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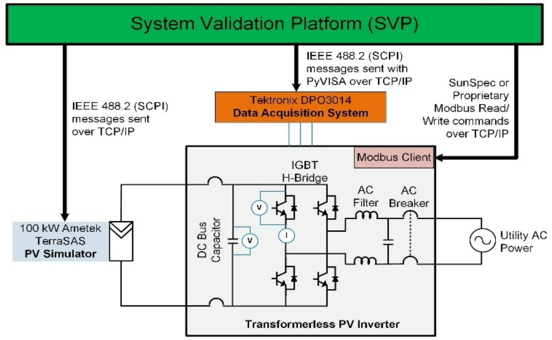
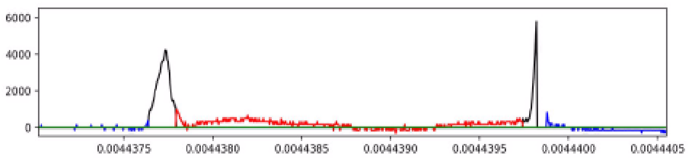
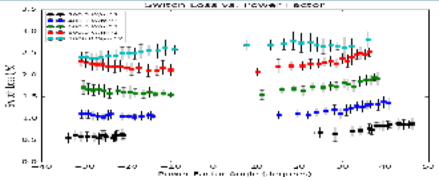
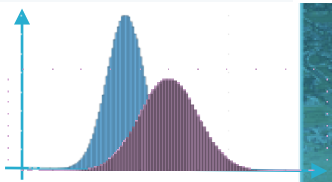
Sandia National Laboratories

Automating Component-Level Stress Measurements for Inverter Reliability Estimation









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June 20-25, 2021

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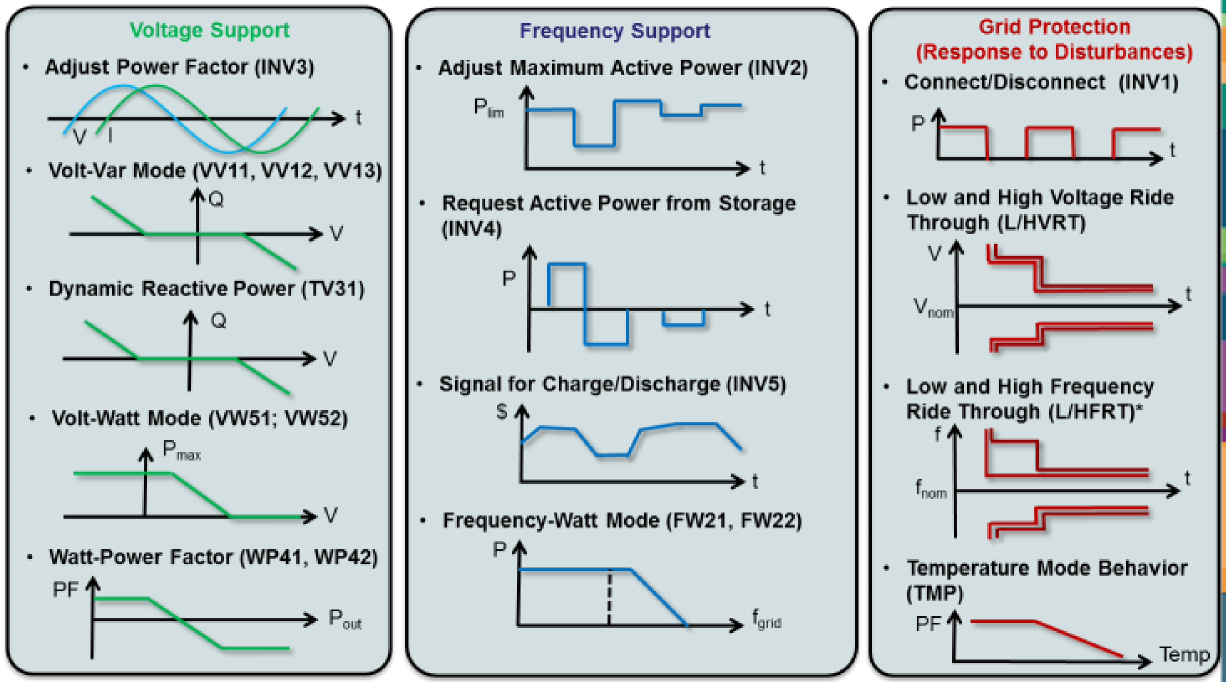
Advanced Inverter Operations and Reliability (1/2)

- **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.



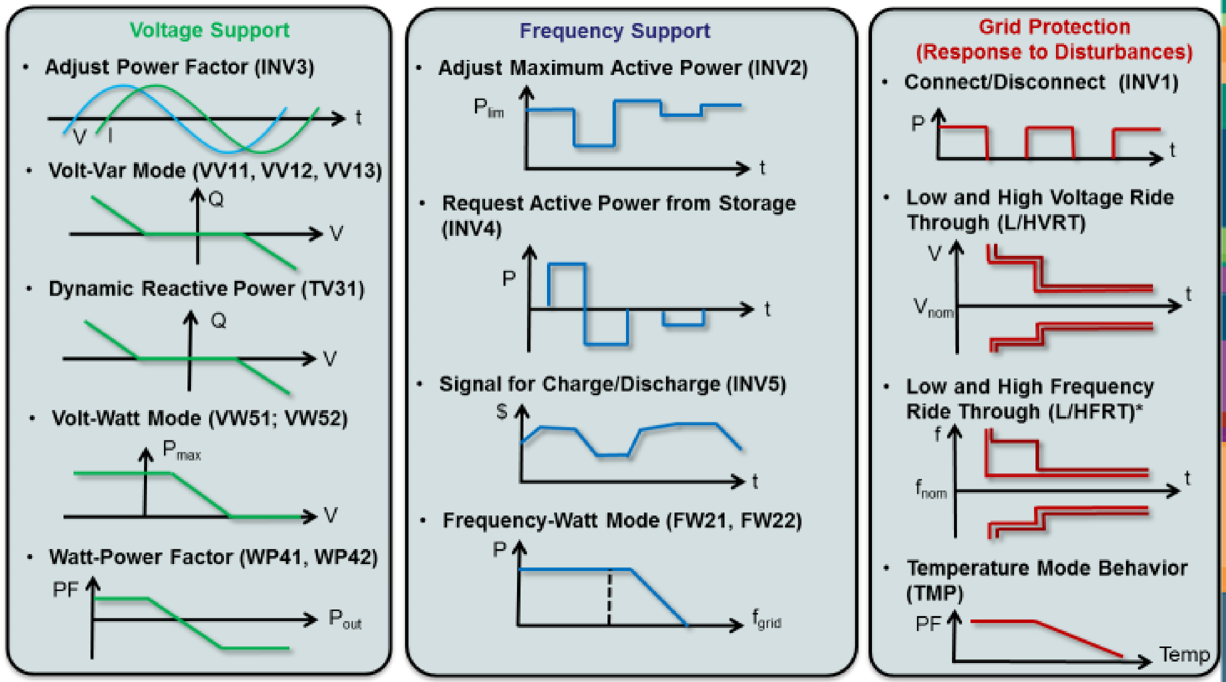
Advanced functions as defined in IEC TR 61850-90-7.
*FRT not included in IEC 61850-90-7, but is in Sandia Test Protocols.

