PV Inverter Performance and Component-Level Reliability

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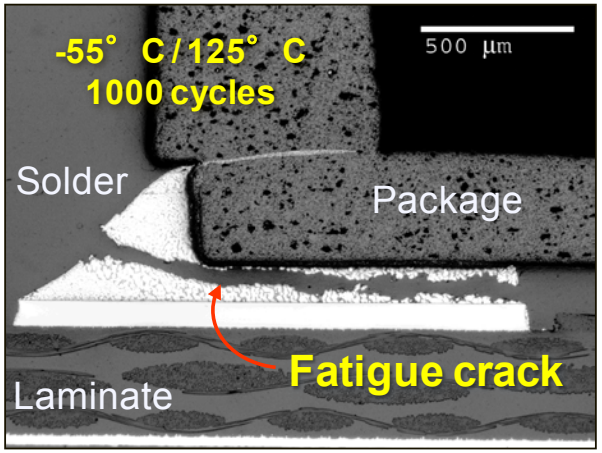
Outline

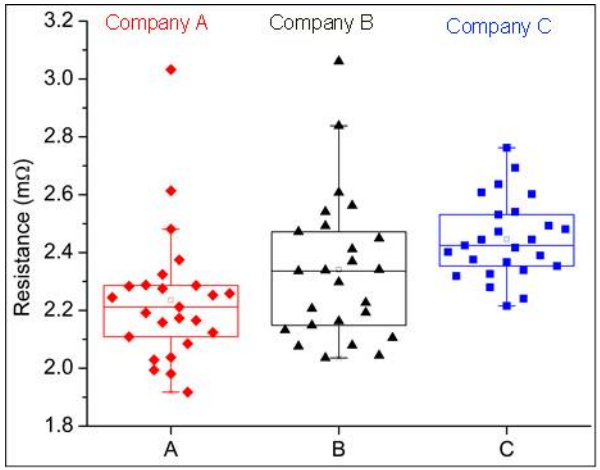
- Inverter Introduction and operation
- PV Inverter Component-Level Reliability
  - Bus Capacitors
  - IGBTs/MOSFET switches
- Future of Inverter Reliability
  - High DC/AC Ratios
  - VAR support
  - Widebandgap devices
  - Microinverter/converter reliability

Sandia PV Reliability Program

PV reliability program spans the spectrum from materials to systems

Focus on Balance of Systems (BOS)





