SAND2022-12321C

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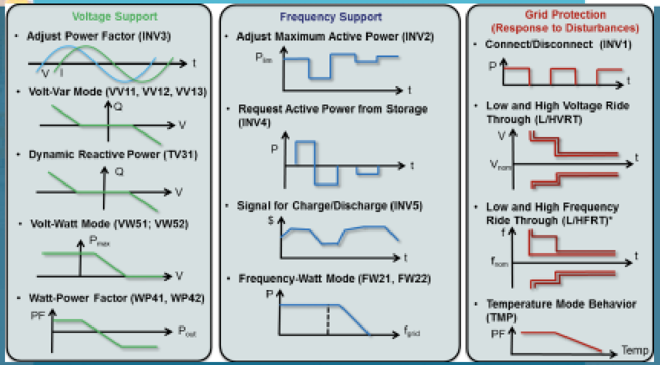
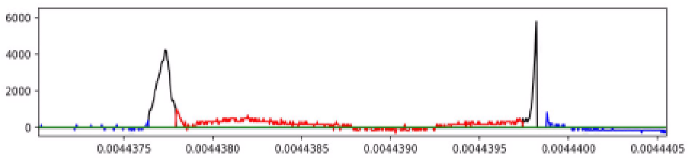
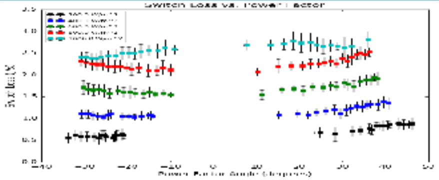
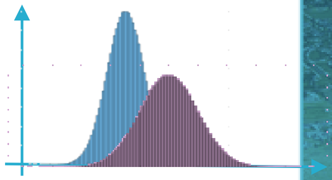
PV inverter reliability: Advanced Inverter Functionality









Jack D. Flicker

Sandia National Laboratories

IEEE Energy Conversion Congress and Exposition (ECCE)

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U.S. DEPARTMENT OF ENERGY NNSA

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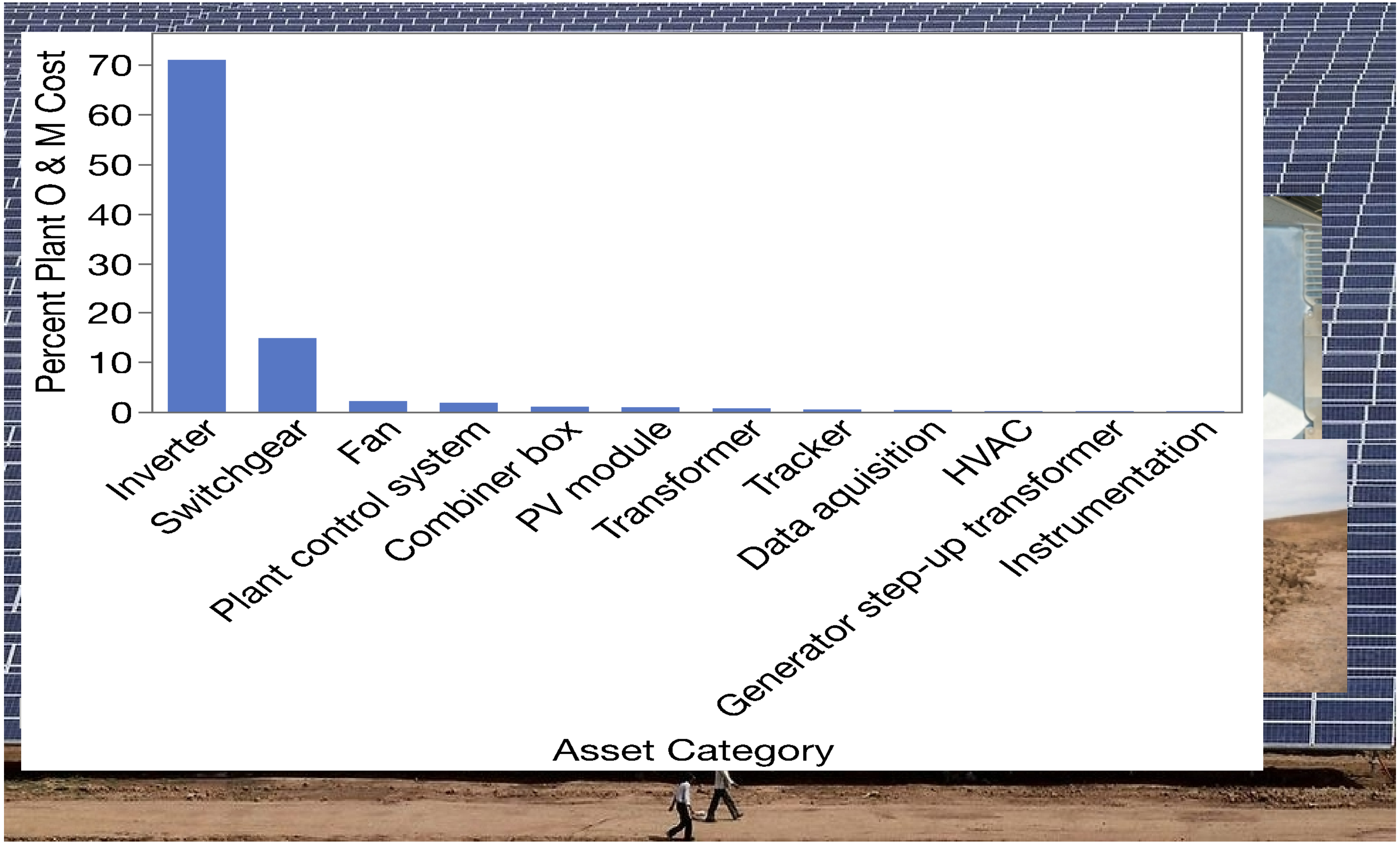
Who does the heavy lifting in a PV system?



- Inverters are complicated machines
  - -Power Conditioning
  - -Grid Monitoring
  - -Array reporting/monitoring
  - -Islanding protection, etc.
- Handling much higher power densities than rest of the system
- Must endure harsh environments with large temperature cycles (ambient and power handling)
  - Increased DC/AC ratios
  - Operating at P_{rated} most of day
- Not only is reliability more challenging, but more consequential when failures occur

