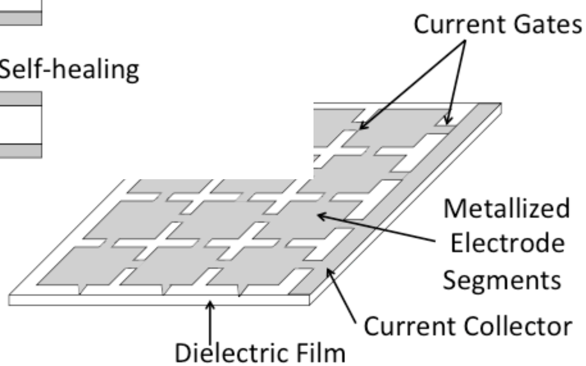
- Presence of defects lowers capacitor breakdown voltages
  - during operation, capacitor locally short
  - quickly heats via Joule heating, thin electrode layer is vaporized
  - locally isolates short and creates small pinhole (~5-8 mm^2)

- Capacitor suffers a small decrease in capacitance
  - lifetime is increased by avoiding catastrophic failure.

Types of Capacitors

Metallized Thin Film - Failure





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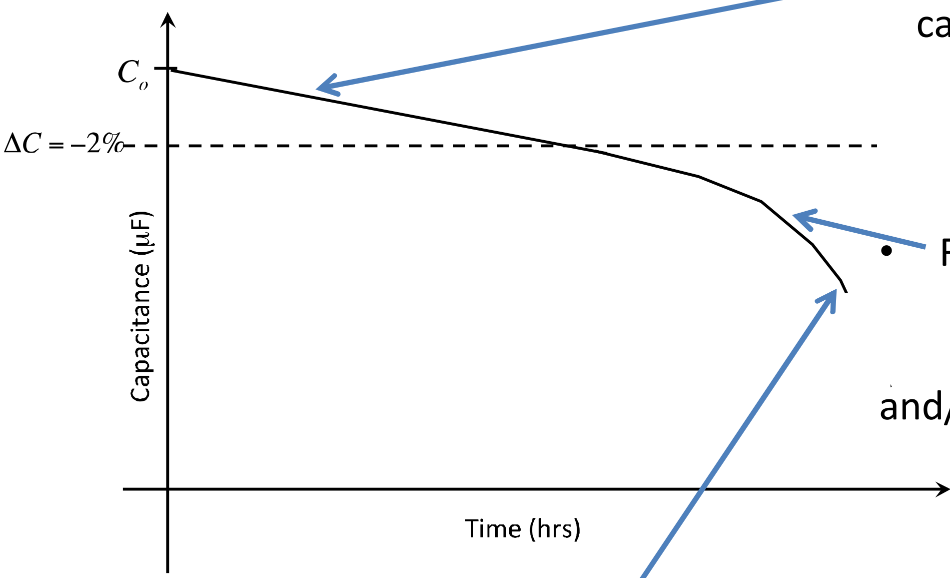
- Clearing behavior should stop catastrophic failure
  - for very large localized defects, short may be large enough entire capacitor can catastrophically fail

- Modern thin film capacitors use a patterned electrode
  - larger patches of electrode separated by thinner current gates
  - normal clearing behavior, current gates unaffected
  - for large failures, the current gates evaporate, isolating the failed segment

Types of Capacitors

Metallized Thin Film – Failure Modes



- For each clearing event, small decrease in the overall capacitance
  - gradual degradation until falls below spec
  - known as soft failure

- Formation of gas inside the can
  - pressure increases inside casing
  - increases degradation via surface erosion, tracking, and/or polymer decomposition
  - localized failure leaves neighboring areas vulnerable

- Clearing event increases, conductive metallized vapor
  - may congregate in air voids or winding edges
  - eventually, voids become conductive
  - catastrophic failure either by:

    vapor pressure ruptures can or,

    flash discharge in the voids/edges

Metallized thin film capacitors are thought to be **intrinsically safer** than electrolytics

But catastrophic failure can **still occur** if used past soft failure

Types of Capacitors

Electrolytic Capacitors

Advantages
- Well characterized behaviors and lifetimes
- Relatively inexpensive ($0.0045/µF, linear)
- Large capacitance per volume (Compact)

Disadvantages
- Often fail catastrophically
- Polar
- Release H_2 gas
- Must be oversized to handle ripple
- High leakage currents
- Main degradation mechanism is ESR increase

Thin-Film Capacitors

Advantages
- "Safer" with longer lifetimes
- Small ESR
- Degradation failure
- Non-polar

Disadvantages
- Not very well characterized
- Relatively expensive ($/µF is exponential)
- Thin metal limits peak current and energy density
- Low operation temperatures (faster degradation and polymer phase transitions)
- Low capacitance per volume (Bulky)