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?

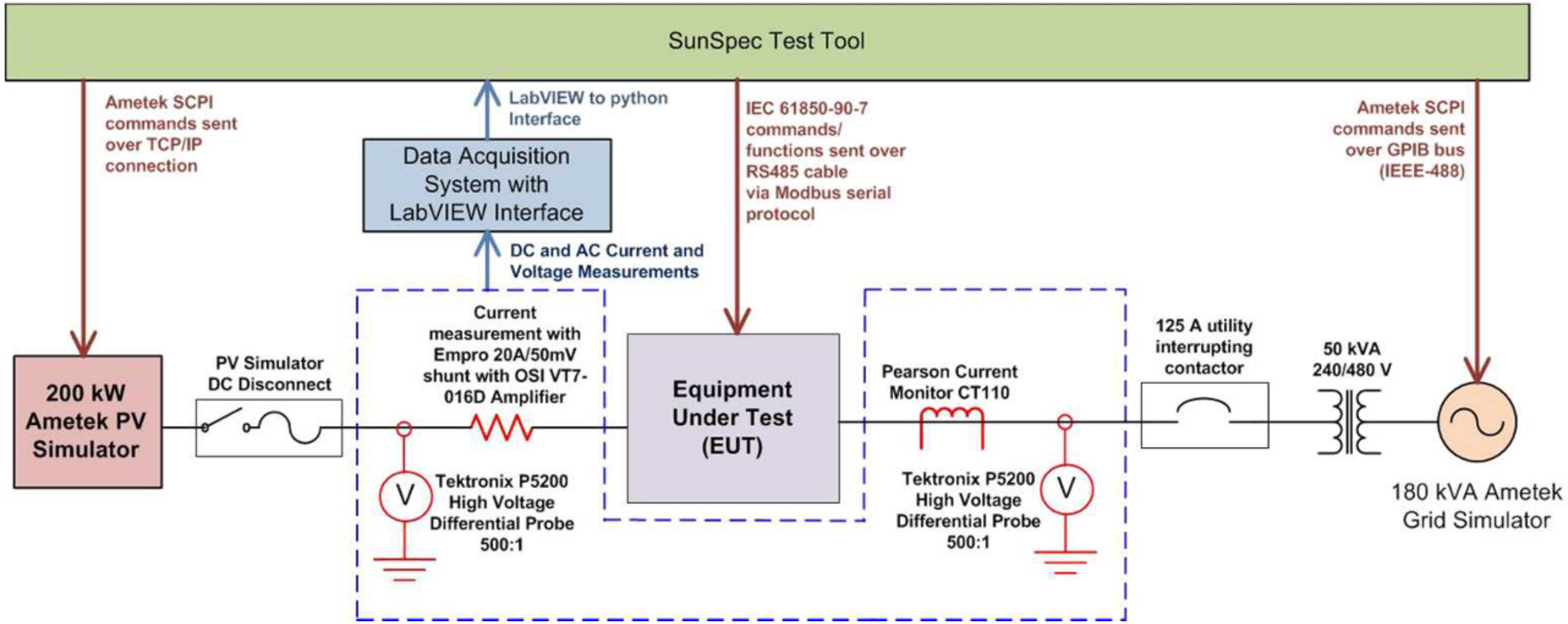


Advanced functions as defined in IEC TR 61850-90-7.
*FRT not included in IEC 61850-90-7, but is in Sandia Test Protocols.

- 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)

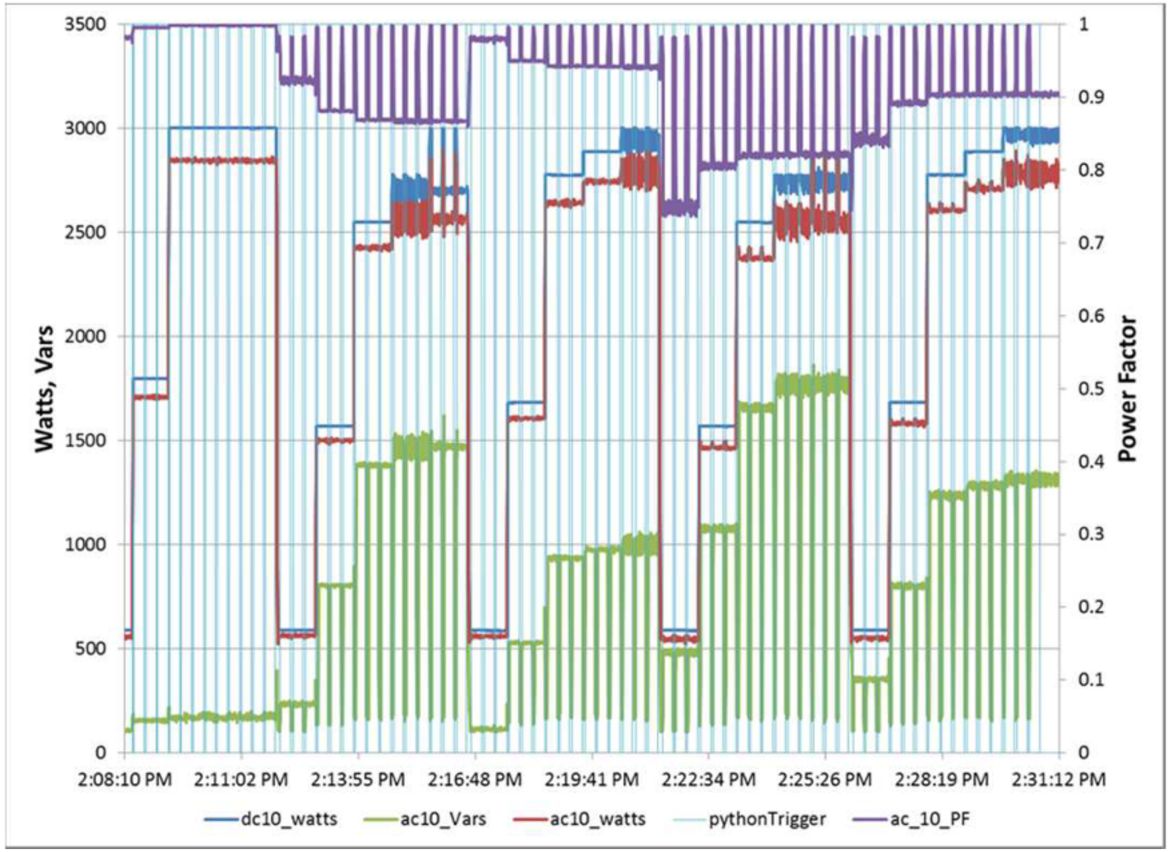
- The open-source System Validation Platform (SVP) initially developed under a Cooperative Research and Development Agreement (CRADA) between Sandia National Laboratories and SunSpec Alliance.