Solder Joint Degradation

Connector Reliability

Inverter Thermal Performance

Advanced Inverter Function

Ground Fault

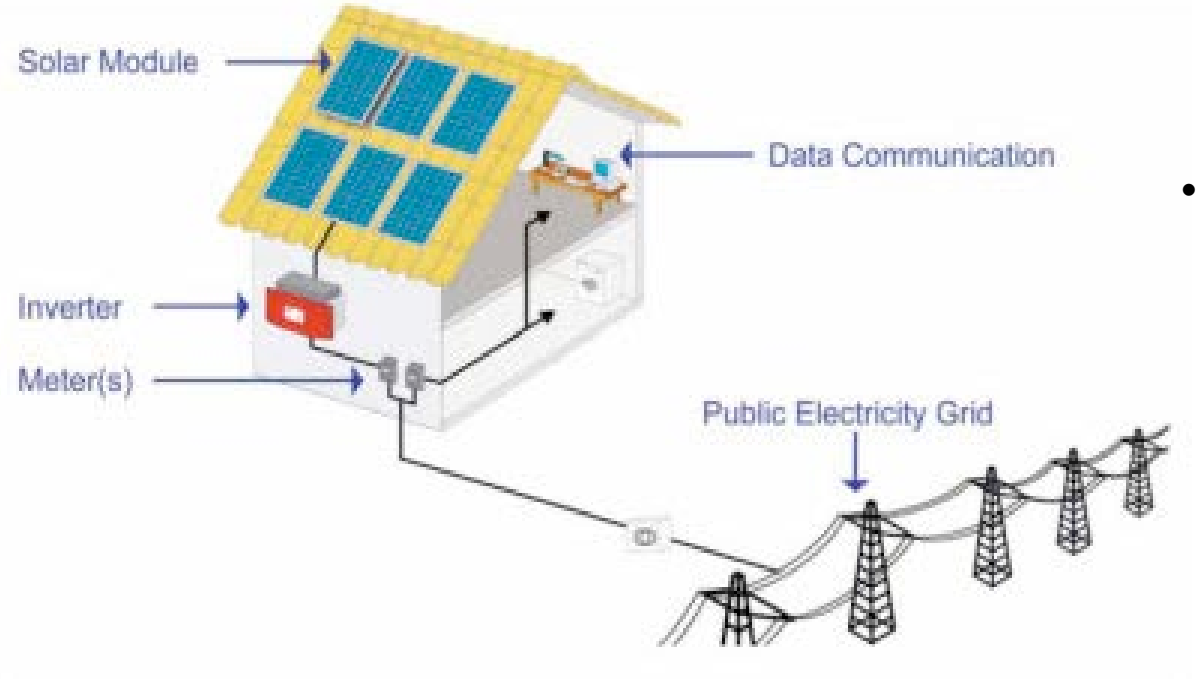
Arc Fault

O & M

Materials | Components | Sub-system | System

Capacitor, IGBT, WBG

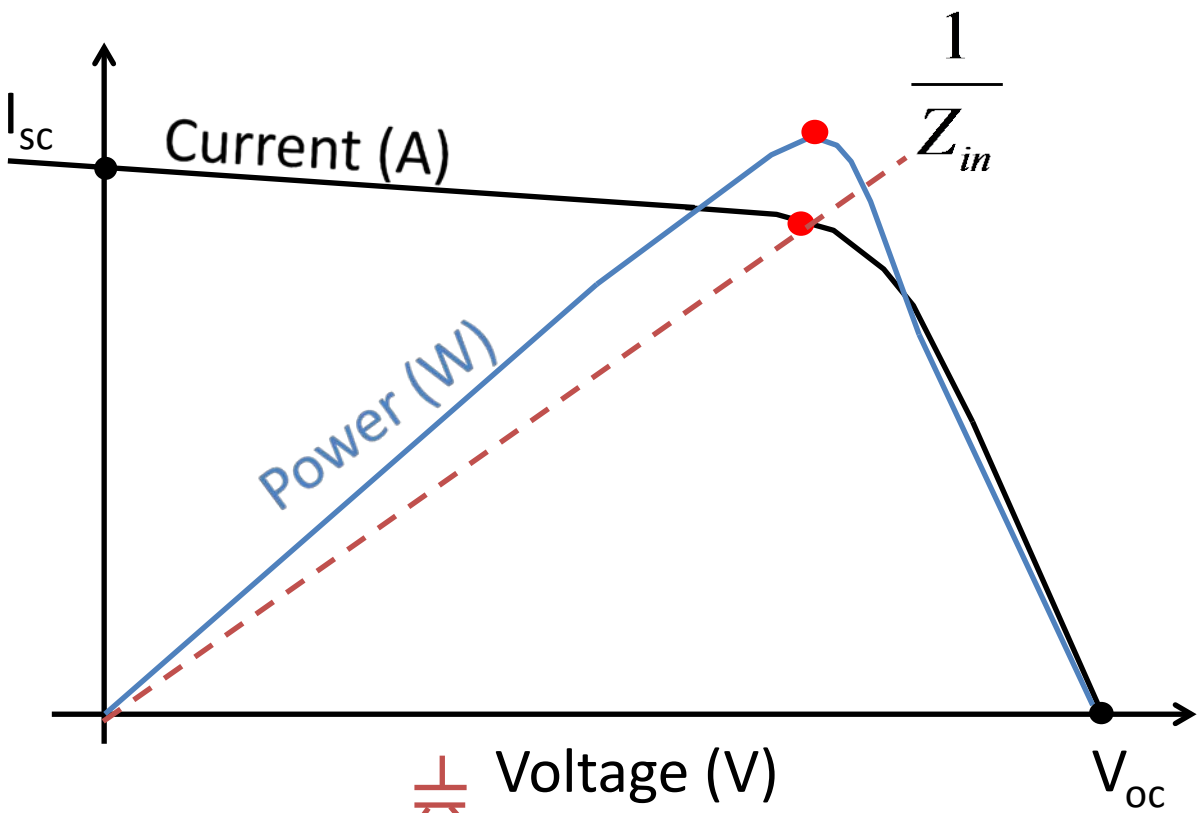
PV Inverter Introduction

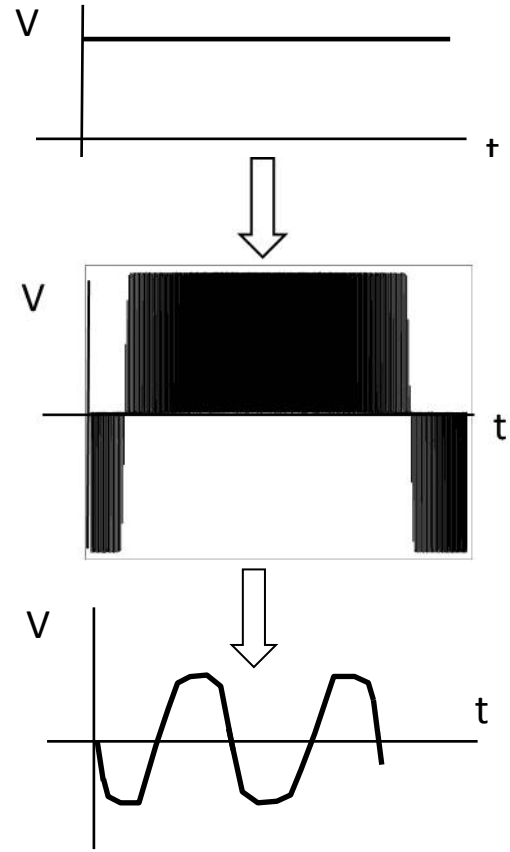


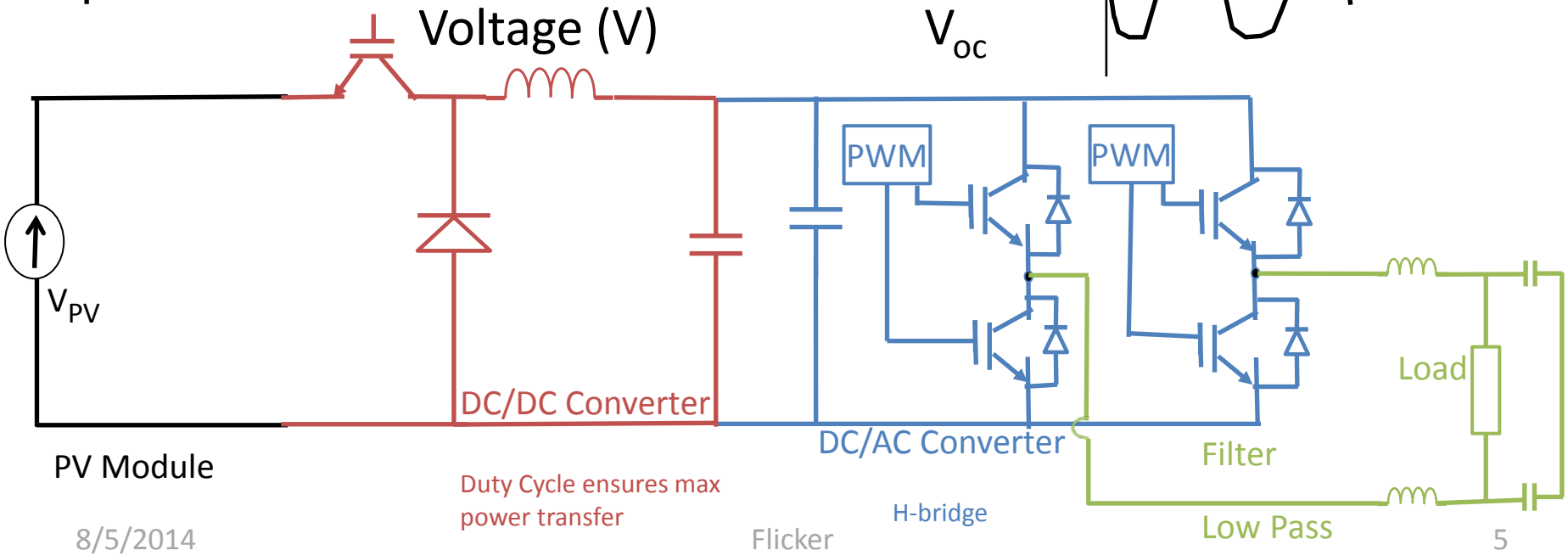
- DC/AC Conversion
  - Maximum power transfer
  - Power quality

- 3 major classes (3 orders of magnitude):
  - 500 kW (utility scale)
  - 5 kW (residential scale)
  - 250 W (microinverter)

- Many various topologies
  - Single/multi-stage
  - Isolated/non-isolated
  - single-/three-phase

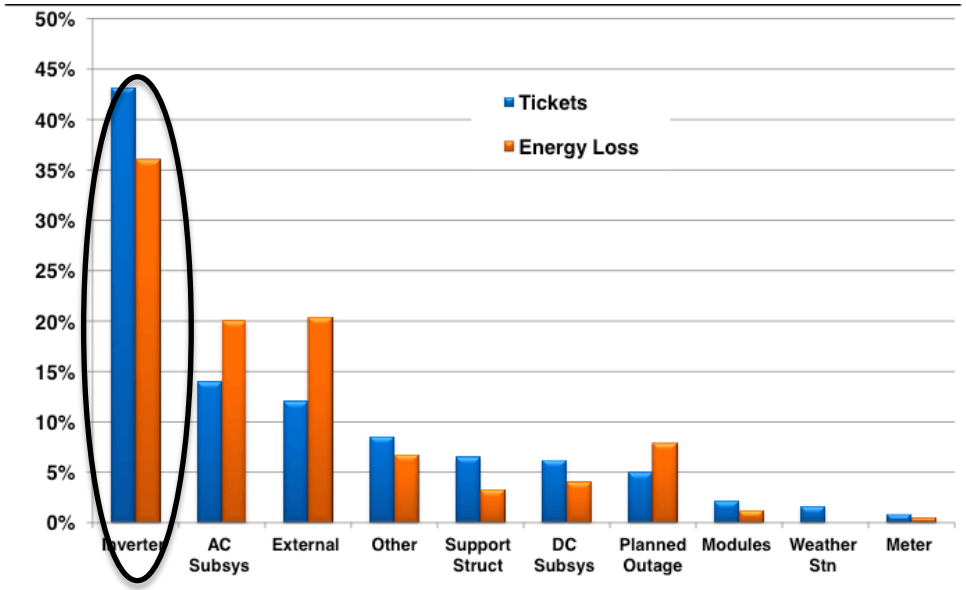

I_{sc}
Current (A)
$\frac{1}{Z_{in}}$
Power (W)
Voltage (V)
V_{oc}


V
t
V
t
V
t


V_{PV}
PV Module
DC/DC Converter
Duty Cycle ensures max power transfer
PWM
PWM
DC/AC Converter
H-bridge
Filter
Low Pass
Load