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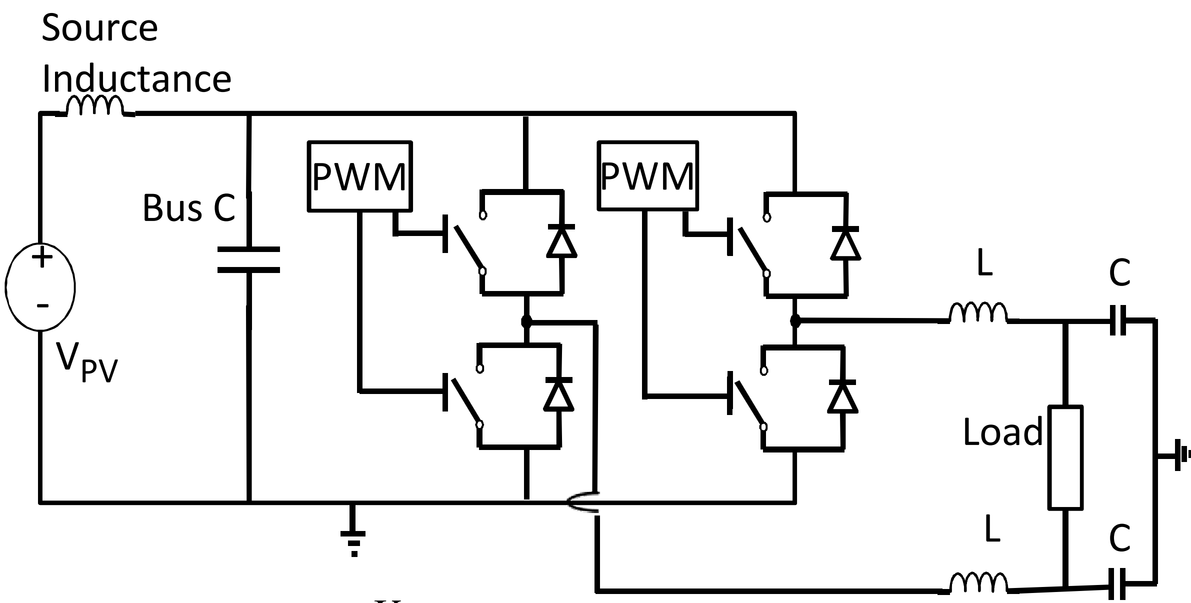
Sizing Bus Capacitors

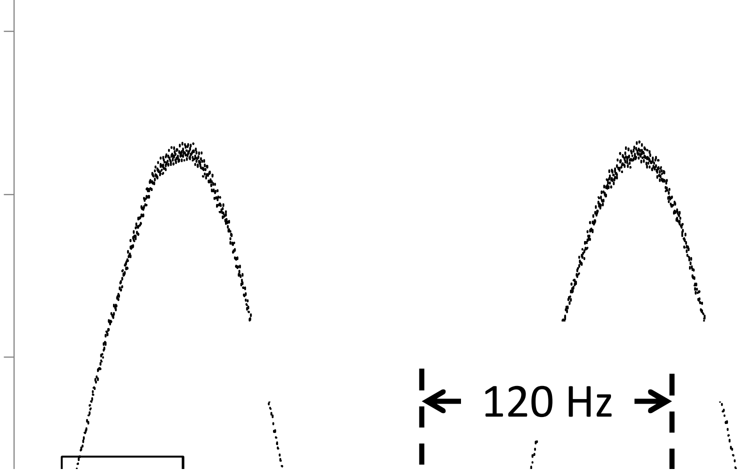


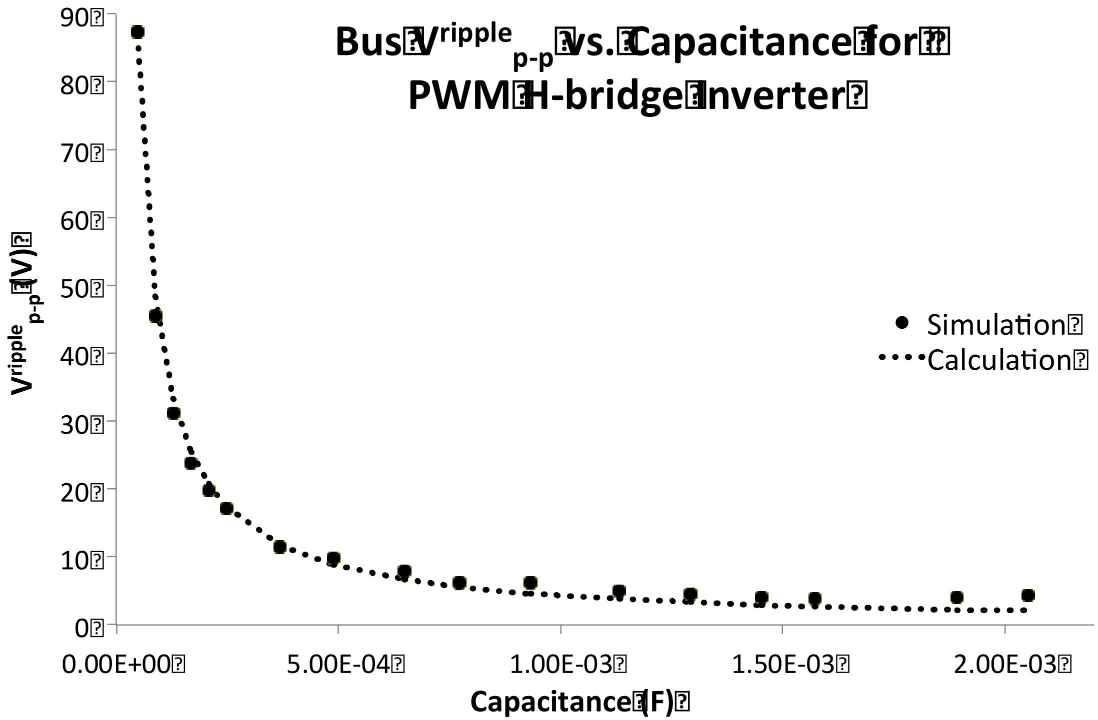
$$V_{p-p}^{ripple} = \frac{V_{PV}}{32 \cdot C_{bus} \cdot L \cdot f_{PWM}^2}$$

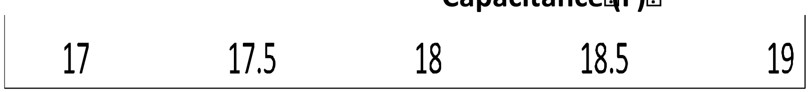
where:
V_{PV} is the solar panel DC voltage,
C_{bus} is the capacitance of the bus capacitor,
L is the inductance of the filter inductors,
f_{PWM} is the switching frequency.