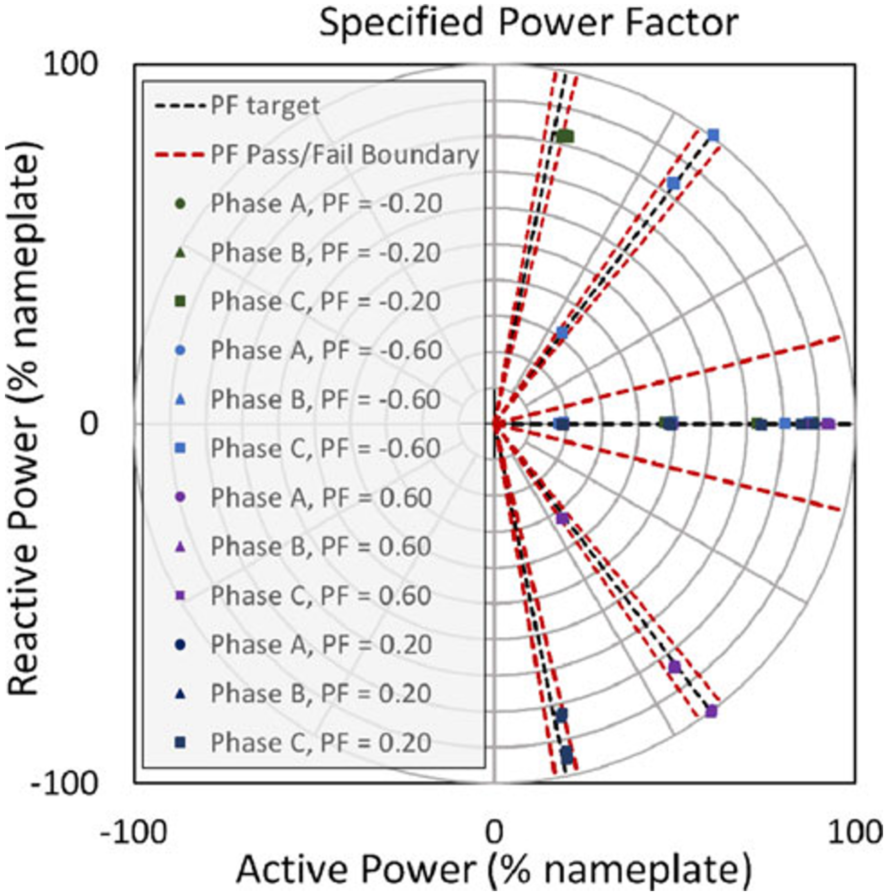


- Range of equipment drivers and test scripts for DER interoperability/electrical characterization experiments.
- Used to evaluate test procedures defined in IEEE 1547.1, UL1741 SA, and IEC TR 61850-90-7.
- Software platform written in Python:
    - Includes ability to script actions for multiple hardware 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.

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 - takes about 25 minutes with the SVP.
  - ~375 measurements for volt/var - takes about 90 minutes with the SVP.

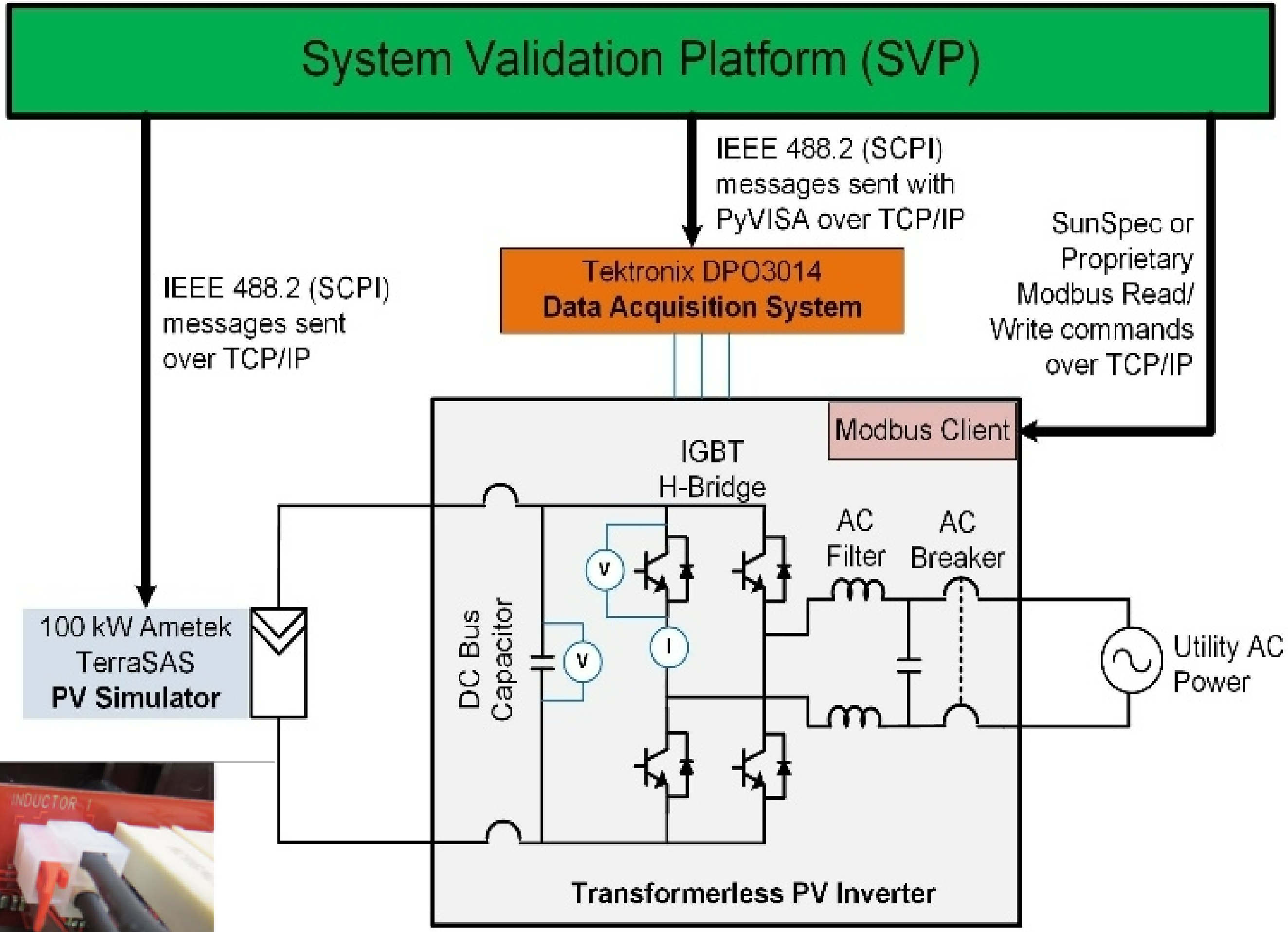




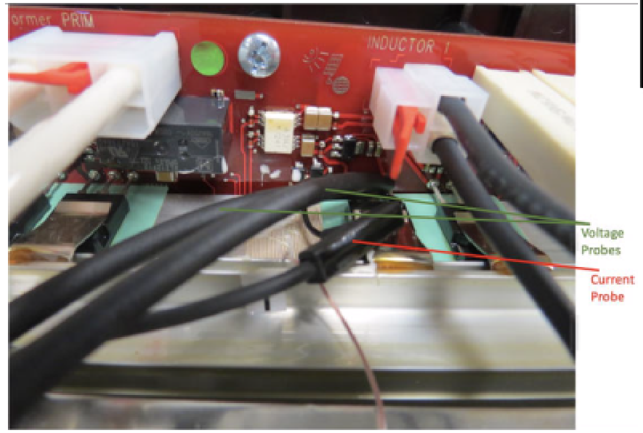
Instead of characterizing the ability of the system to perform advanced inverter functions, can we harness SVP to calculate component level stress metrics over a range of advanced inverter functions?