…and operational capabilities will only increase over time

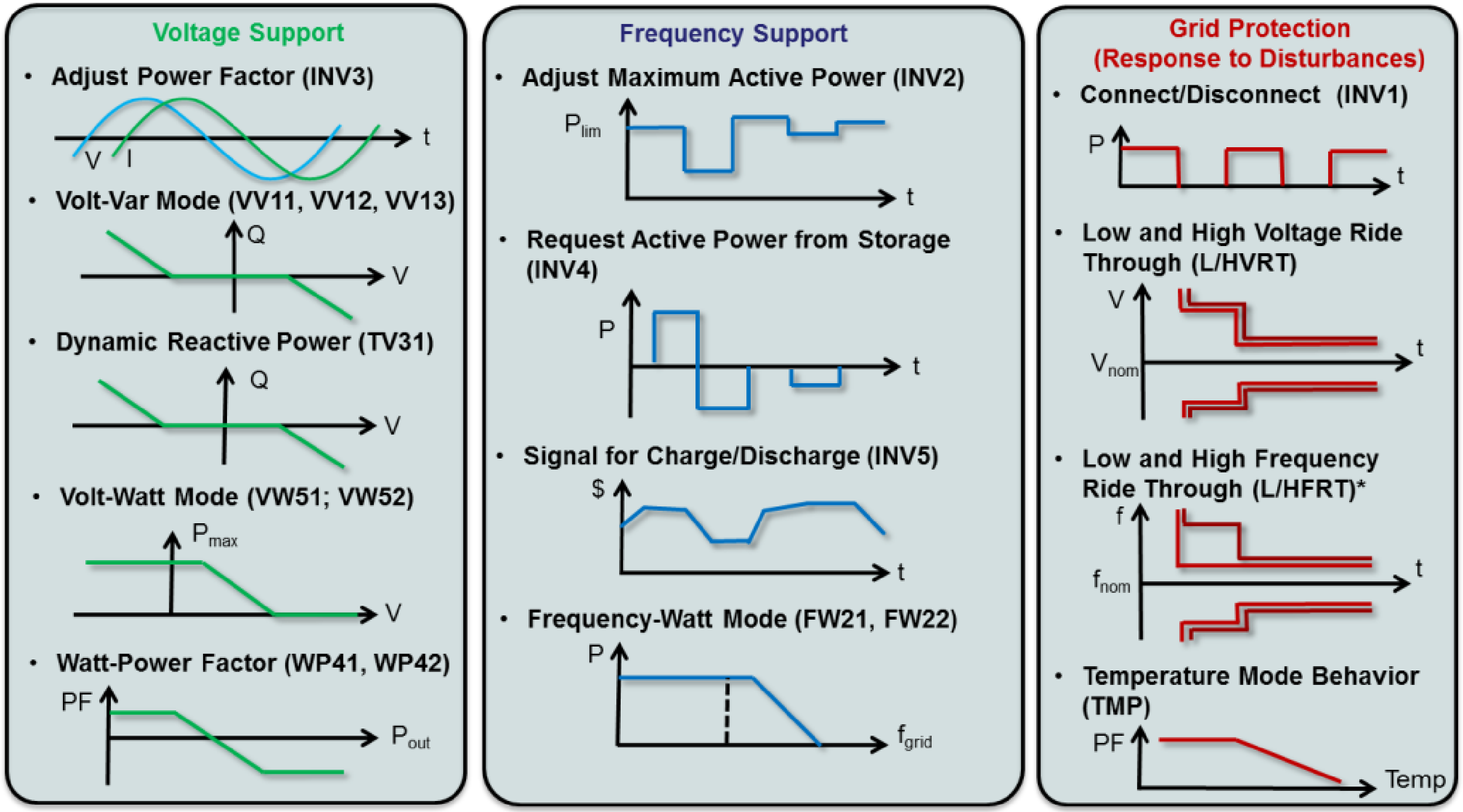
Slide Courtesy Peter Hacke, NREL

Adapted from: S. Lokanath and P. Williams, *IEC TC82 WG 3 & 6 Meeting, Tempe, AZ, May 14, 2016*

Advanced Inverter Operations and Reliability (1/2)

- **Historically, inverters have had a very simple objective:**
  - Convert DC power to AC power regardless of grid conditions.
  - Maximize power injected into the grid.

- **Monumental shifts in inverter operations occurred Sept 8th 2017:**
  - HI and CA required advanced inverter functionalities.
  - Inverters expected to not only inject power, but also support the grid through advanced inverter functions.
    - ➢ *Voltage support, frequency support, or grid disturbance.*
  - IEEE 1547-2018 standardized for all of U.S.
  - Inverters become "good grid-izens"



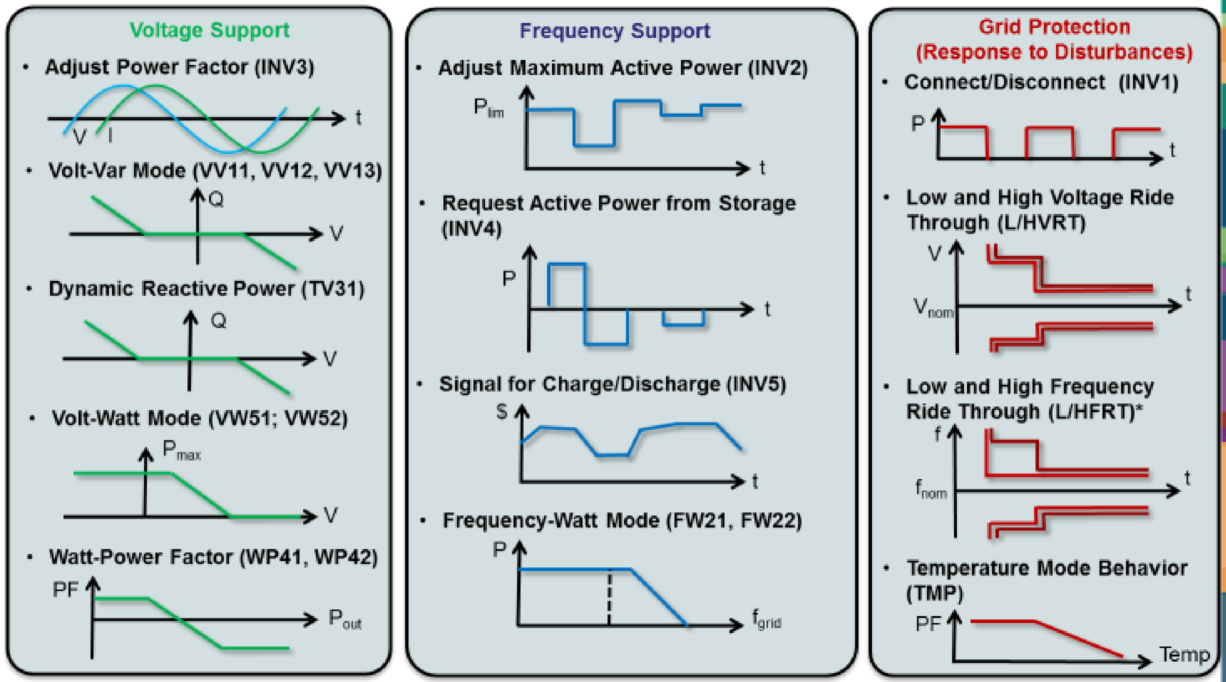
Advanced functions as defined in IEC TR 61850-90-7.
*FRT not included in IEC 61850-90-7, but is in Sandia Test Protocols.

Advanced Inverter Operations and Reliability (2/2)

- Many units no longer operate at "nominal" usage conditions.
- Impact of advanced inverter functions on lost revenue (e.g. curtailment) have been considered.
- Little to no discussion in long-term reliability impact of advanced inverter functions.

Will an inverter operating at non-nominal operating conditions have a significant effect on inverter reliability?

Does this require updated reliability testing protocols (by either manufacturers or standards making bodies) to capture this?