- Voltage ripple much larger for single phase inverters
- 3-Phase inverters have much ripple cancellation due to circuit topology
- Smaller number of large capacitors vs. large number of small capacitors

M. Salcone and J. Bond. IEEE International Electric Machines and Drives Conference (IEMDC), pp 1692–1699, 2009.







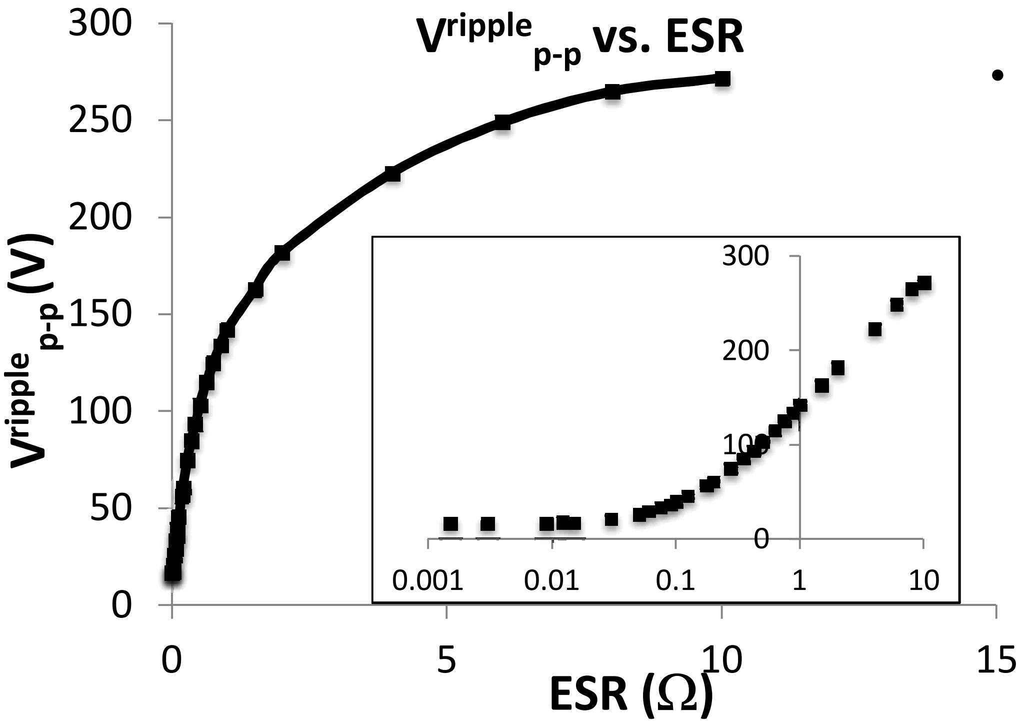
icitors

- Bus and load voltage of a simulation shows ripple on DC bus for 250μF capacitor
- AC ripple with frequencies 120Hz and 10kHz due to IGBT switching
  - Much easier to filter
- Ripple as a function of C_{bus} shows 1/C dependence

$$V^{ripple}_{p-p} = \frac{V_{PV}}{32 \cdot C_{bus} \cdot L \cdot f^2_{PWM}}$$

- Diminishing returns for C_{bus}>500μF
- Typically tens of volts (peak to peak) in inverter circuit