Current Inverter Reliability Capacitor

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



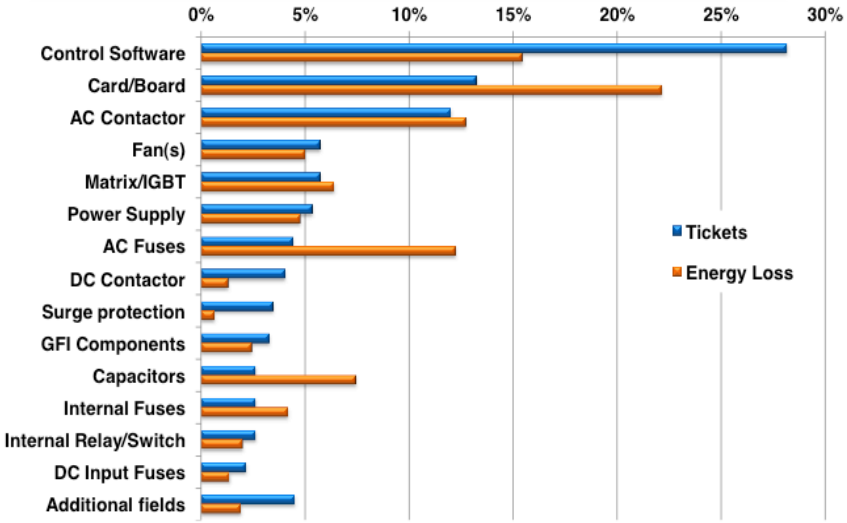
- One reason Reliability
  - Repair/replace multiple times over system lifetime
  - SunEdison says inverter 36% of energy losses from inverter

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

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

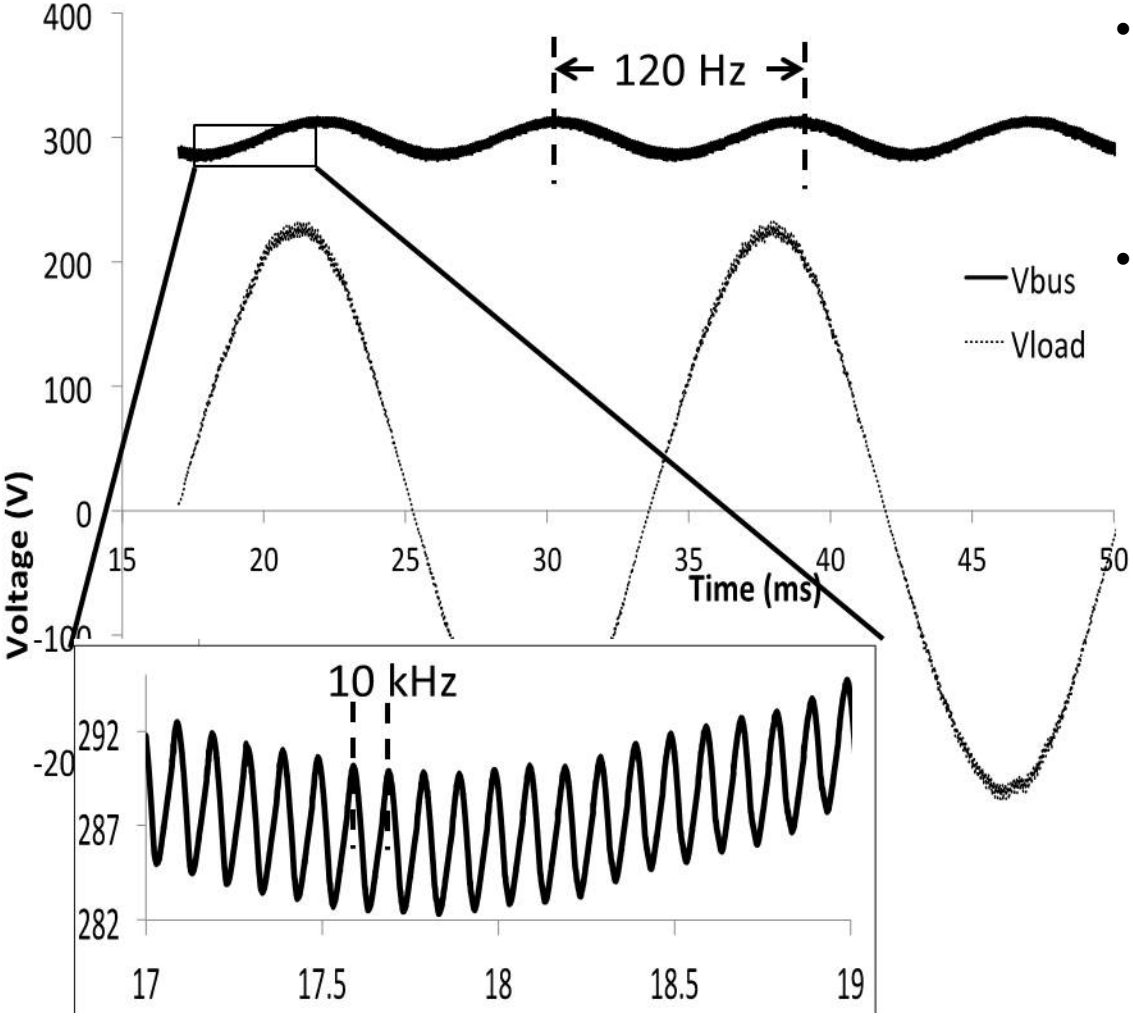
- Must endure harsh environments (humidity, corrosive) with large temperature cycles (ambient and power handling)

- Much disagreement about specific failure mechanisms, but capacitors, PCB, and semiconductor switches generally agreed to be top three failure causes



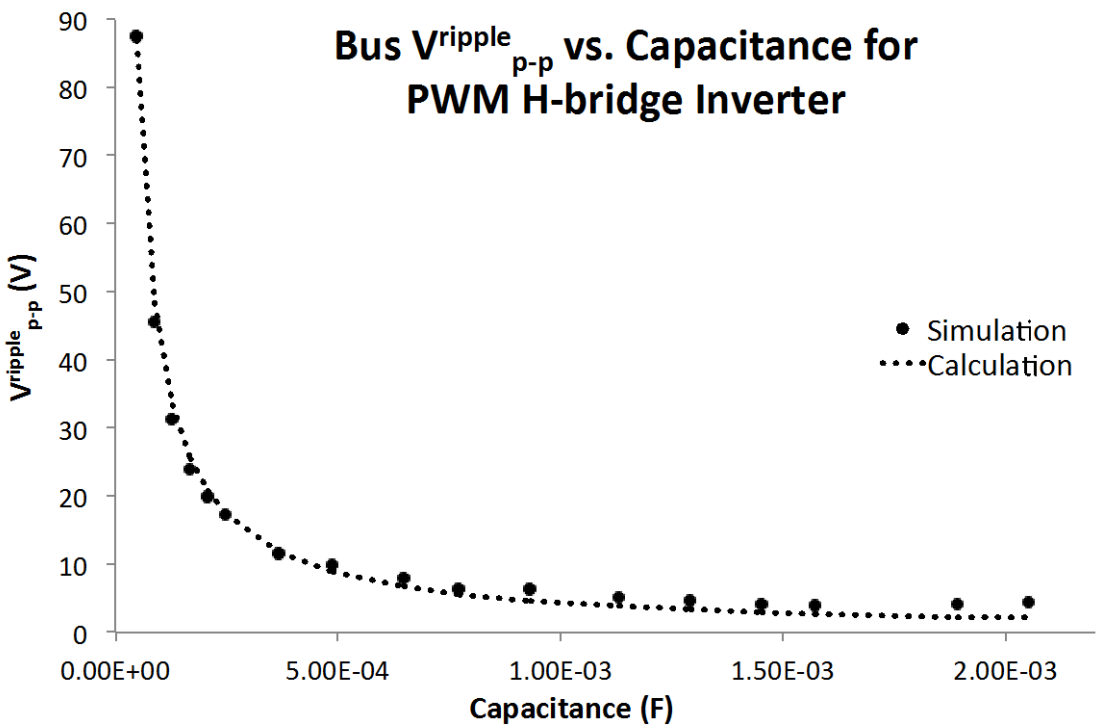
U.S.Dept. of Defense, *Reliability Prediction of Electronic Equipment Military Handbook 217F, Feb. 28, 1995.*