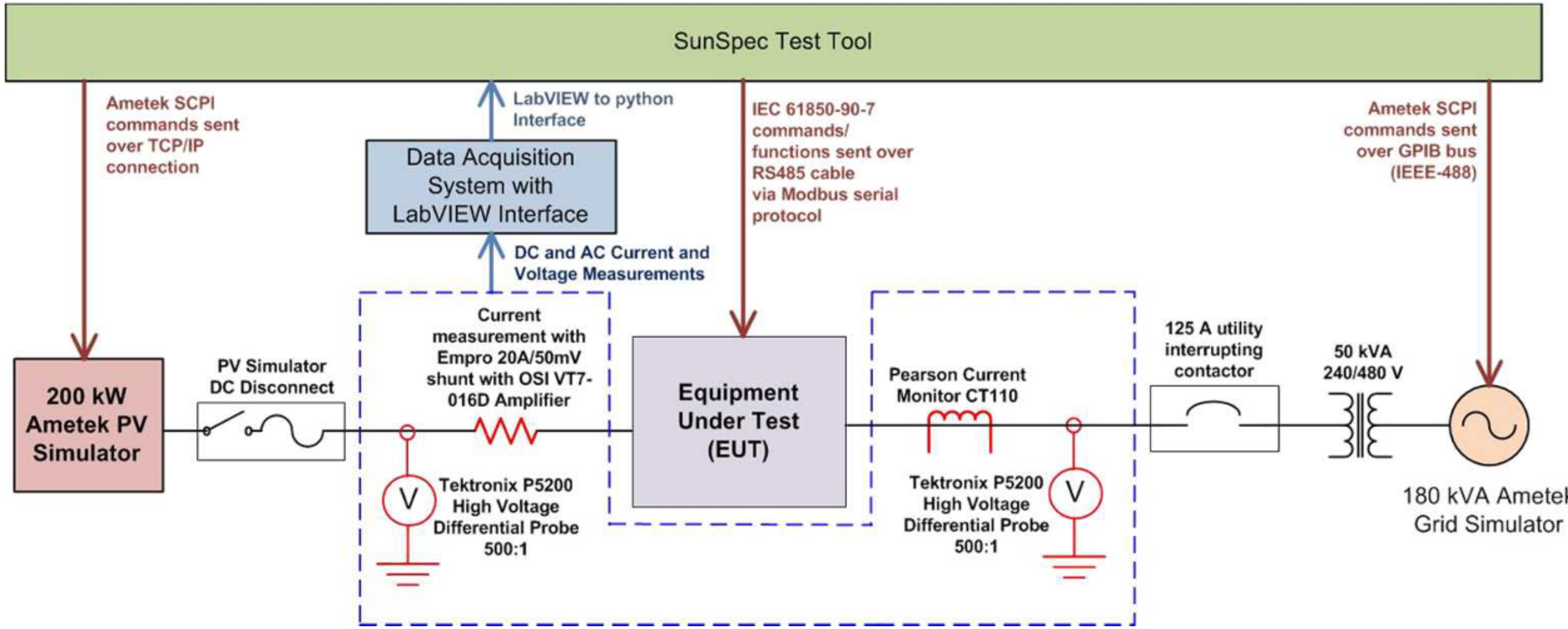


Advanced functions as defined in IEC TR 61850-90-7.
*FRT not included in IEC 61850-90-7, but is in Sandia Test Protocols.

- Using the System Validation Platform (SVP):
  - We have instrumented and autonomously measured inverter component stress for a variety of different advanced inverter operating conditions
  - Originally developed as flexible framework to autonomously measure system-level inverter operations for certification

System Validation Platform (SVP) (1/2)

- The open-source System Validation Platform (SVP) initially developed under a Cooperative Research and Development Agreement (CRADA) between Sandia National Laboratories and SunSpec Alliance.



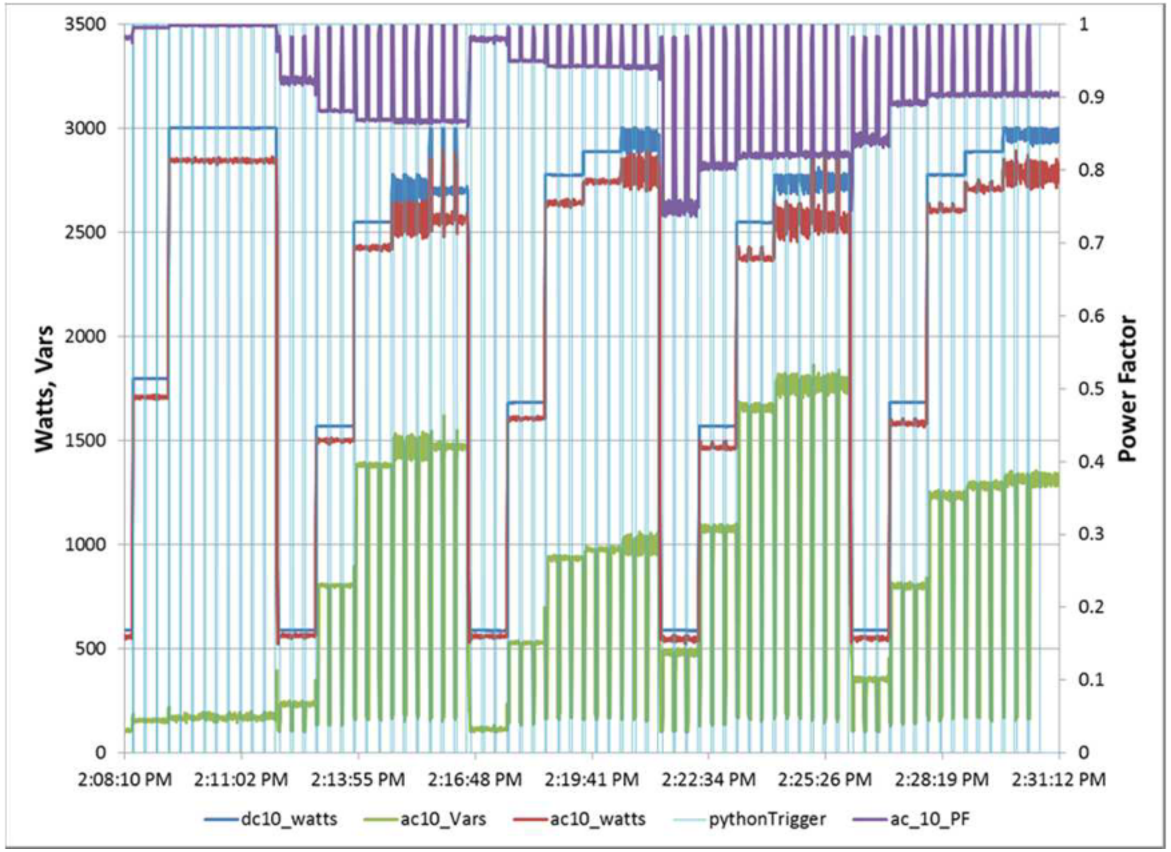
- Range of equipment drivers and test scripts for DER interoperability/electrical characterization experiments.