Sizing Bus Capacitors



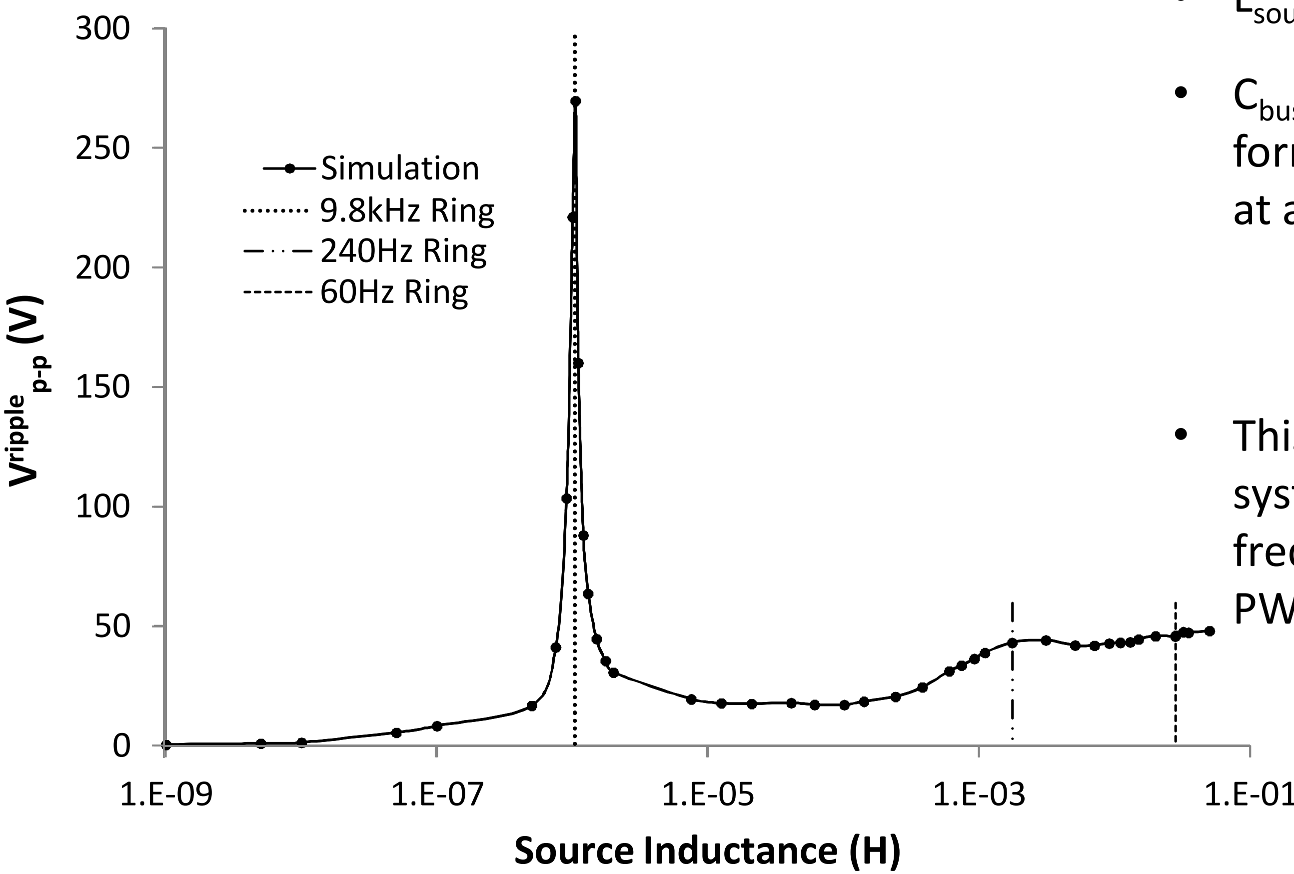
$$\frac{ESR}{ESR_o} = \frac{1}{1 - k \cdot t \cdot e^{\frac{-E_a}{T}}}$$

k is a constant dependent on the capacitor design (~1.77)
E_a is an activation energy (≈4700 eV)

- Large increase in ripple voltage for ESR values above ~100mΩ
  - Electrolytic capacitors have higher ESR values (~20mΩ, but up to 100mΩ for HV capacitors)
  - Metallized thin film have lower ESR (~1mΩ)
- ESR is primary degradation mode of capacitors
  - In electrolytics, ESR increases due to electrolyte evaporation or H_2O consumption due to oxide reforming
  - Over time, ESR of electrolytic capacitors follow a linear-inverse relation

G. Rhoads and A. Smith, IEEE Electronic Component Conference, 1984, p. 156.

Sizing Bus Capacitors



- Correctly sizing C_{bus} is important, but not the only consideration.
- L_{source} must be considered
- C_{bus} and L_{source} will interact to form LC oscillator which can ring at a resonant frequency:

$$f_{ring} = \frac{1}{2\pi\sqrt{L_{source}C_{bus}}}$$

- This can be very detrimental to system performance if the ringing frequency is a multiple of the PWM carrier or triangle signal

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Capacitor Lifetime

$$L(T, I, V) = L_o K_T K_R K_V$$

Electrolytics

Activation energy assumed to be oxide reduction

"rule of thumb": lifetime will halve every 10^{o}C above rated operation temperature

Metallized Thin Film

"rule of thumb": lifetime will halve every 8^{o}C above rated operation temperature

Temperature Acceleration Factor

$$K_T = \frac{L_1}{L_2} = \frac{K e^{\frac{-E_a}{k_B T_1}}}{K e^{\frac{-E_a}{k_B T_1}}}$$

$$= e^{\frac{E_a}{k_B T_2} - \frac{E_a}{k_B T_1}}$$

$$= e^{\frac{E_a}{k_B}\left[\frac{1}{T_2} - \frac{1}{T_1}\right]}$$

$$= e^{\frac{E_a}{k_B}\left[\frac{\Delta T}{T_1 T_2}\right]}$$

Usually data fit to Arrhenius relationship

Most important acceleration factor, esp. for smaller capacitors

Capacitor Lifetime

$$L(T,I,V) = L_o K_T K_R K_V$$

Ripple Acceleration Factor

$$\begin{aligned} T_c &= T_a + \Delta T \\ &= T_a + P \cdot R_{th} \\ &= T_a + I^2_{ripRMS} \cdot ESR(f,T_c) \cdot \frac{1}{h \cdot S} \end{aligned}$$

Electrolytics

Larger ESR, so more susceptible to heating due to ripple

Metallized Thin Film

Smaller ESR, less heating due to ripple

Gradual internal heating of the capacitor which is not accounted from by K_T

Dependent on ESR and thermal resistance

More important for larger capacitors

Highly dependent on manufacturer

Capacitor Lifetime

$$L(T,I,V) = L_o K_T K_R K_V$$

Voltage Acceleration Factor

$$K_V = \frac{V_{applied}}{V_{rated}}^{-N}$$

Electrolytics

N is typically between 0 and 6

Metallized Thin Film

N is typically between 10 and 20

Large due to direct electron impacts causing crosslinking or scission of polymer chains