Current Inverter Reliability Capacitor



- 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

Current Inverter Reliability Capacitor



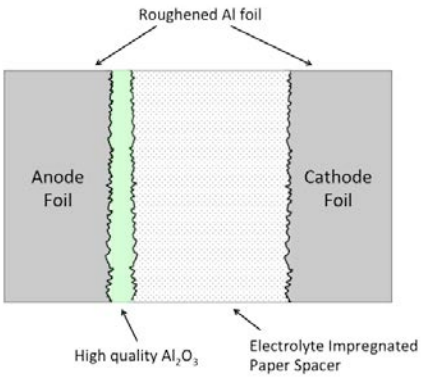
- Bus and load voltage of a simulation shows ripple on DC bus for 250µF capacitor
- AC ripple with frequencies 120Hz and 10kHz due to IGBT switching
  - Much easier to filter
- Ripple as a function of C_{bus} shows 1/C dependence

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

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

Current Inverter Reliability Capacitor

Electrolytic Capacitors



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

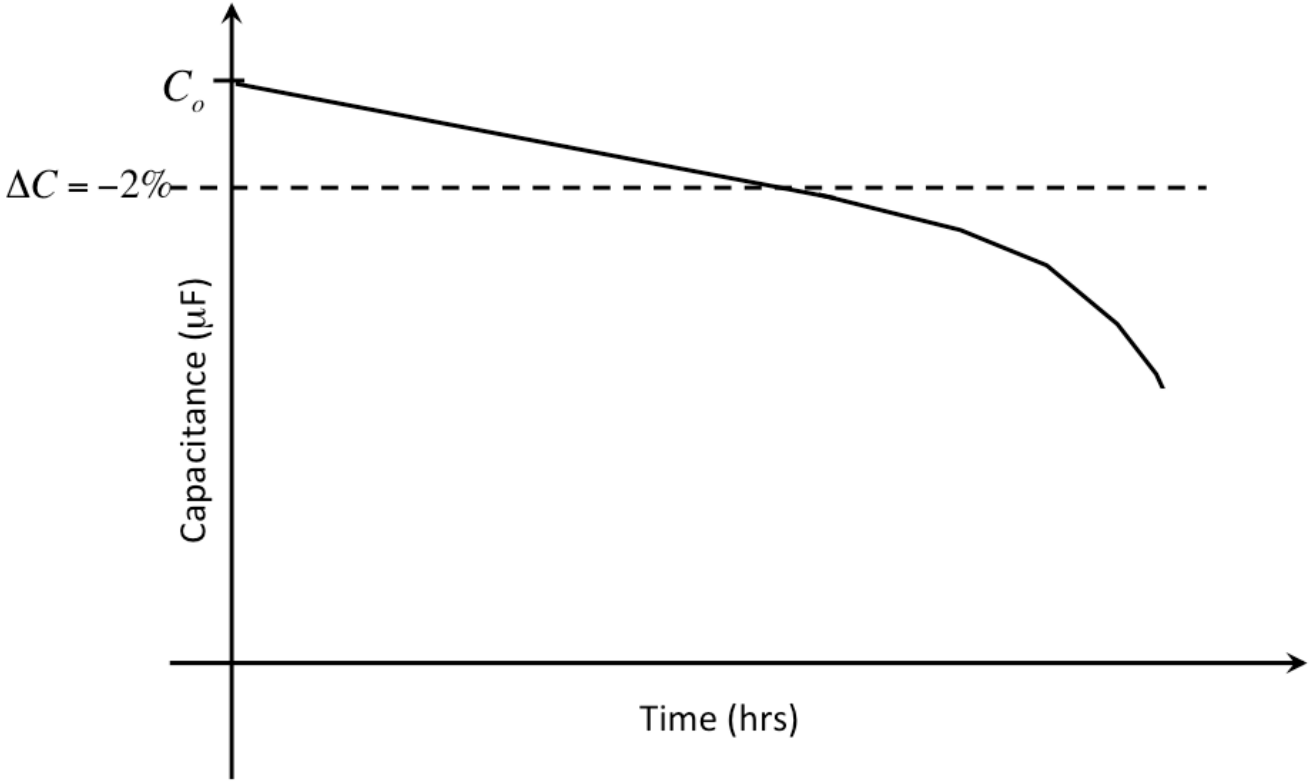
Disadvantages
- Often fail catastrophically
- Polar
- Release H_2 gas
- Must be oversized to handle ripple
- High leakage currents
- Main degradation mechanism is ESR increase

Thin-Film Capacitors

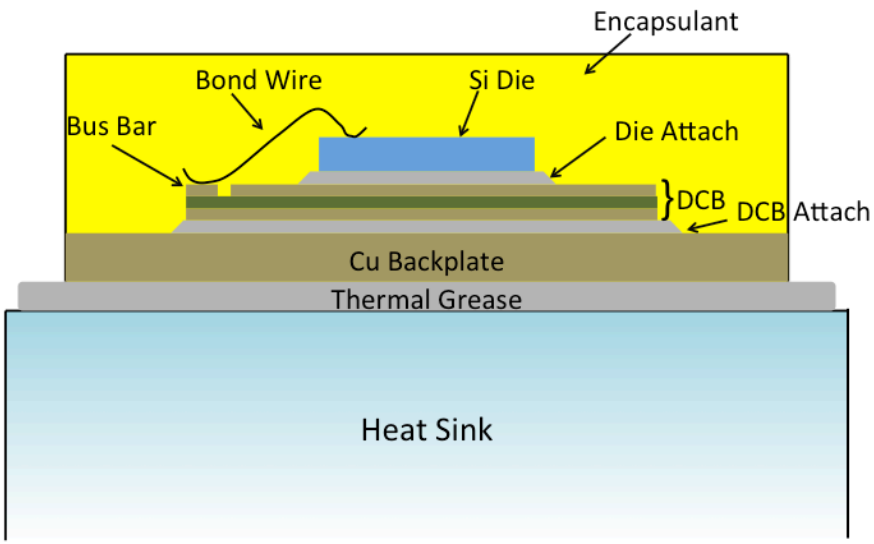
Advantages
- "Safer" with longer lifetimes
- Small ESR
- Degradation failure
- Non-polar

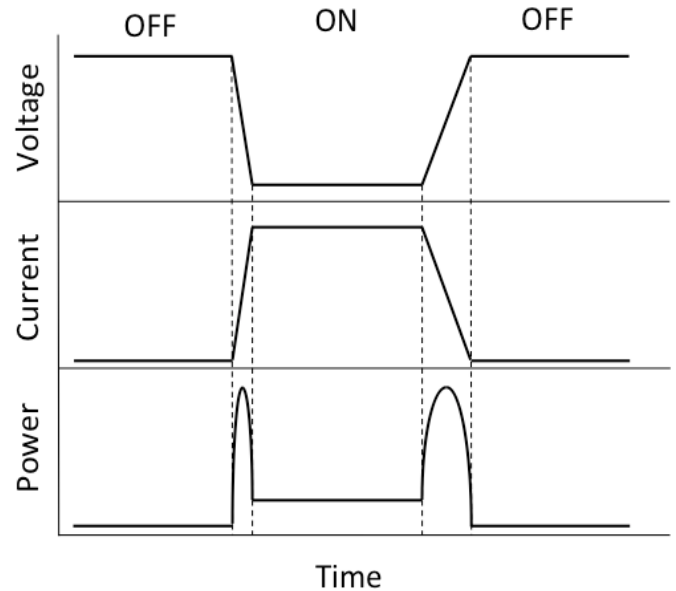
Disadvantages
- Not very well characterized
- Relatively expensive ($/µF is exponential)
- Thin metal limits peak current and energy density
- Low operation temperatures (faster degradation and polymer phase transitions)
- Low capacitance per volume (Bulky)