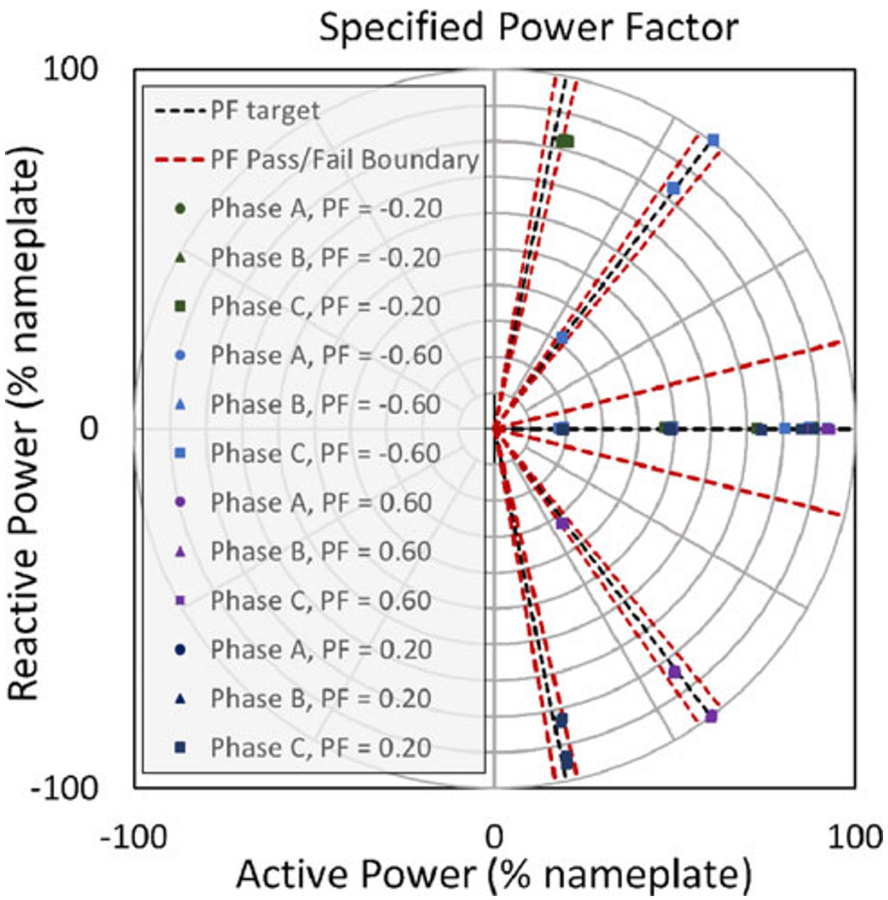
- Software platform written in Python:
  - Includes ability to script actions for multiple hardware devices .
  - Uses a library of device drivers and abstraction layers:
    - Drivers have been created for PV simulators, grid simulators, DER, data acquisition systems, load banks, and switches
    - Allows the same test logic (SVP scripts) to be run at multiple laboratories with different equipment.
    - Originally developed for interoperability requirements: IEEE 1547.1, UL1741 SA, and IEC TR 61850-90-7

Used to autonomously evaluate parameterized operation conditions over entire operation range

System Validation Platform (SVP) (2/2)

- UL 1741 SA test permutations are large due to the number of settings in each advanced DER function:
  - ~75 measurements for fixed power factor → ***25 minutes with SVP***
  - ~375 measurements for volt/var - → ***90 minutes with SVP***

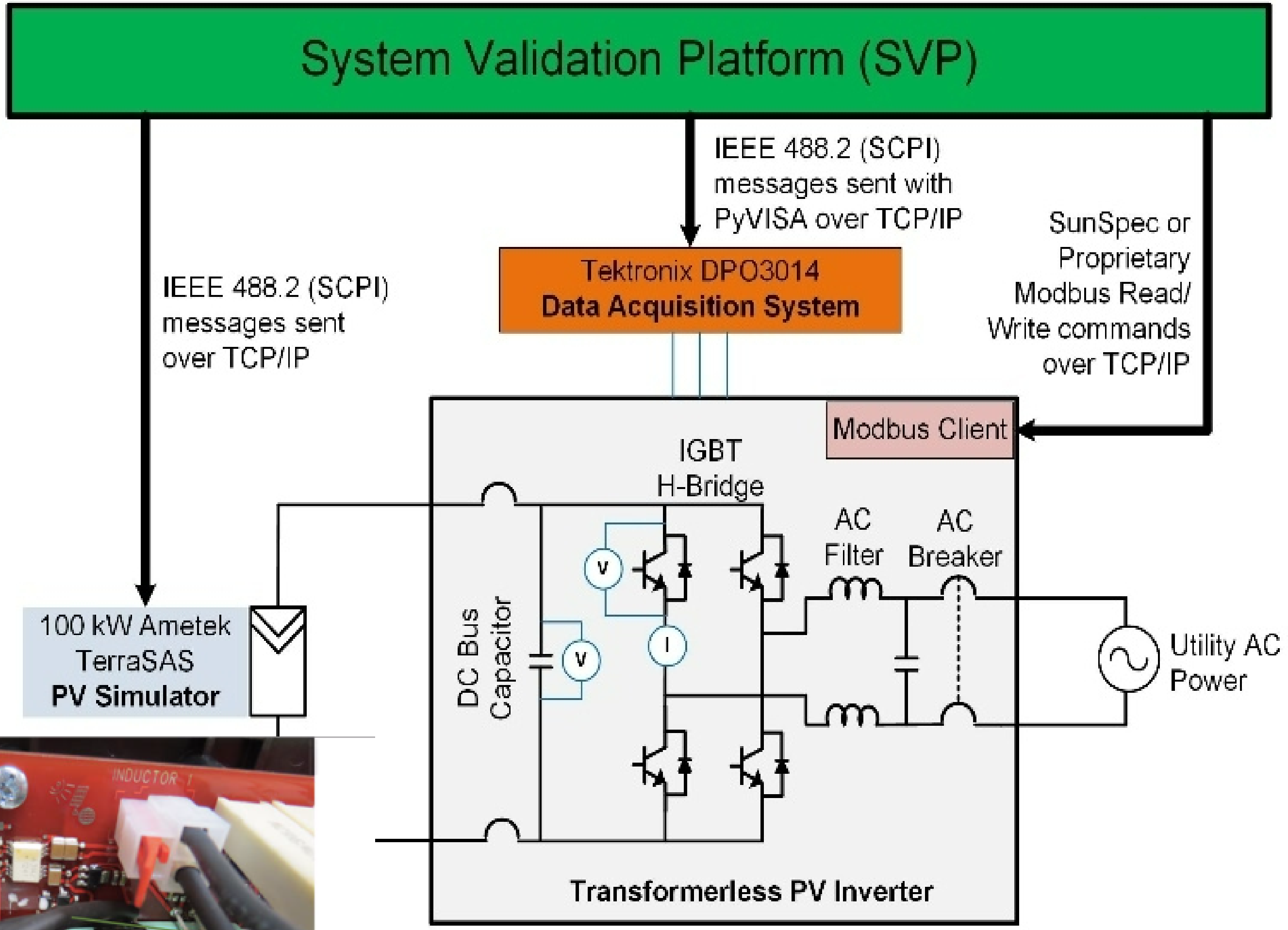




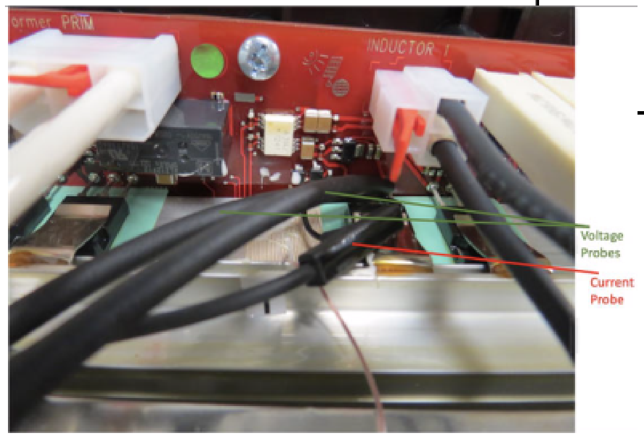
Instead of characterizing the ability of the system to perform advanced inverter functions, can we harness SVP to calculate component level stress metrics over a range of advanced inverter functions?