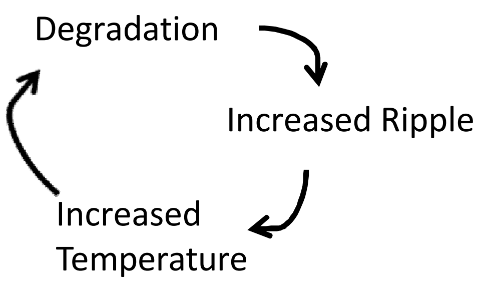
More of an effect for larger capacitors

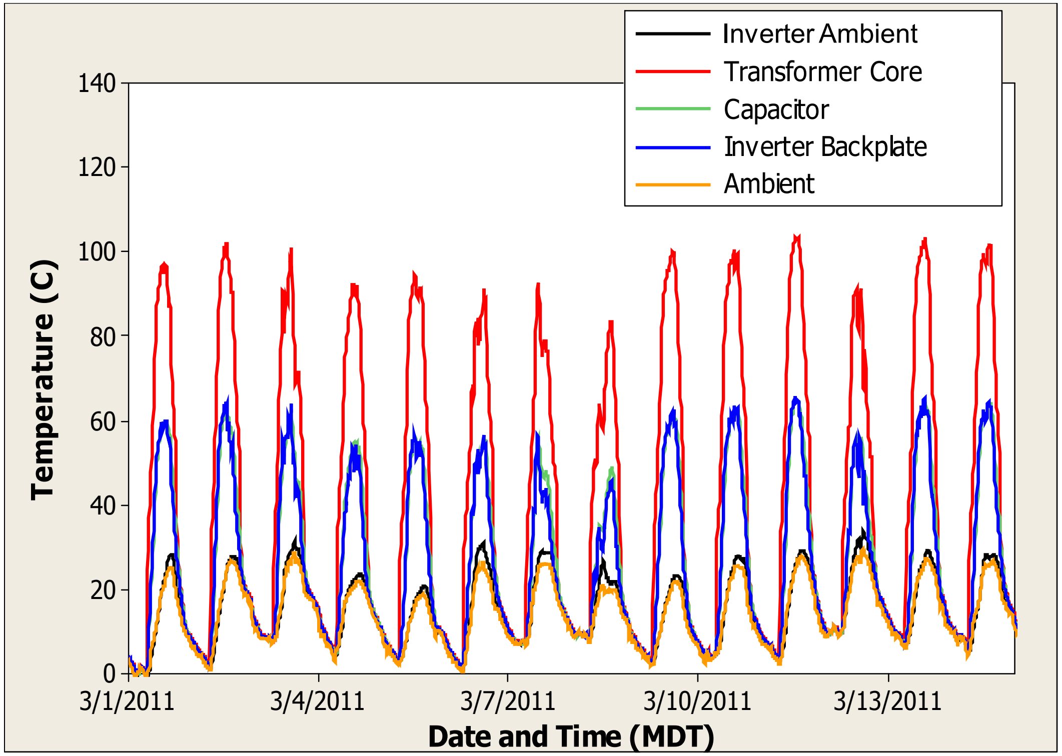
N is an exponential fit that varies by manufacturer and packaging

NB: Generic lifetime equations differ from manufacturer to manufacturer and take into account both theoretical and empirical relationships depending on capacitor construction and design.

Capacitor Lifetime

- Doesn't account for internal heating effects (ripple current, ESR) over time
  - Positive feedback mechanism





*Courtesy Rob Sorensen

- Would only expect long lifetimes for capacitor sized (for ripple current, voltage, and temperature) *well above* actual working condition

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Capacitor Lifetime

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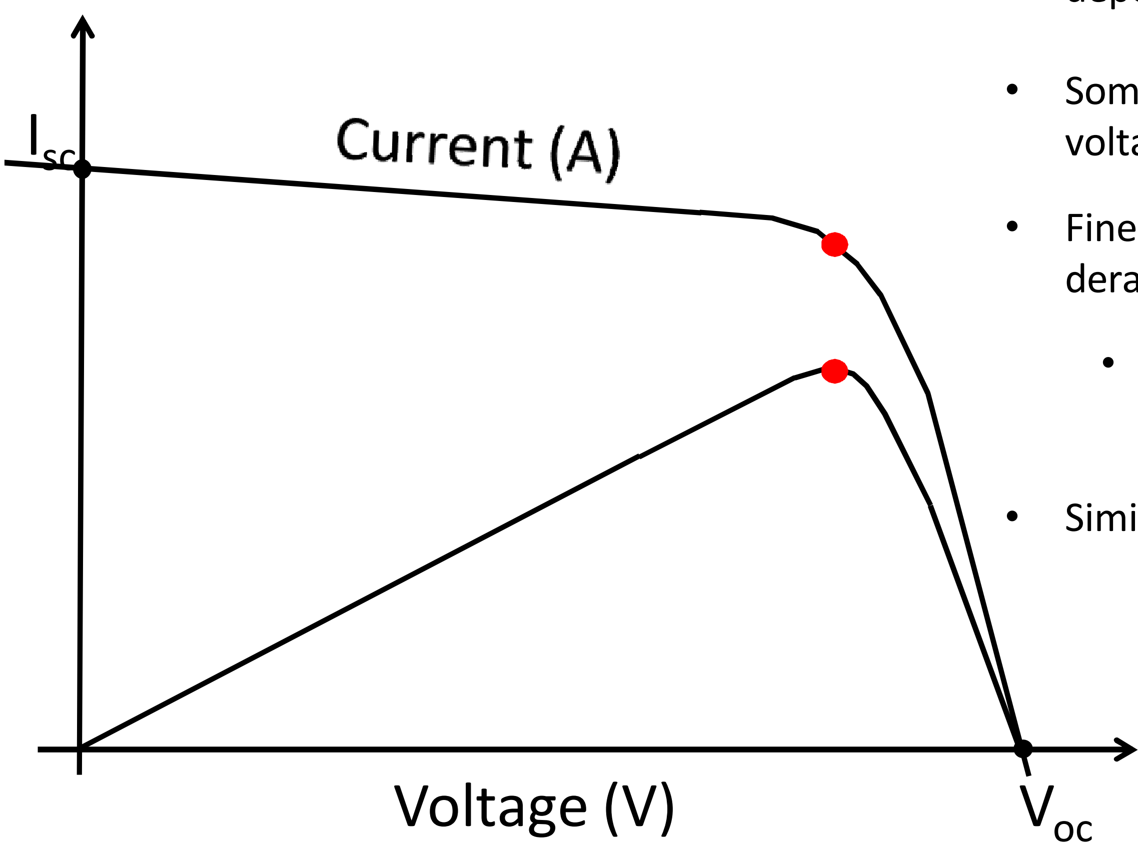