Current Inverter Reliability Capacitor



Current Inverter Reliability IGBT



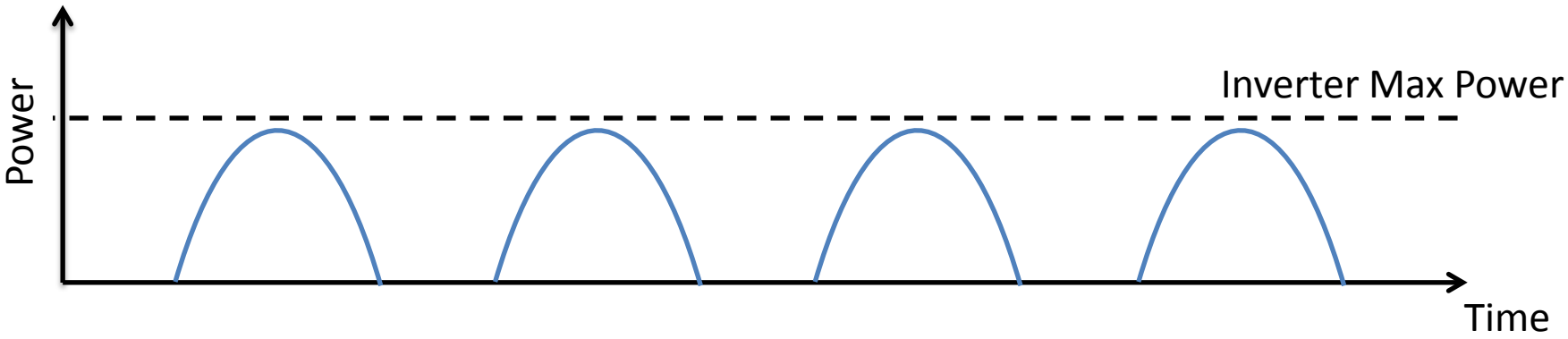


CTE mismatch between metal and Si die

- 4% of controlled power dissipated as heat
- two temperature cycles
  1. short term power cycling
  2. long term ambient temperature

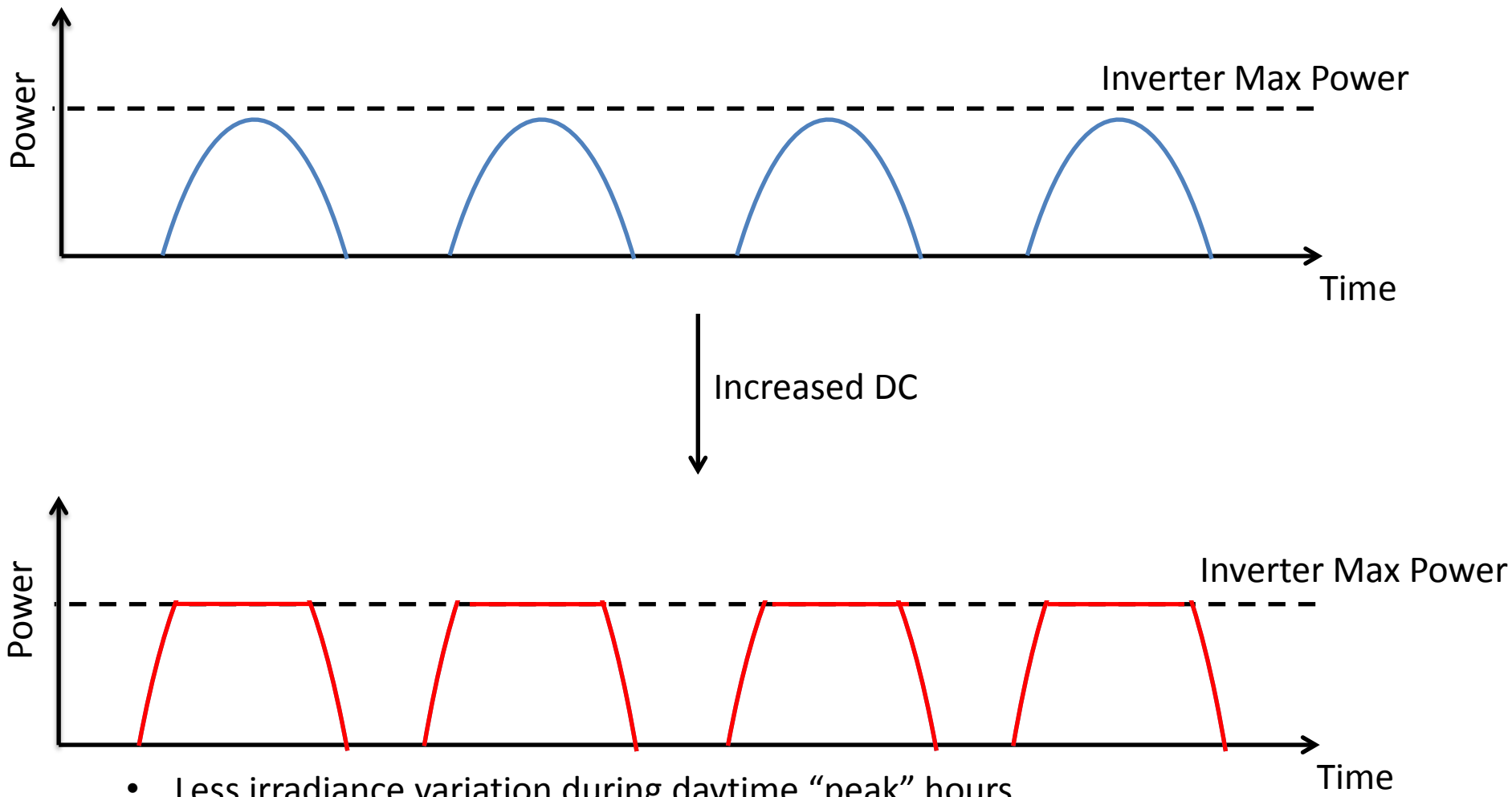
- Companies moving to metal loaded epoxies for cost/environmental reasons, but have much poorer performance
- Die attach degradation leads to voiding
  - Decreased heat transfer away from die
  - Increase in turn-off time, increase power dissipation in junction

Future of Inverter Reliability
High DC/AC Ratios



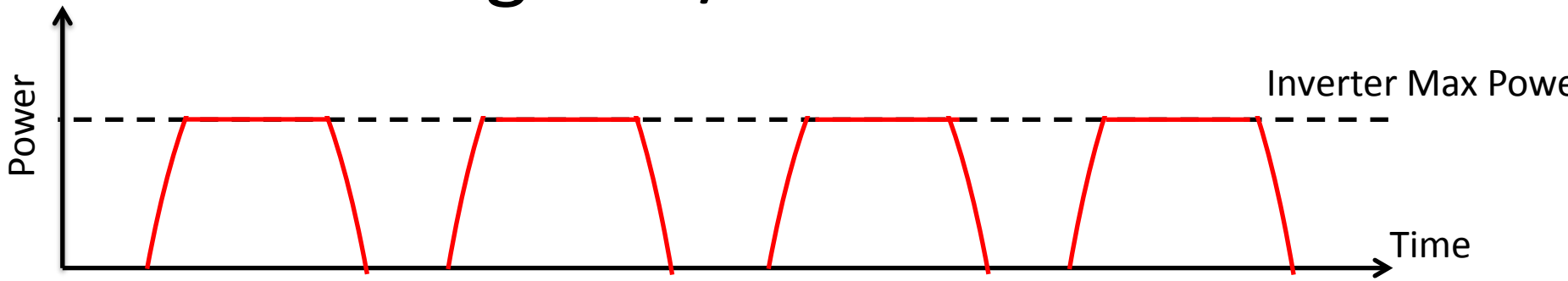
- PV plants can/do experience high variability during peak daytime hours
  - →High power demand(air conditioning)
  - →Difficult to predict supply, so cannot match demand
- Utilities value consistency as much as power generation capability
- As panel prices decrease, wasted power less important
- Can make PV more consistent by increasing DC:AC ratio