Harnessing SVP for Reliability Measurements

- New Tektronix oscilloscope driver and reliability script were created
- Directly measures/calculates component stress
- Paired with SVP script to automate stress evaluation for a range of PV irradiance values and power factors.
- ***Produce inverter component stress maps under different operating conditions***

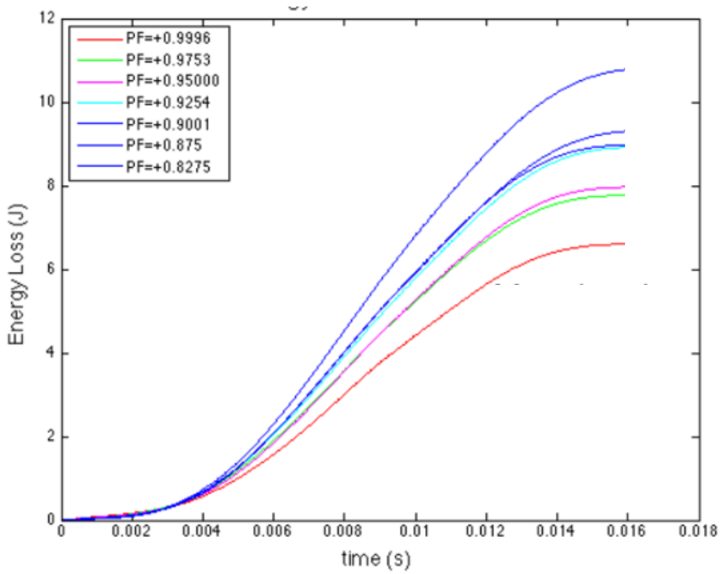


- Allows for flexible measurement of any accessible component inside the inverter
  - switches, capacitors, inductors, etc.
- Set of experiments to measure loss of **switches in H-bridge** and **DC bus capacitor**



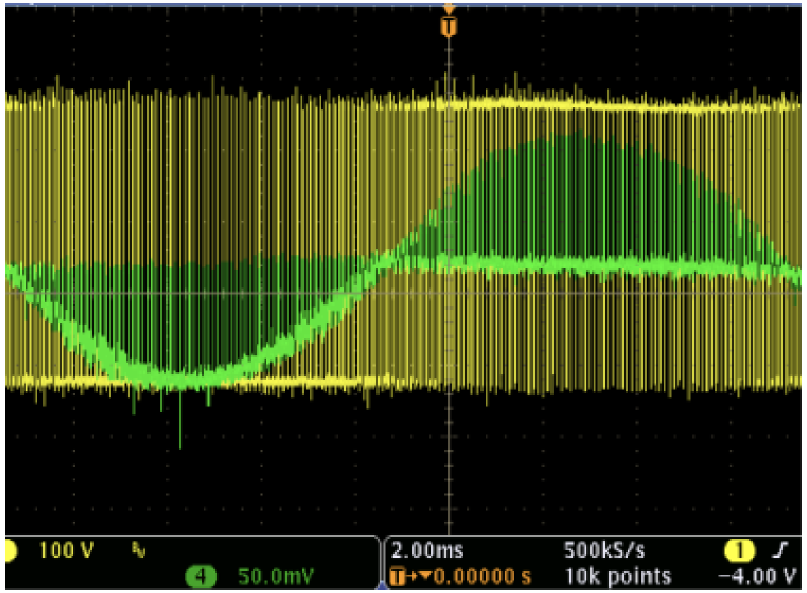
Measuring loss in H-bridge Switch –Setup

- Autonomous run carried out to measure MOSFET switch loss in H-bridge:
  - Single-phase, 3 kW inverter.
  - Loss measured at power factors from -0.85 to 0.85 in 0.01 increments.
  - At each PF, 20 measurements taken serially and averaged together
  - Irradiance values of 200 W/m^2 to 1000 W/m^2 in 200 W/m^2 increments.