- Capacitor may be stressed additionally depending on inverter behavior
- Some inverters size capacitors for working voltage of V_{oc}
- Fine for normal conditions, but temperature derate moves working voltage to/near V_{oc}
  - Capacitor doubly stressed by higher temperature and higher voltage
- Similar voltage stress for power curtailment

Lifetimes will become shorter if inverters partake in ancillary service (e.g. LVRT, VAR management)

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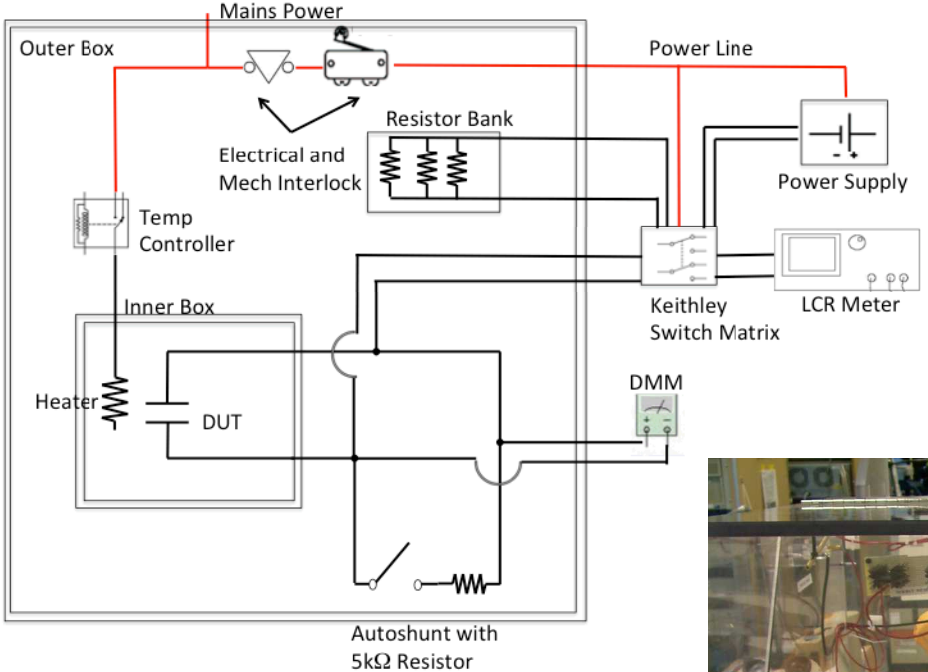
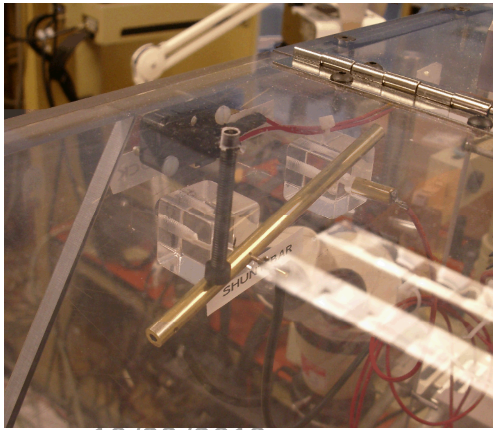
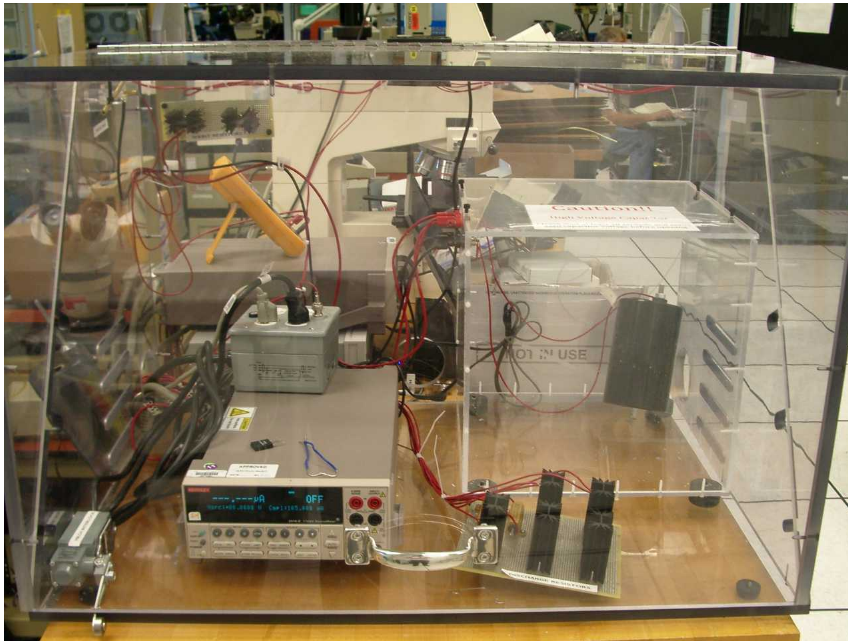
Work at Sandia