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.

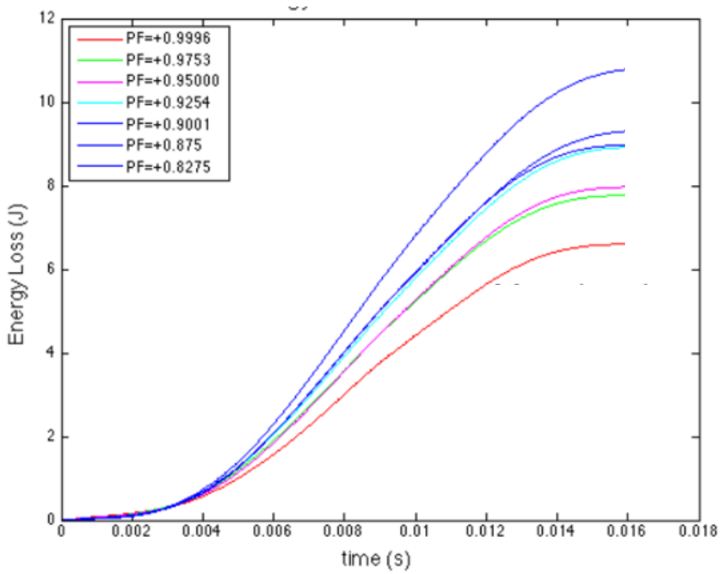


- Allows for flexible measurement of any accessible component inside the inverter
  - switches, capacitors, inductors, etc.
- Set of experiments to measure loss of **switches in H-bridge** and **DC bus capacitor**



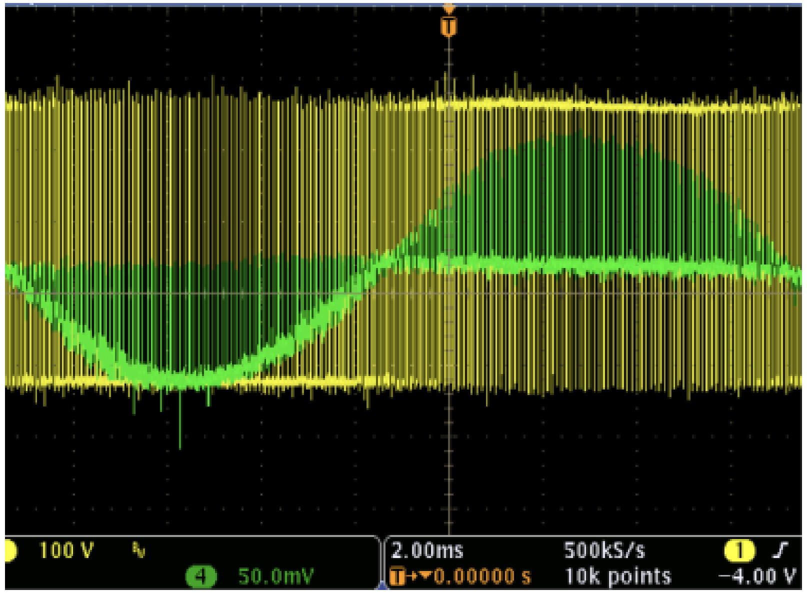
Measuring loss in H-bridge Switch –Setup (1/2)

- 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 0.1 increments.
  - At each PF, 20 measurements taken serially and averaged together.
  - Irradiance values of 200 W/m² to 1000 W/m² in 200 W/m² increments.



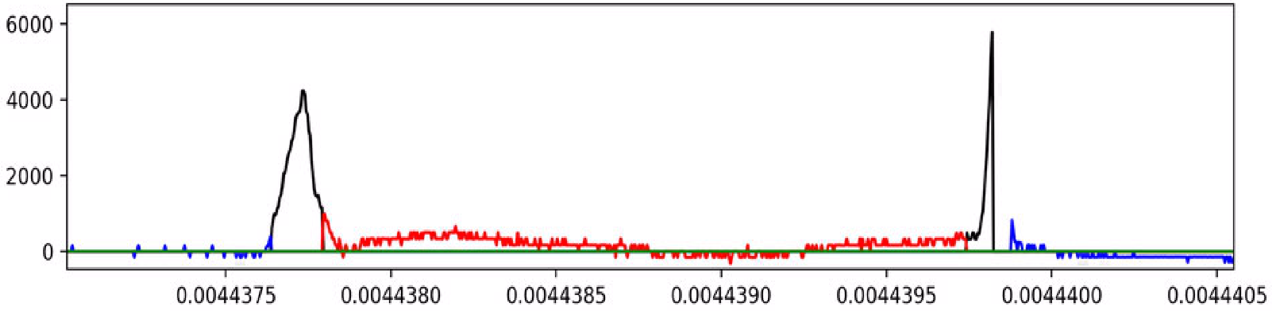
4. Increment PF, irradiance, etc.