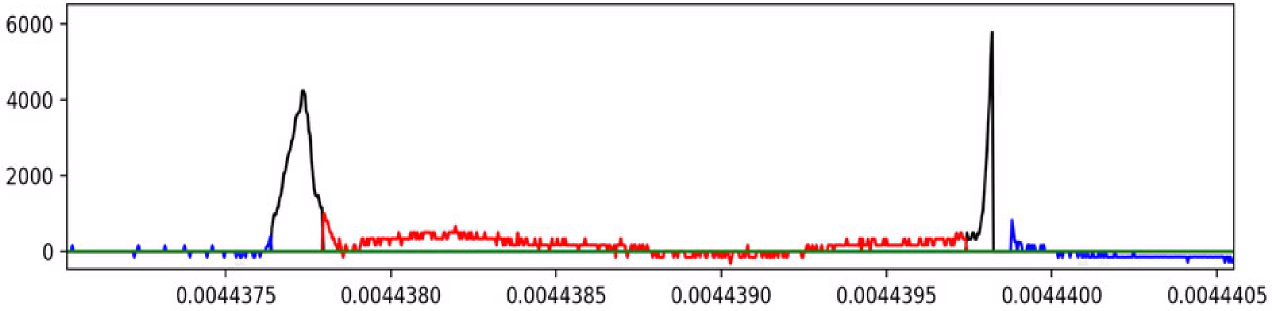


4. Increment PF, irradiance, etc.

1. Measure Switch Voltage/Current

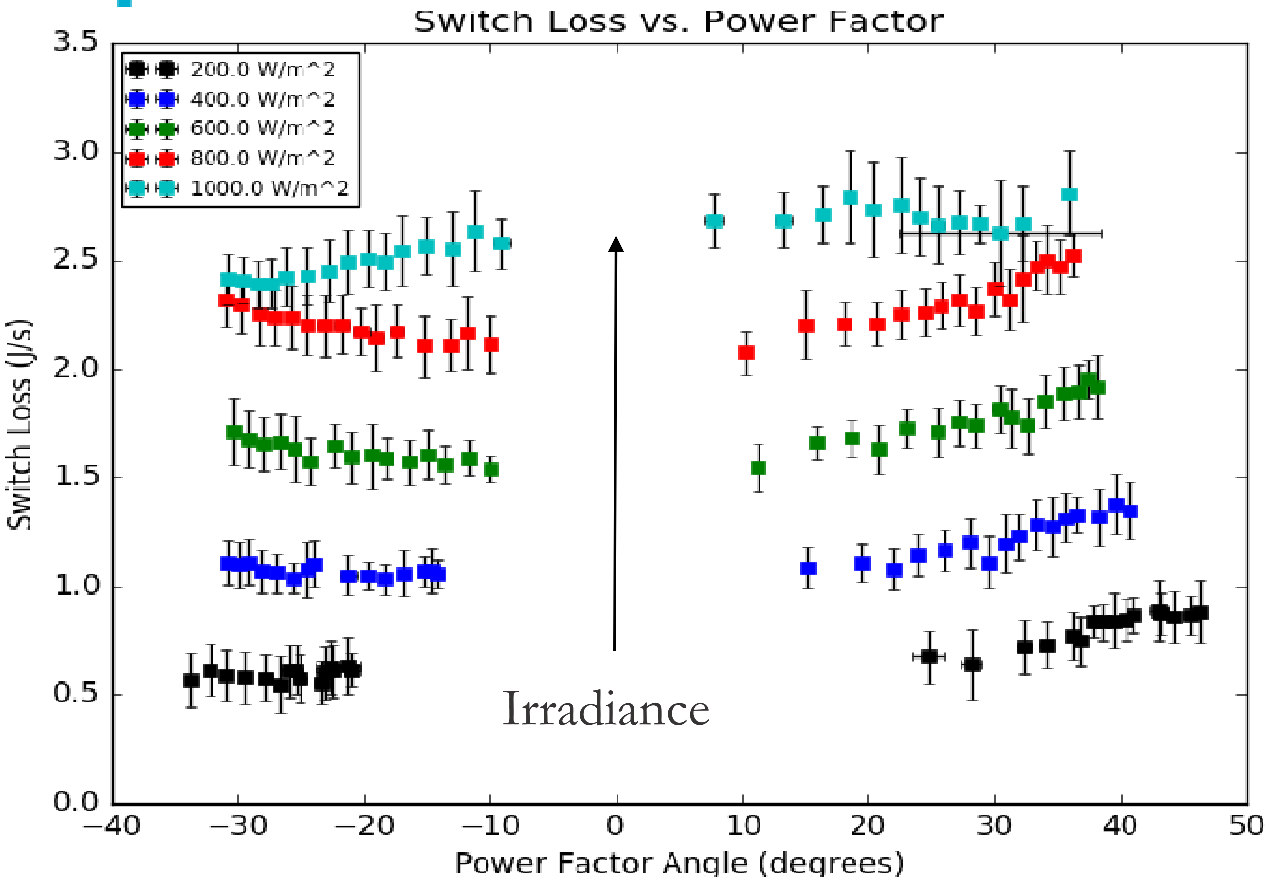


2. Calculate Switch Power



3. Cumulative switch loss per cycle

Measuring loss in H-bridge Switch –Results



- System level efficiency shows increased loss:
  - With increased irradiance.
  - At increased positive power factor.
- Total change in efficiency is approximately1%:
  - Additional ~30 W of loss at high PF.
- Switching loss is directly related to:
  - Irradiance level.
  - Positive power factor:
    - At high irradiance, also increase in switch loss for negative power factor.
    - Minimum loss at unity PF.

- 1000 W/m^2 measurement switching loss affected by system curtailment.
- Corresponds to device loss map as a function of irradiance and PF.

How can we use loss maps to extract information about expected useful life?

J. Flicker, J. Johnson, P. Hacke, and R. Thiagarajan, "Automating Component-Level Stress Measurements for Inverter Reliability Estimation," *Energies,* vol. 15, no. 13, p. 4828, 2022.

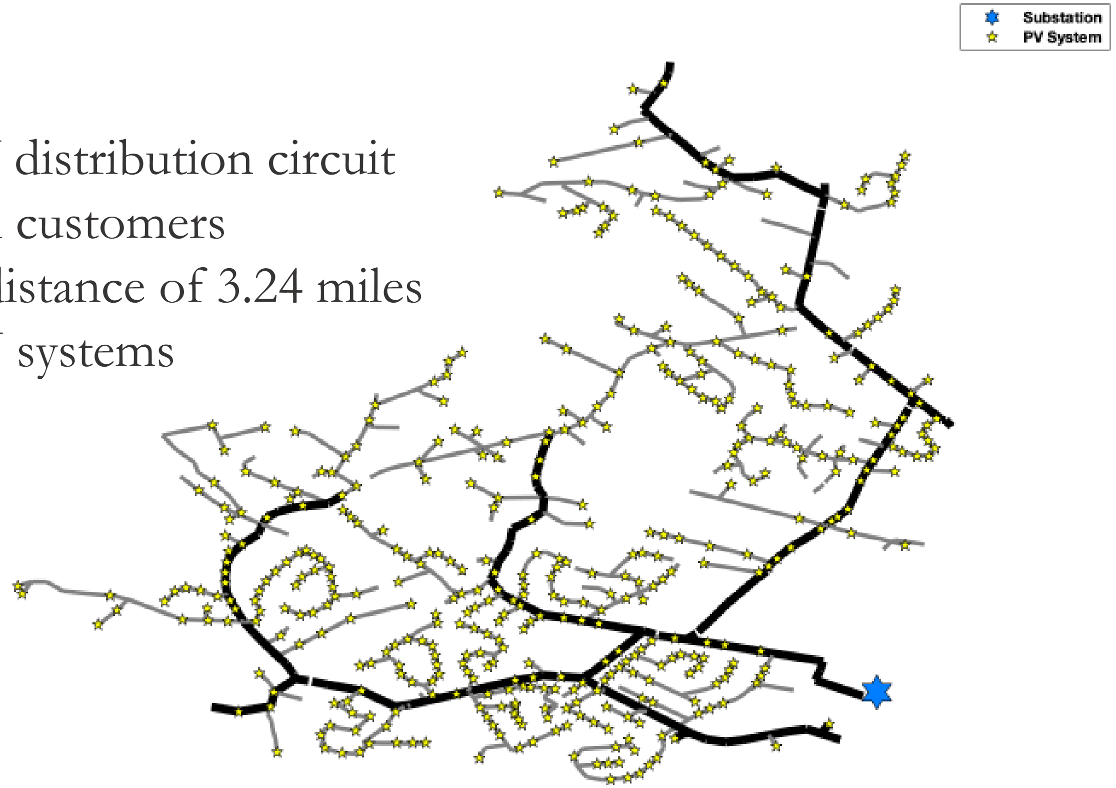
Preliminary Lifetime Calculations (1/4)