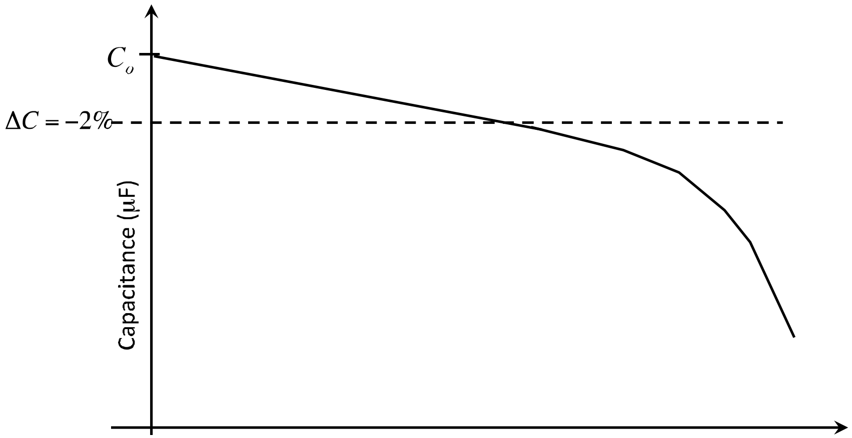
Capacitor Test Setup

- Single Capacitor Test
- up to 1000V, 1mF capacitor
- 10 VA limit
- Variable voltage and temperature