1. Measure Switch Voltage/Current

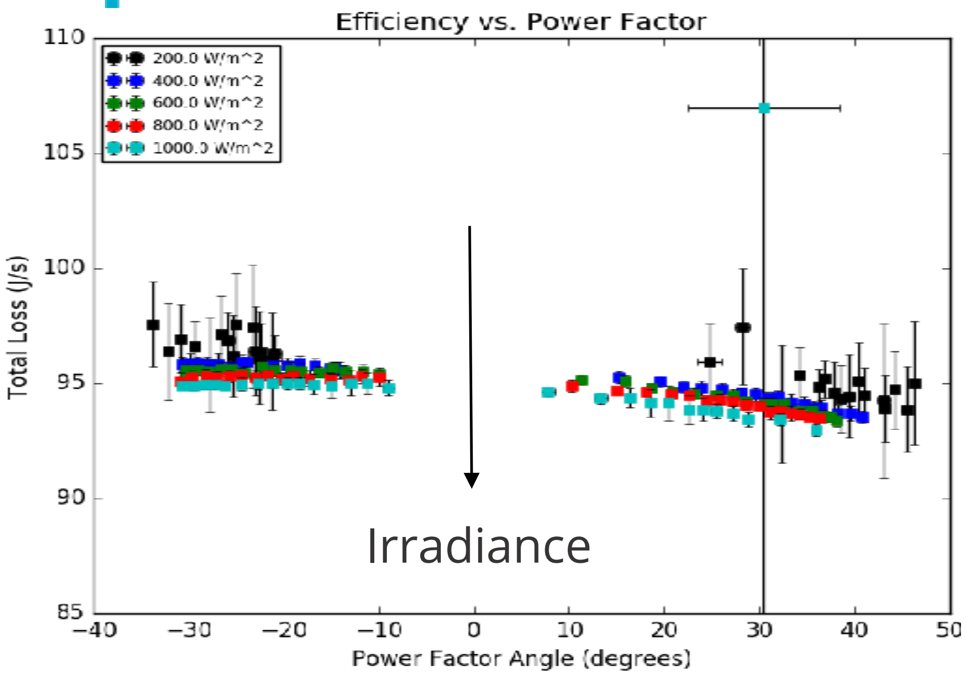


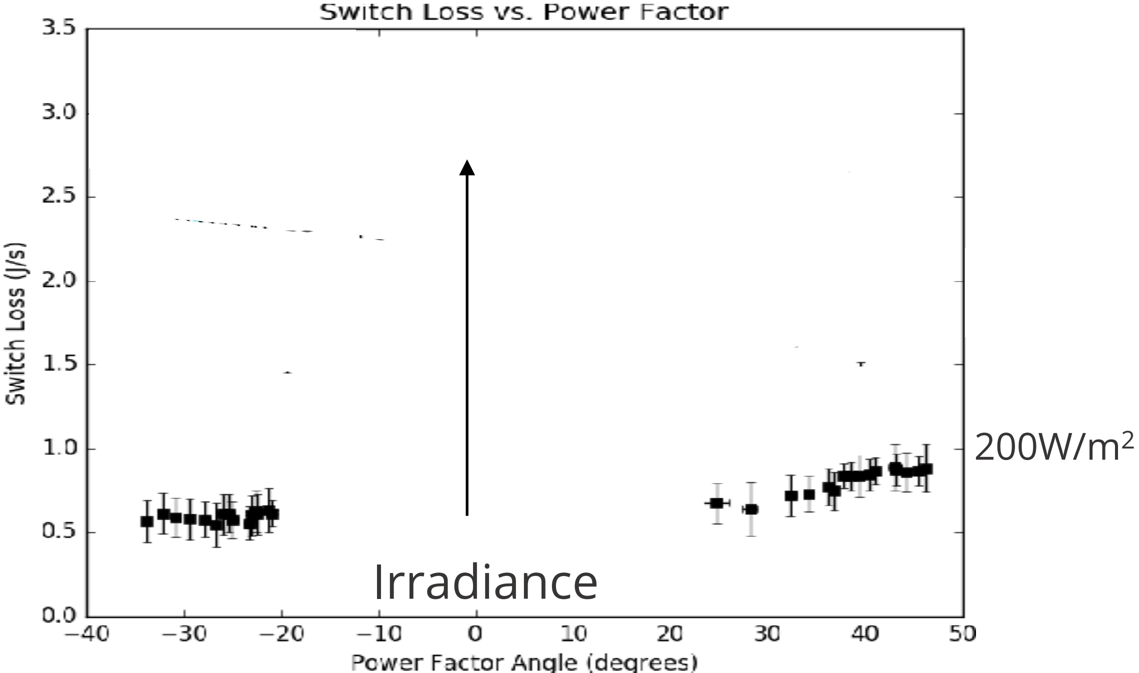
3. Cumulative switch loss per cycle

2. Calculate Switch Power



Measuring loss in H-bridge Switch –Setup (2/2)

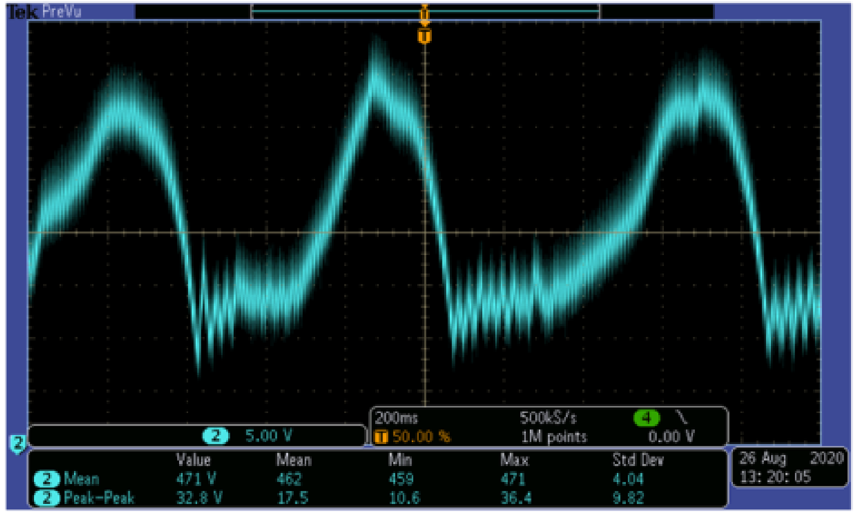




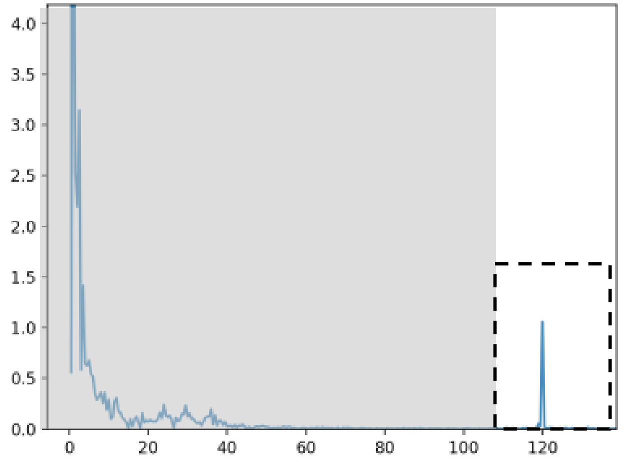
- System level efficiency shows increased loss:
  - With increased irradiance.
  - At increased positive power factor.
- Total change in efficiency is approximately1%:
  - Additional ~30 W of loss at high PF.
- Switching loss is directly related to:
  - Irradiance level.
  - Positive power factor:
    - At high irradiance, also increase in switch loss for negative power factor.
    - Minimum loss at unity PF.
  - Corresponds to ~10% of 30W loss expected by system-level measurements.
- 1000 W/m^2 measurement switching loss affected by system curtailment.
- Corresponds to device loss map as a function of irradiance and PF.