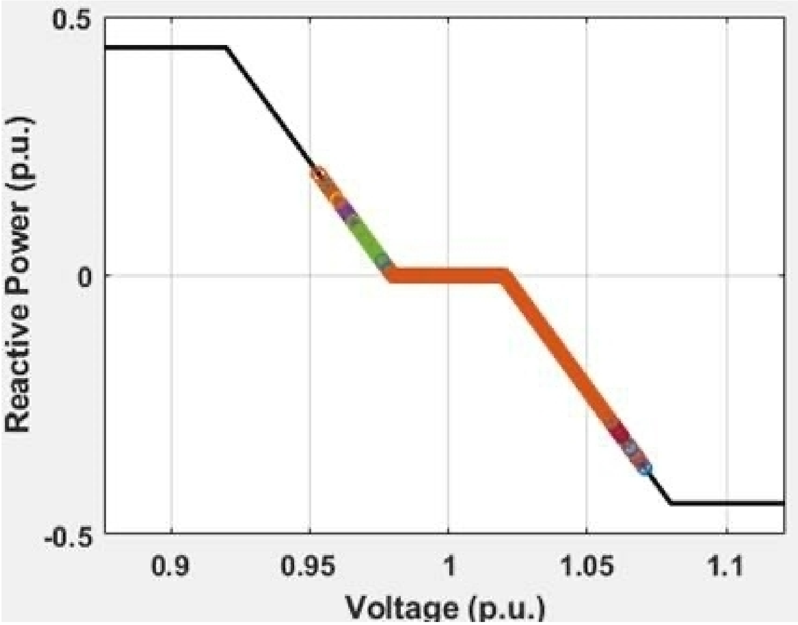
- In any real system inverters respond based on programmed Volt-VAr curves

- Utilized quasi-static time series (QSTS) simulations modified EPRI Ckt5 test feeder
  - Yields time series power data (real/reactive) for each inverter in system
  - Based on pre-programmed advanced inverter operation profile

<u>Ckt5 Feeder</u>

- Actual 12.47 kV distribution circuit
- 1,379 residential customers
- Maximum bus distance of 3.24 miles
- Total of 701 PV systems





Operating points of all 701 inverters at a single time step for IEEE 1547 Category B

- J. A. Azzolini and M. J. Reno, "Impact of Load Allocation and High Penetration PV Modeling on QSTS-Based Curtailment Studies," in *IEEE Power & Energy Society General Meeting (PESGM)*, 2021.
- EPRI, "Enhanced Load Modeling: Leveraging Expanded Monitoring and Metering," vol. 3002015283, 2019.

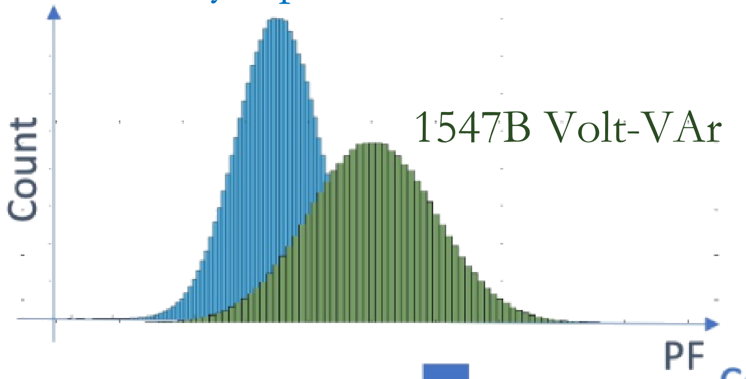
Preliminary Lifetime Calculations (2/4)

Operational System

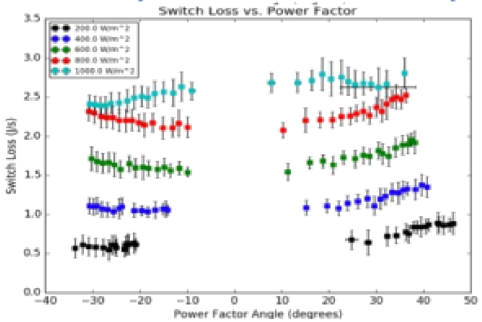
QSTS
Results

Advanced Inverter Mission Profile

Unity Operation



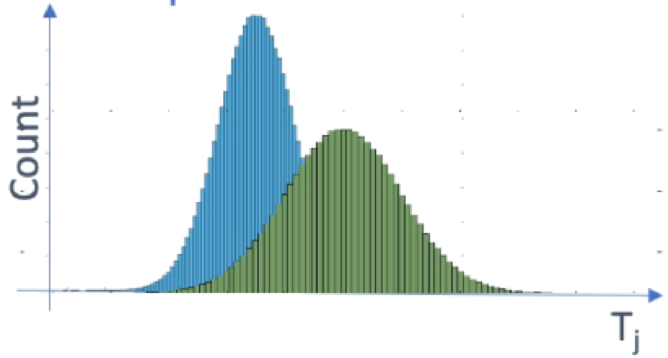
Component Stress Map



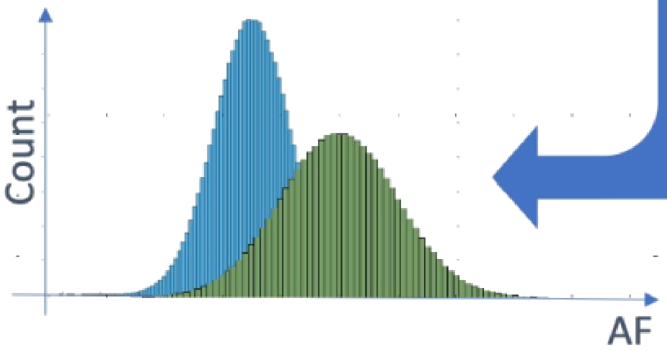
Lifetime Model

$$A_F = e^{\frac{E_a}{R}\left(\frac{1}{T_j^{InvA}} - \frac{1}{T_j^{InvB}}\right)}$$

Component Stress Profile



AF Collective



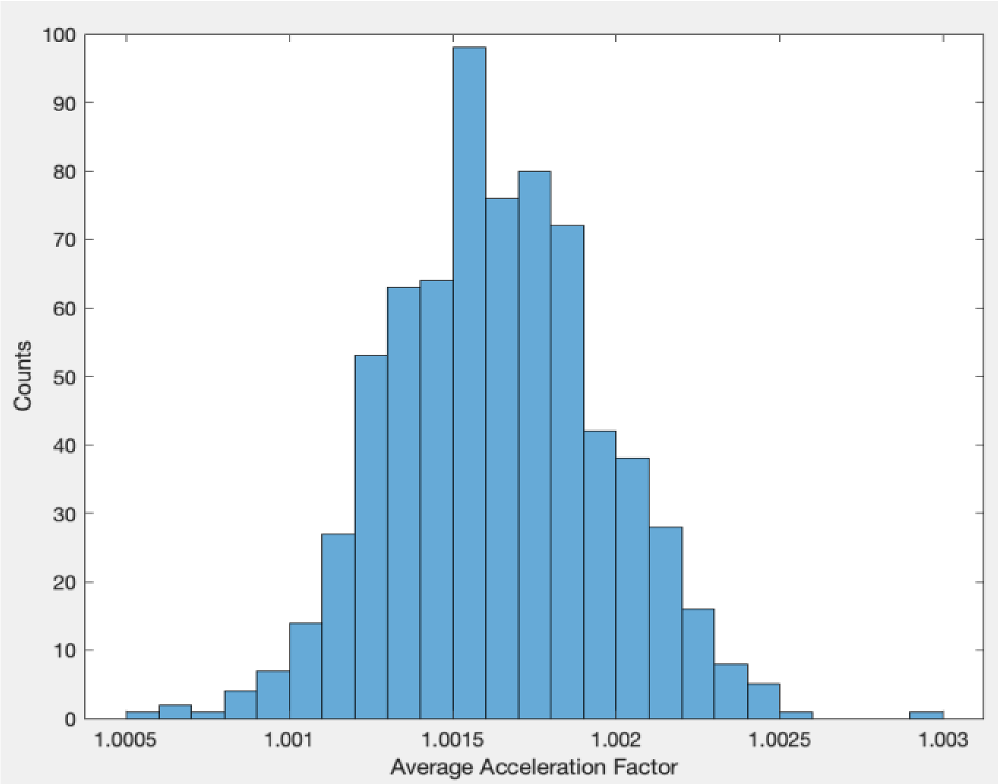
Average Relative Aging Factor

$$\frac{1}{A_{F,avg}} = \sum_i \frac{p_i}{A_{F,i}}$$

NB: Same process for any pairwise comparison. Same inverter with different operating modes or two different inverters in system