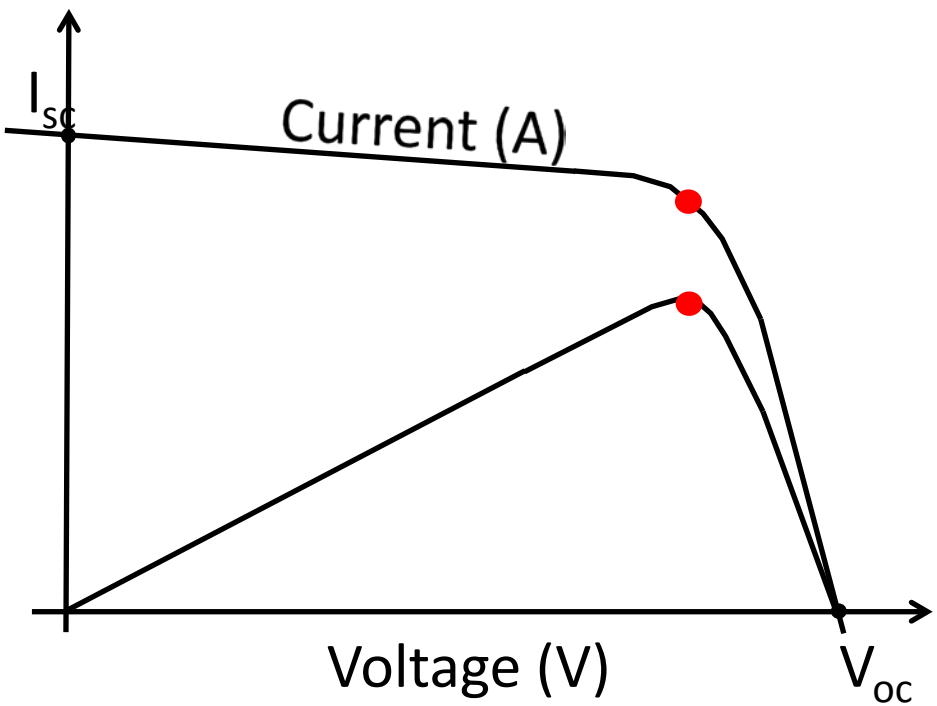
Future of Inverter Reliability
High DC/AC Ratios



- Less irradiance variation during daytime “peak” hours
- Power output profile looks more like base generation

Future of Inverter Reliability
High DC/AC Ratios





- DC/AC Ratios have been climbing in new PV installations
- High DC/AC Ratios can be very challenging inverter reliability environments
- Inverter at maximum power for many hours during the day
- Lifetimes will become shorter due to high power/high voltage environments

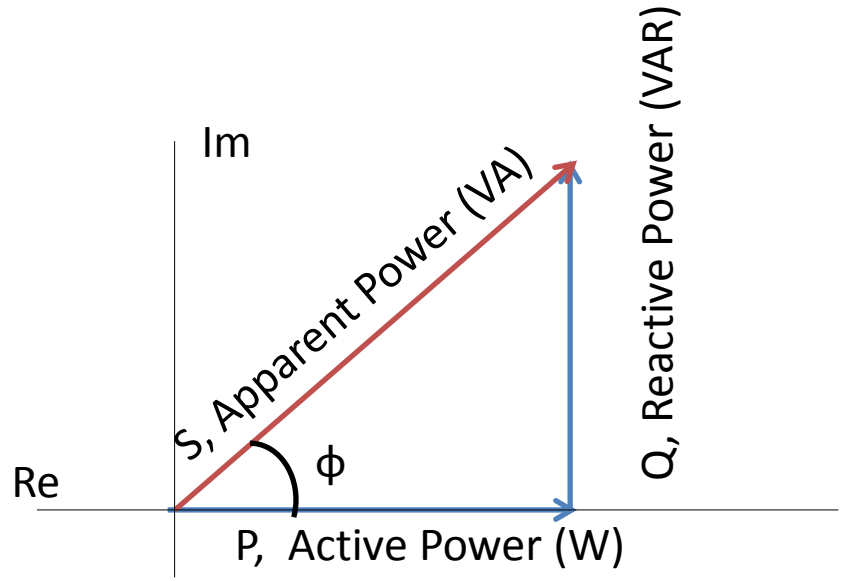
Future of Inverter Reliability
VAR Support

Alternating current described by a sine wave:

$$V(t) = V_p \cdot \sin(\omega t)$$

$$I(t) = I_p \cdot \sin(\omega t + \phi)$$

$$S(t) = I \cdot V \Rightarrow P\cos(\omega t) + iQ\sin(\omega t)$$



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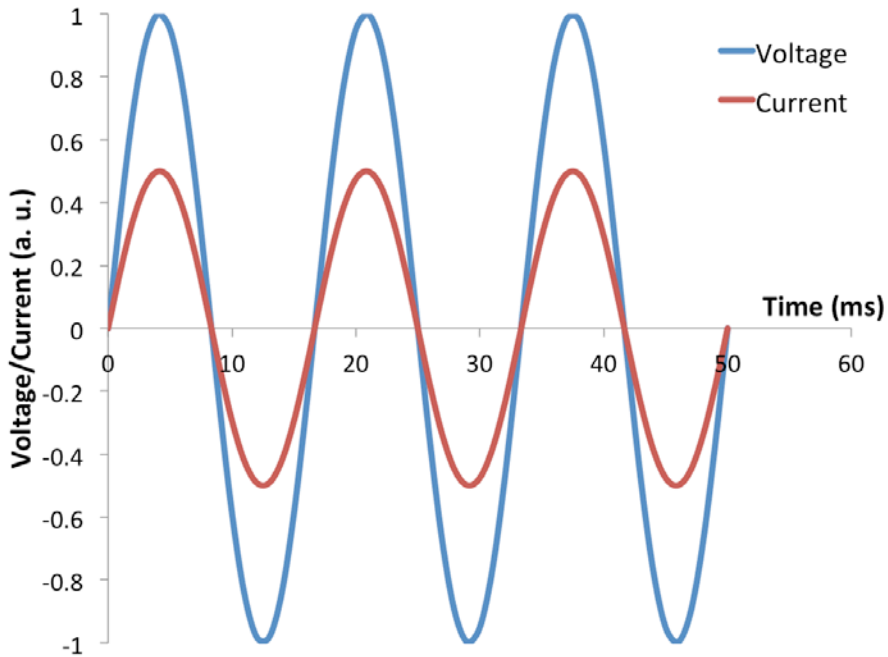

$\phi=0$

Purely resistive

Voltage and Current in phase

Q=0, S=P

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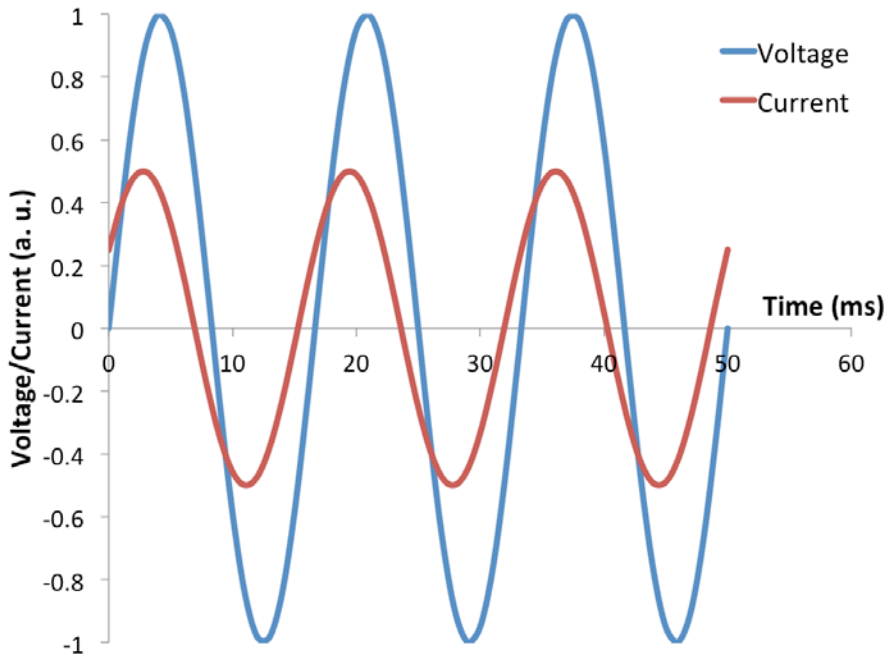