Bus Voltage/Current Measurements—Setup

1. Measure Capacitor Voltage/Current



2. Fourier Transform and filter to ~120HZ



3. Increment PF, irradiance, etc.

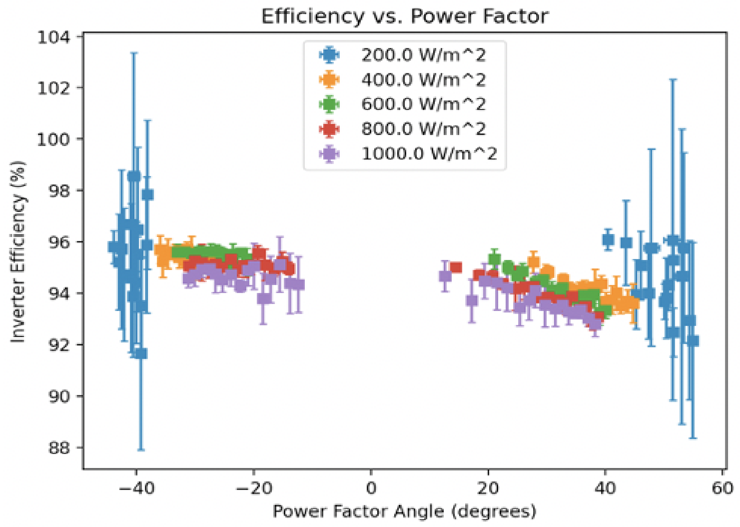
- Capacitor degradation usually attributed to two factors:
  - Magnitude of Voltage stress.
  - Self-heading due to current ripple (~120Hz).

- Carried out tests on 3 devices from two manufacturers:
  - Manufacturer A, 3 kW single phase device.
  - Manufacturer B, 3 kW single phase device.
  - Manufacturer B, 24 kW three phase device.

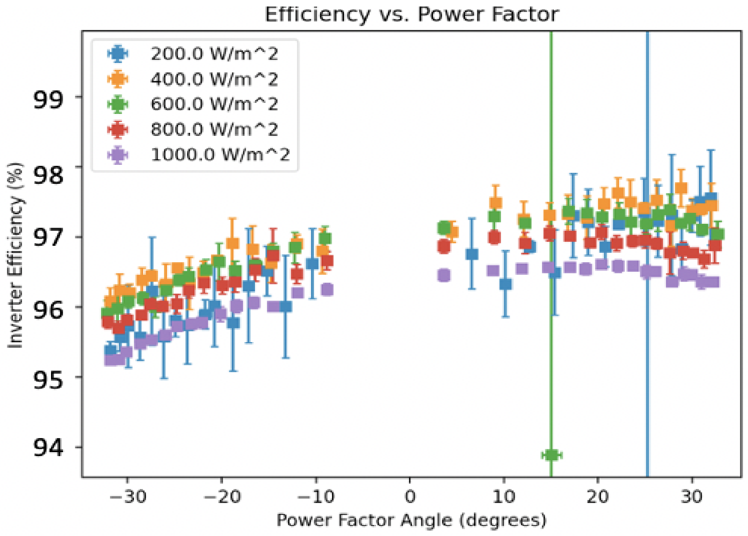
- Data for power factors ranging from -0.85 to 0.85 in 0.5 step increments:
  - Magnitude of Current/Voltage across capacitor.
  - Voltage/Current ripple:
    - Filtered Fourier Transform of waveform for frequencies 110-130 Hz.

Bus Voltage/Current Measurements—Results (1/3)

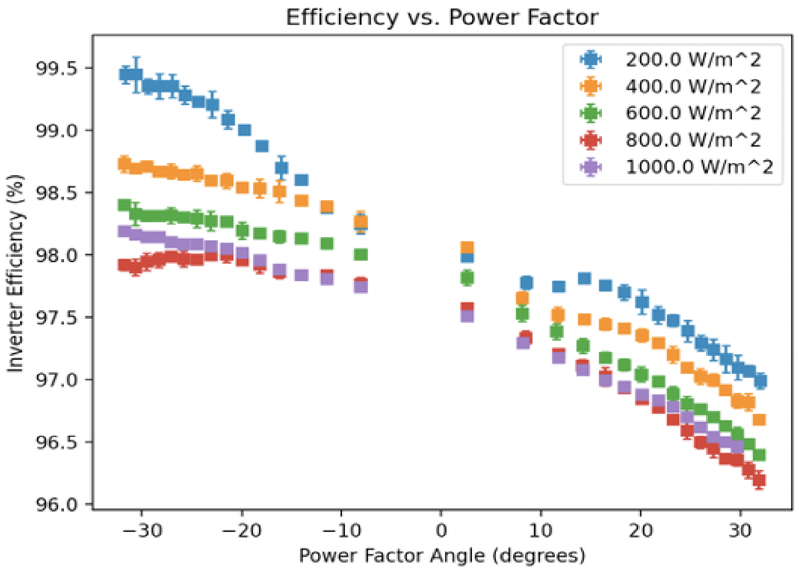
Manufacturer A Single phase



Manufacturer B Single phase



Manufacturer B Three phase

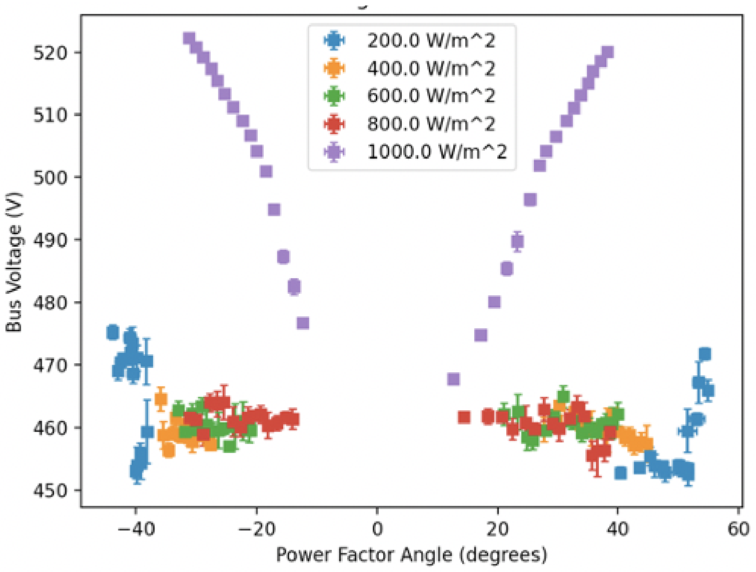


Efficiency

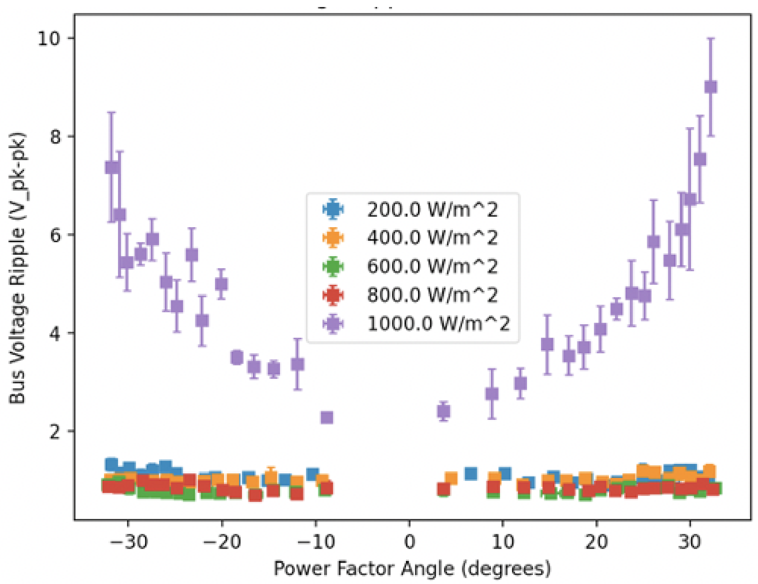
- Three different devices show significant differences.
- Device 3 shows significantly higher efficiency
  - Largest dependence of efficiency on PF
  - 99.5% at high negative PF to a low of 96% at high positive PF
- Device 2 maximum efficiency occurs at high positive PF with high irradiance
- Device 1 shows a much smaller dependence on irradiance than Devices 2 and 3
- Efficiency behavior is function both of control as well as topology
  - Ex. if on-state losses are a large component of the total system loss → would expect a significant dependence irradiance.