This is a <u>general framework</u>, can substitute in any system, operating mode, stress map, and lifetime model

Preliminary Lifetime Calculations (3/4)



- Calculated relative change in average acceleration factor (AF_{avg}) for 701 inverters operating in EPRI Ckt5 test feeder
- Compared static unity power factor (PF=1) vs. IEEE 1547 Category B default volt-var curve

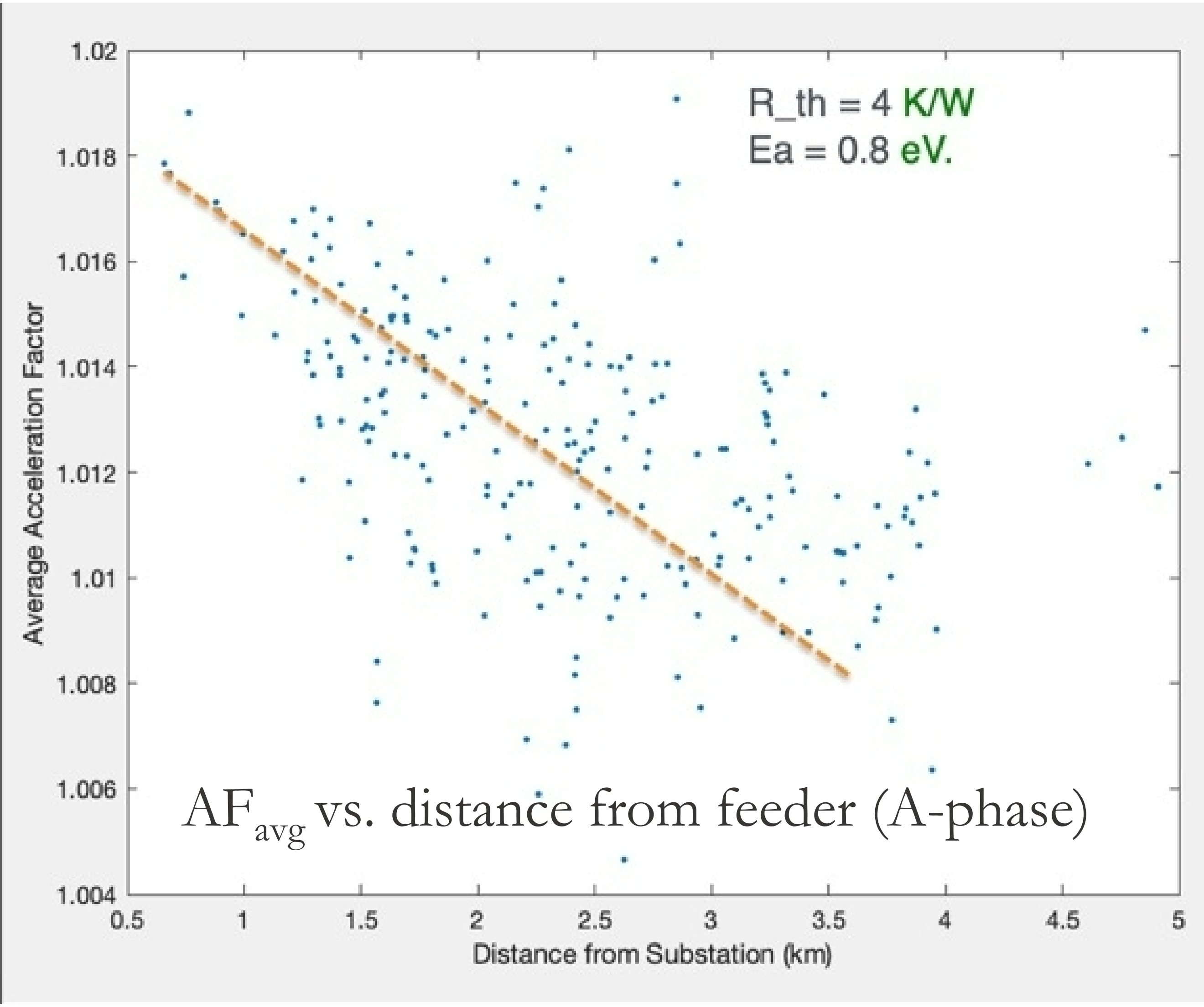
- Mean AF_{avg} for inverters in the system :
  - 1.0015±0.00033
- Incorporation of IEEE 1547 Category B volt-var curve results in only a **0.15% faster degradation** rate for the median inverter
- If standard inverter has a 20-year lifetime, the median inverter would fail only **12 days earlier**
- Depending on assumptions → corner case up to ***1.8% faster degradation***
  - 4.5 month earlier failure

Problem solved!?

Probably not

- Indicates that switching loss is ***probably not*** limiting failure mechanism for Volt-Var operation
- Need to evaluate for ***all other*** competing failure mechanisms
  - 100s to 1000s of other mechanisms

Preliminary Lifetime Calculations (4/4)



AF_{avg} vs. distance from feeder (A-phase)

- Extract information on individual inverters in system
- Aging rate for inverters correlated to **distance from the substation**
  - Additional aging -0.25%/km from substation
  - Inverters closer to substation experience ***greater stress***
- Substation operates at high end of ANSI (~1.05 pu) to offset low voltage at end of feeder
- Inverters near substation work more often to lower the voltage *and* against stiff substation interconnect
  - Operate at non-unity more often *and* at higher PF than the inverters at ends of feeder

NB: Results ***highly*** dependent on system specifics (line length, voltage, inverter number/placement, etc.).
Not necessarily generalizable to all systems

Conclusions

- Inverters are required to be good "grid-izens" and provide grid support through ***advanced inverter operating functions***
- These functions may introduce additional stress compared to typical operational conditions
- Significant evaluation and testing is required to understand impacts to inverter reliability, similar to certification testing (but harder)
- Introduced ***general experimental and simulation framework*** to couple experimental component-level stress measurement data with system-level operational data
  - SVP used to autonomously evaluate component stress for parameterized operating conditions
  - QSTS simulations used to model expected inverter power factor operation 701 inverters
  - Degradation due to switch loss from volt-var operation ***is not*** a significant contributor to early failure

Thank you

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Principle Member of Technical Staff

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