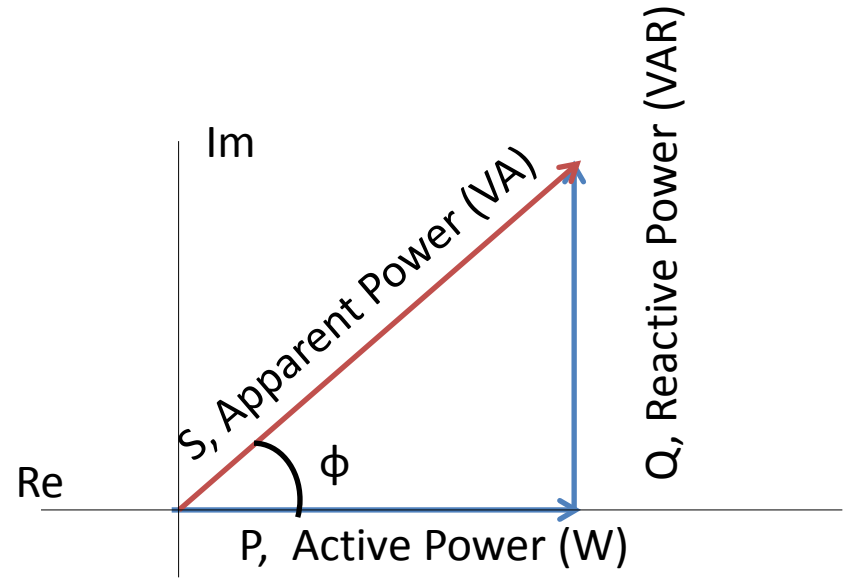

Φ>0
Capacitive System
Voltage lags Current
Q>0, Source VARs

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VAR Support

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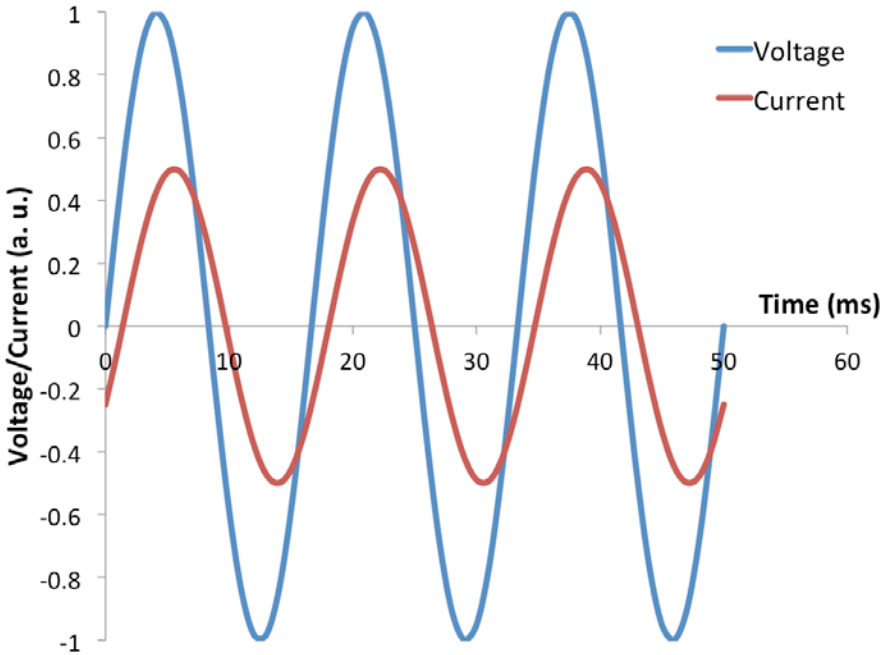
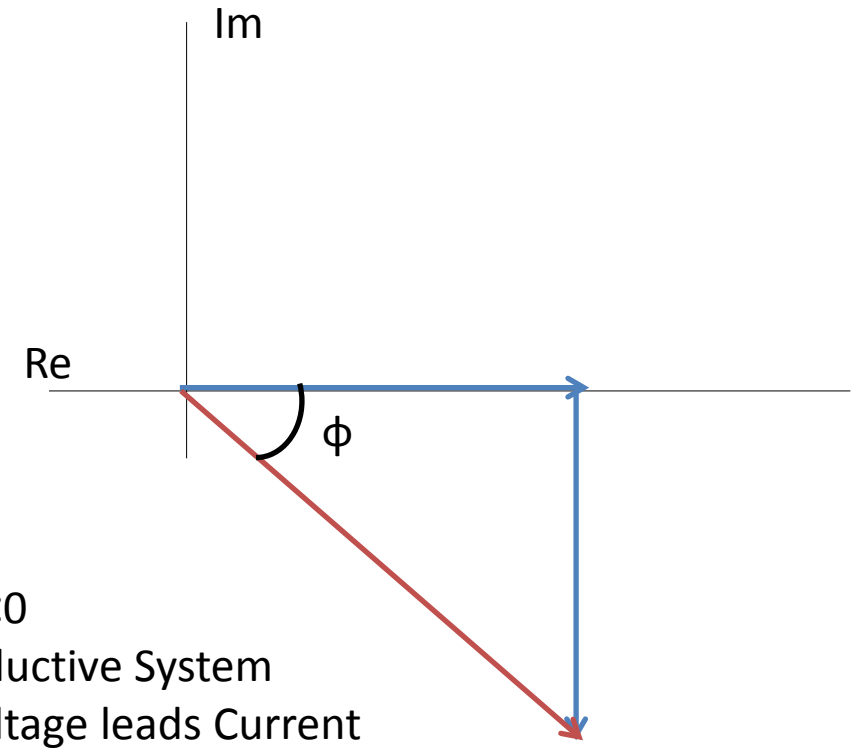




Φ<0
Inductive System
Voltage leads Current
Q<0, Sink VARs

Future of Inverter Reliability
VAR Support

Used to stabilize grid voltage (voltage droop or rise) and change grid power factor

- Utilities want PF≈1 because maximize active power efficiency

Many blackout events caused by **unexpected** hot days

- Larger usage of air conditioning units than expected
- Large inductive loads coming online causes current inrush

  → Grid voltage decreases

  → Grid PF moves away from 1
- Lower voltage causes higher current draw (at lower efficiencies)

  → further decrease line voltage
- Higher current flow heats overhead line

  → sags and shorts on a tree

  → overloading other lines in blackout

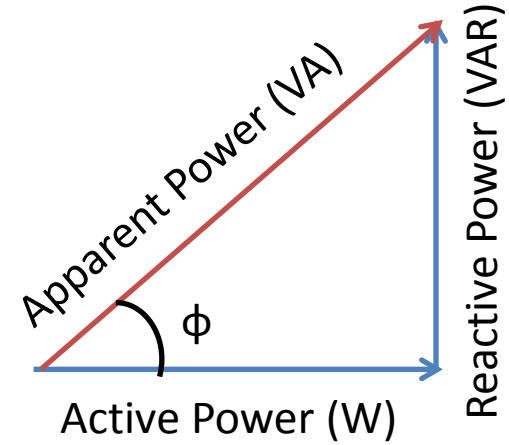
Two solutions to this problem:

1. Increase generating capacity via peaker (Natural Gas or Diesel) plants

   Slow to come online (~10 min), Expensive to operate
2. Increase grid capacitance to cancel out inductive loads (bring PF to 1, resist V droop)

   Fast, capacitor banks are expensive with reliability issues

Future of Inverter Reliability
VAR Support



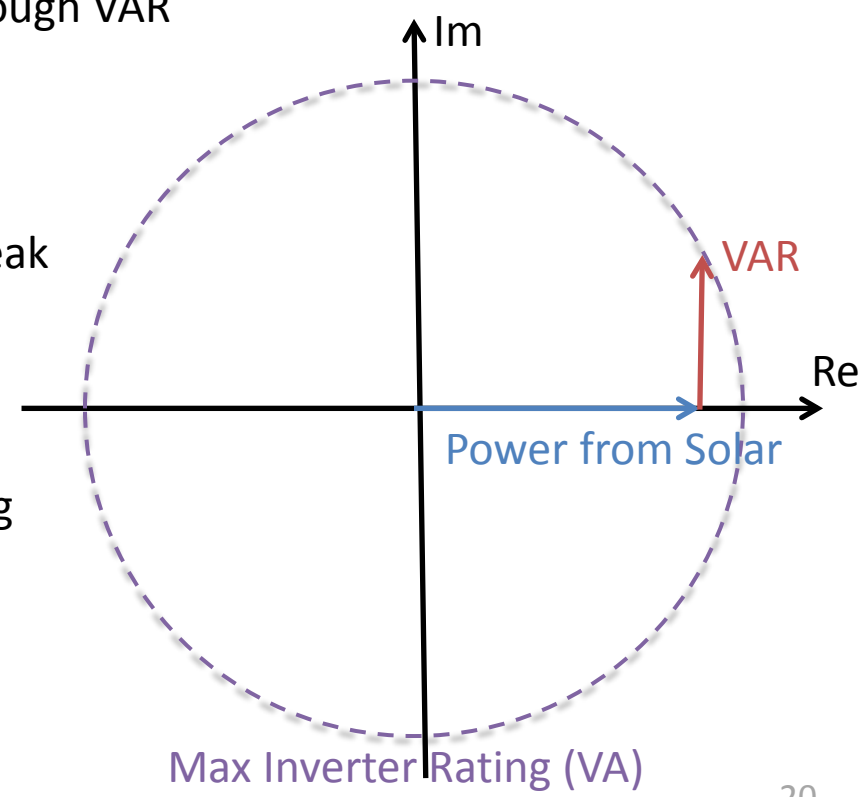
Historically, utilities have asked inverters to disconnect from grid

- Inverters can alter ϕ easily through switching schemes
- Easily and quickly become capacitive/inductive (source/sink VARs)
- Now, utilities asking to stabilize the grid through VAR support

In the future, VARs may become monetized

- Incentive for operators to control VARs at non-peak active power hours
- Inverters can source/sink VARs at full power handling of inverter during all inverter operation
- Lower inverter efficiencies when sourcing/sinking VARS

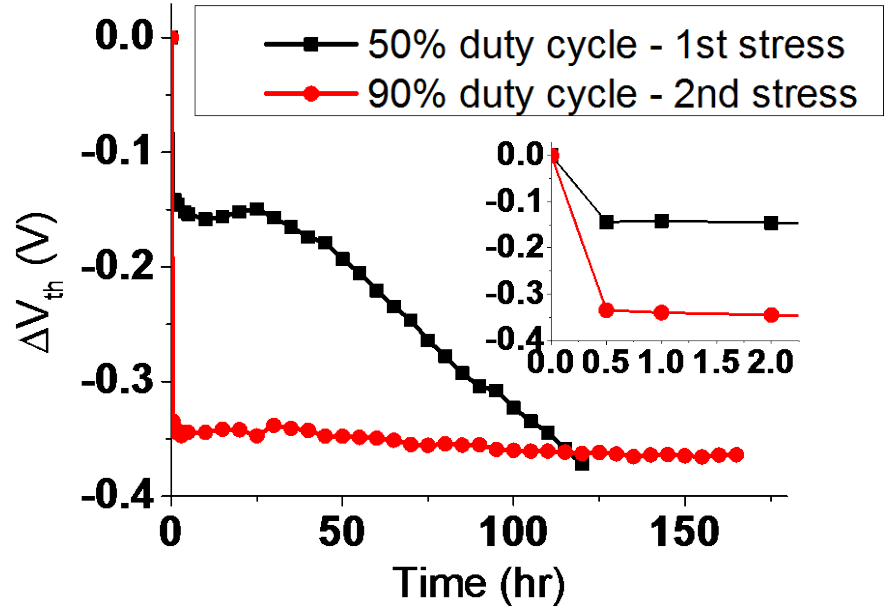
→Increased aging rates, more internal heating →shorter lifetimes



Future of Inverter Reliability
Widebandgap Devices (SiC, GaN)

- Larger bandgap
  →Fewer devices, greater Voltages
- Smaller resistive losses
  →Higher switch frequencies
  →Smaller inductors/capacitors
- Better thermal conductivity

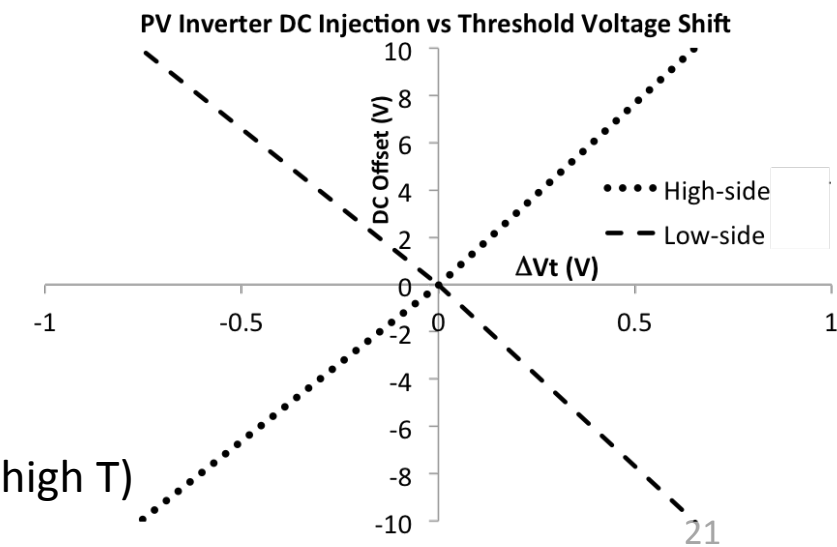
  10% of weight and 12% of volume



SiC MOSFETS suffer from V_T instability

V_T shift due to charge trapping at gate oxide
- SiO_2 bulk traps
- SiC/SiO_2 interface traps

Worse in SiC than Si
- SiC/SiO_2 interface quality is much poorer
- WBG means less conduction band offset with SiO_2
- Thermal activation of carriers over barrier (esp. at high T)



Future of Inverter Reliability Microinverter/Microconverters

- Mounted on module
- More extreme diurnal temperature cycling
  - Increased stress on componentry
  - More difficult thermal management
  - Customers require the inverter lifetime = module lifetime (~20 years)
    - Centralized inverters have warranties ~10 years

- One MLPE unit for every module
  - 5,000 units per MW of PV
  - Tens of thousands to millions of MLPE in installation
  - Difficult to impossible to track and repair/replace units as they fail
    - Unique challenge of PV installations operations and maintenance (O&M)

Statistical Reliability and lifetime extension is critical to successful implementation of O&M schemes for large solar installations

Number of safety, qualification, and reliability standards being developed

IEC62093 (Paul Parker)

62109-3

PREDICTS (Jack Flicker)-Currently seeking members for working group

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