Bus Voltage/Current Measurements—Results (2/3)

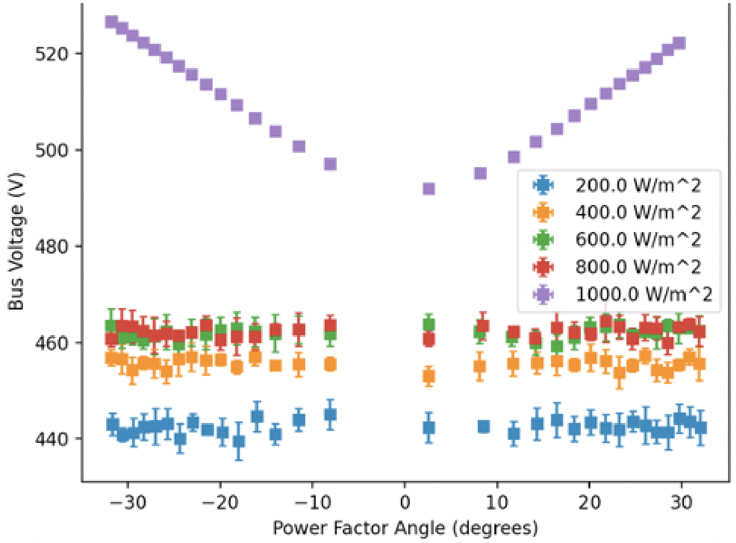
Manufacturer A Single phase



Manufacturer B Single phase



Manufacturer B Three phase



<u>Mean Capacitor Voltage</u>

Irradiance

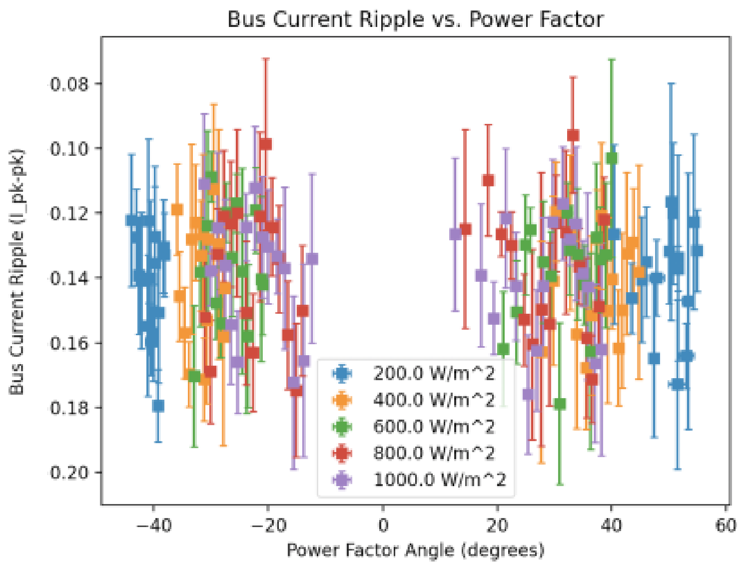
- Significant increase in capacitor voltage when curtailing for all devices (as expected.
- Devices 1 and 2 show no dependence.
- Device 3 shows increasing voltage stress with irradiance.

Power Factor

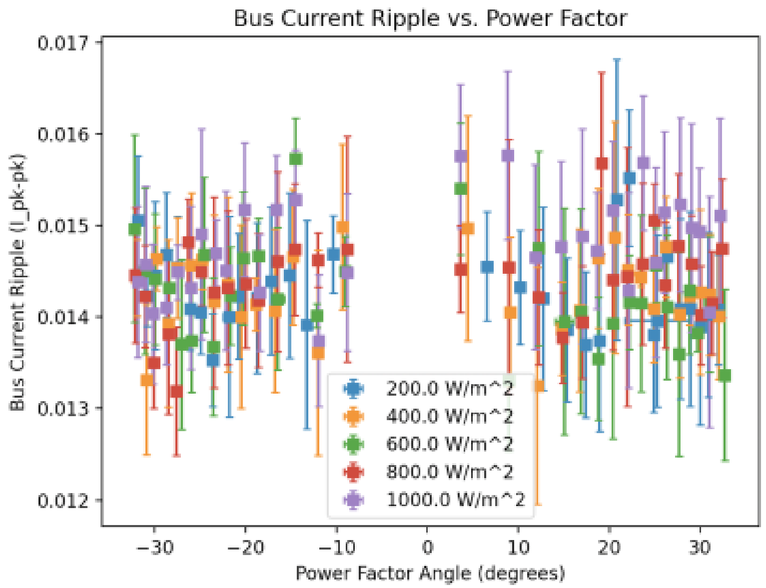
- No dependence of capacitor voltage on power factor.

Bus Voltage/Current Measurements—Results (3/3)

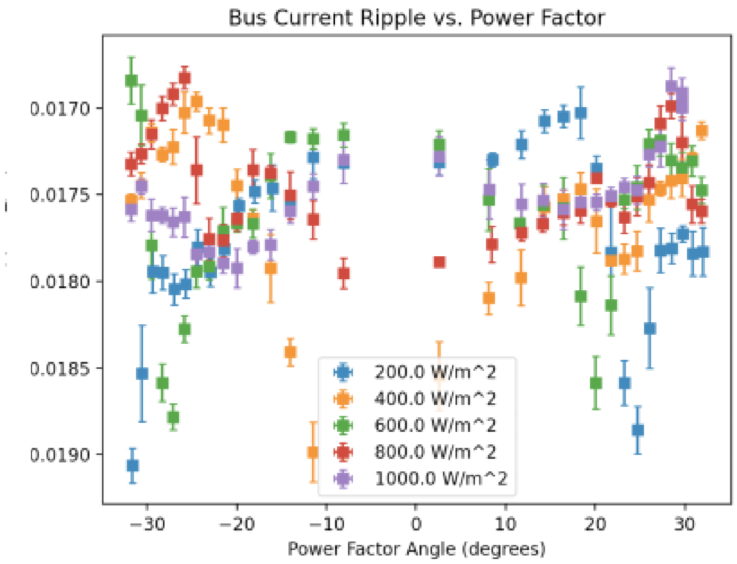
Manufacturer A Single phase



Manufacturer B Single phase



Manufacturer B Three phase



<u>Current Ripple</u>

- For all devices, no dependence on either PF or irradiance.
- Device 2 and 3 have equivalent ripple magnitudes.
- Current ripple on Device 1 is 10x higher than Device 2 and 3.