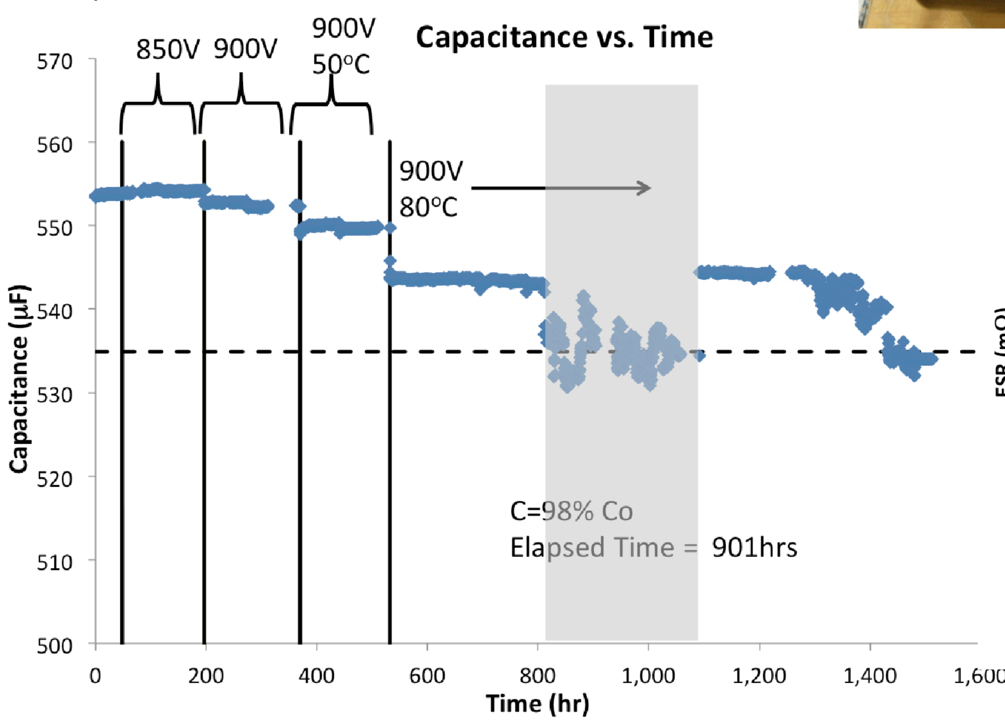


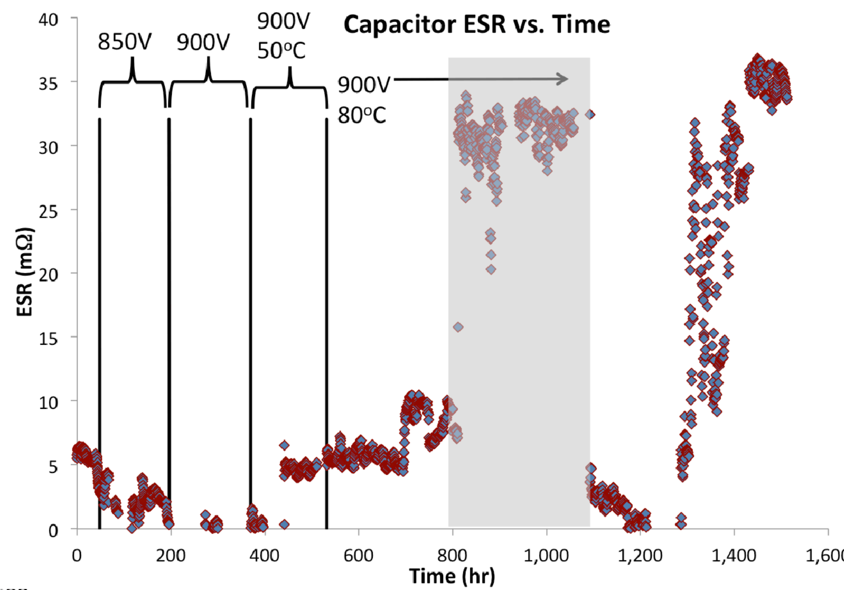


Work at Sandia

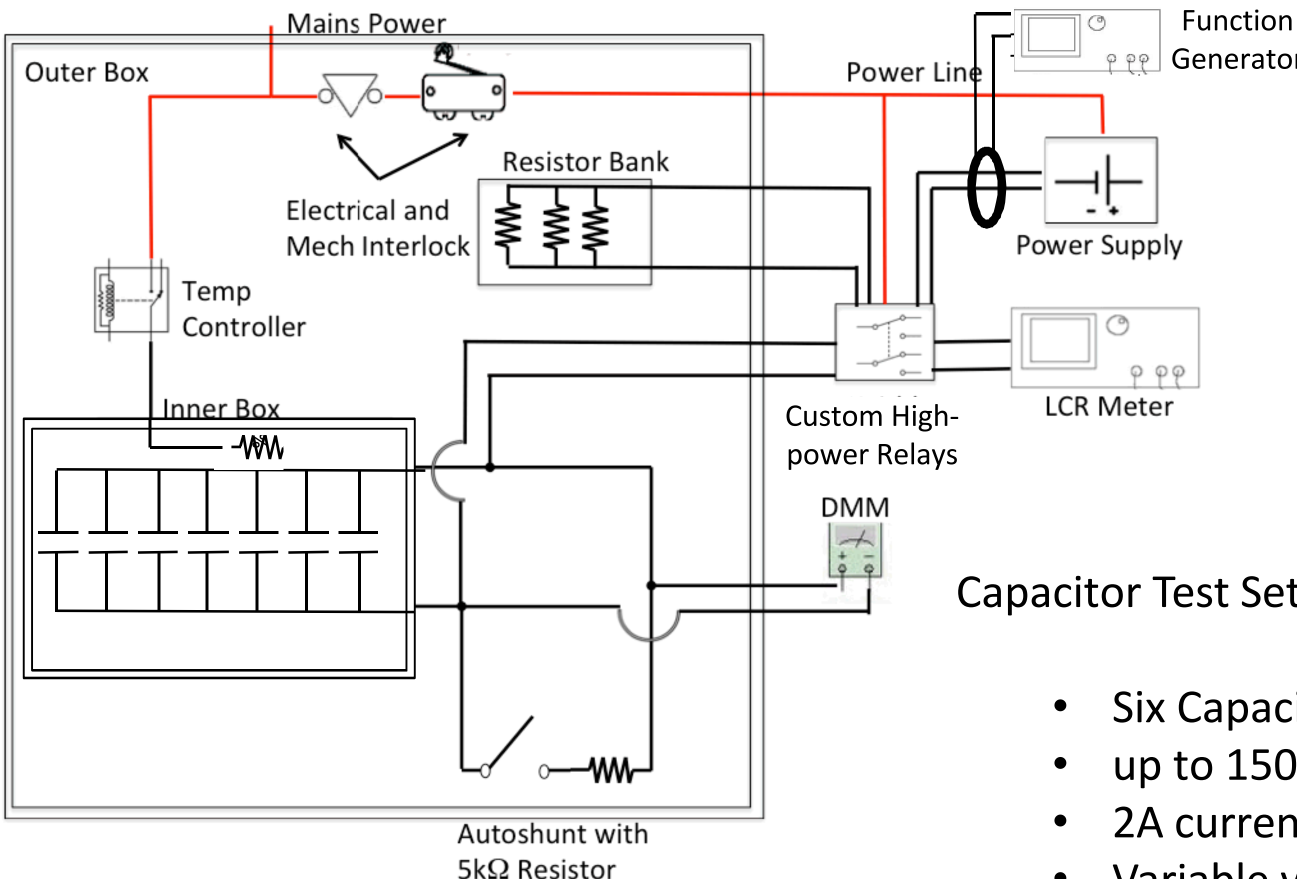


800V, 600µF Capacitor
Listed 5,000 hr life @ 85°C, 800V
200,000 hr life @ 60°C, 800V





Future Work



Capacitor Test Setup

- Six Capacitor Test
- up to 1500V, 1mF capacitor
- 2A current limitation
- Variable voltage, temperature, and ripple

Summary

- Capacitor health has direct correlation to PV operation due to voltage ripple
  - Voltage ripple decreases PV utilization ratio
  - Magnitude of ripple voltage influenced by capacitor size, source inductance, and capacitor ESR
  - Proper understanding of capacitor and inverter behavior over time is needed to maximize capacitor lifetimes especially regarding advanced functionality
- Sandia National Labs conducting experiments on bus capacitor reliability
  - Metallized thin film reliability studies for temperature/voltage/ripple stress
    - Industry moving towards replacing electrolytic capacitors, even for residential systems
    - Less lifetime data known regarding metallized thin film
    - Idea that metallized thin film capacitors are inherently safer, even long after soft failure
    - Degradation “fingerprint” for use in future prognostics and health management (PHM) systems

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