Conclusions

- Demonstrated the utility of the SVP framework to be applied to automated reliability measurements.

- Described a method of incorporating traditional reliability measurement equipment (e.g. oscilloscope) into the SVP:
  - Can evaluate traces to calculate parameters of interest.
  - Flexible with stress and component type.
  - Can be utilized with any advanced inverter function (f-W, V-V, LVRT, etc).

- Utilized this framework to carry out example measurements on component stress as a function of advanced inverter function:
  - Measured switch loss as a function of power factor and irradiance level:
    - Increasing loss at larger non-unity power factors.
    - Replicated in system-level measurements.

  - Measured capacitor voltage and current:
    - Voltage and current ripple shows no dependence on power factor.

Future Work (1/2)

- We have presented a tool for characterizing component stress as a function of parameterized advanced inverter operation.

- This tool can be used to determine relative stress under different operating conditions.

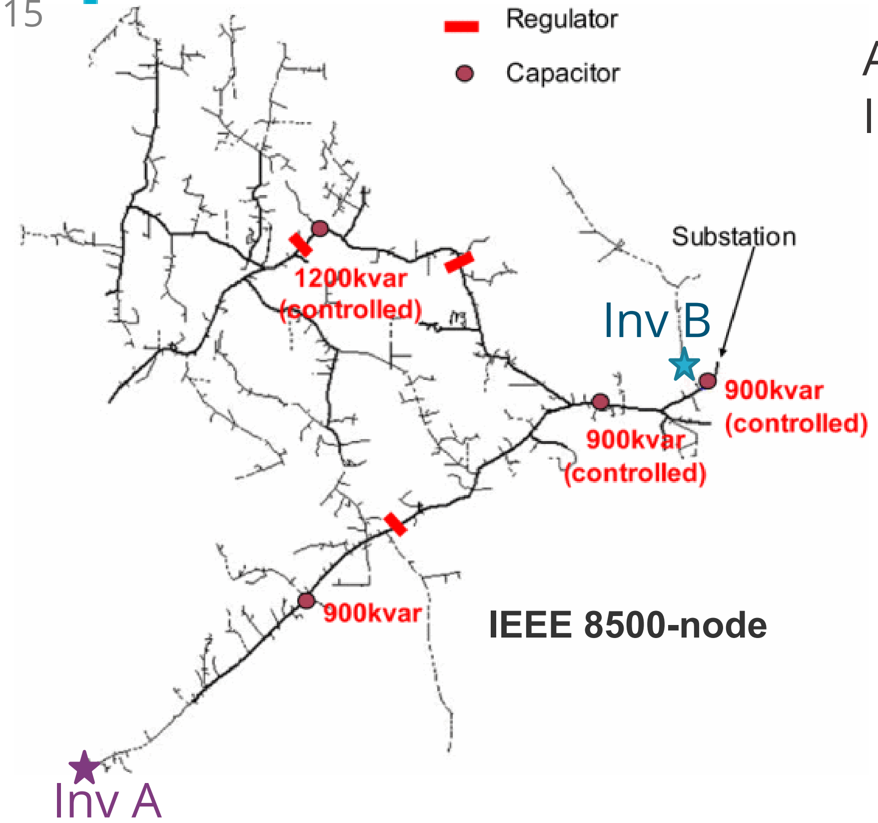
- **But how does this relate to fielded unit lifetime?**

  - Assuming:
    - The relevant measured stress is the cause of failure.
    - Stress can be linearized over the fielded mission profile.

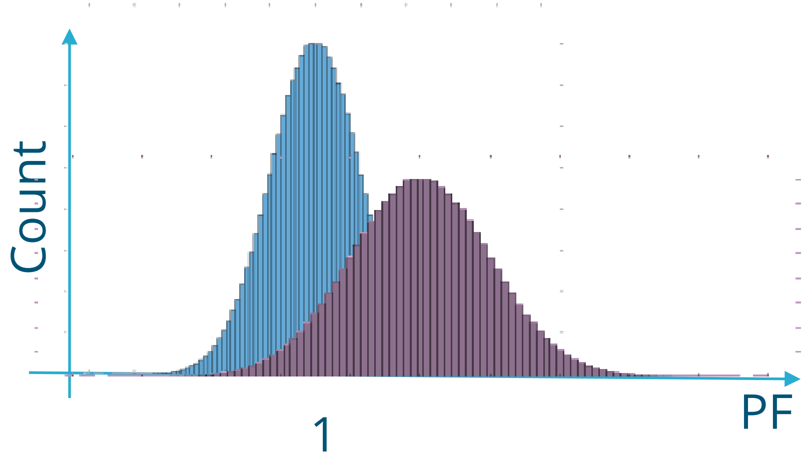
  - Then with:
    - Mission profile of advanced inverter operation .
    - Stress map.
    - Lifetime model.

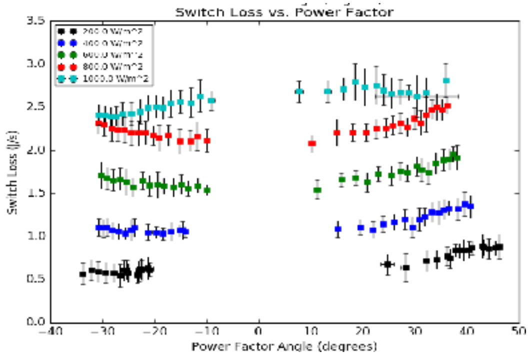
- It can be possible to find relative reduction in useful life.

Future Work (2/2)

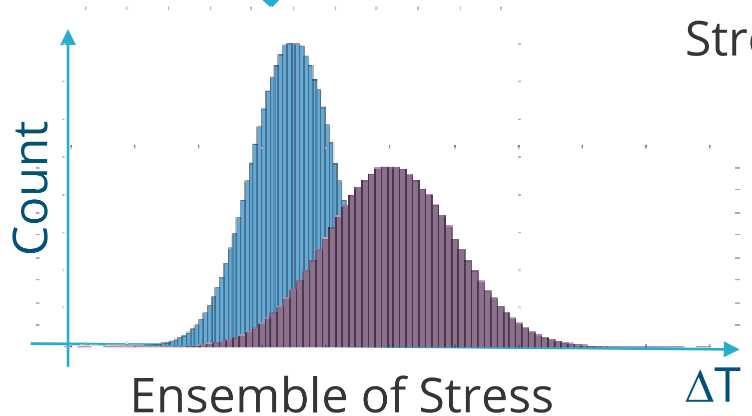


Advanced Inverter profile





Stress Map



Lifetime Model

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

Average Relative Aging Factor

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

R. F. Arritt and R. C. Dugan, "The IEEE 8500-node test feeder," *IEEE PES T&D 2010*, 2010, pp. 1-6, doi: 10.1109/TDC.2010.5484381.

Thank you

Jack D. Flicker, PhD

Principle Member of Technical Staff

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