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# Live state of health monitoring of inverter subsystems

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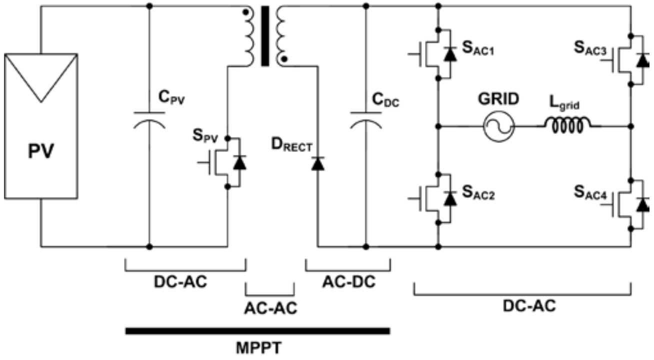
NREL

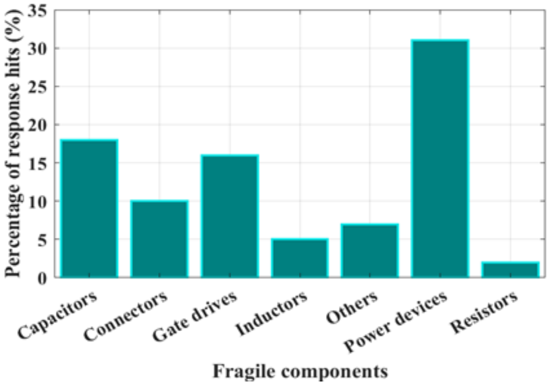
# Components of a PV Subsystem and Reliability Issues

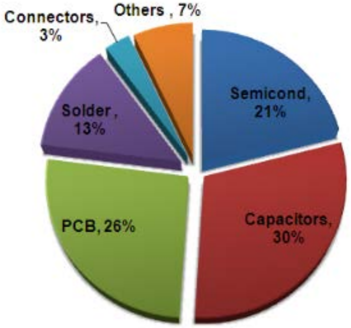




Power electronic converter circuit for PV power harvesting

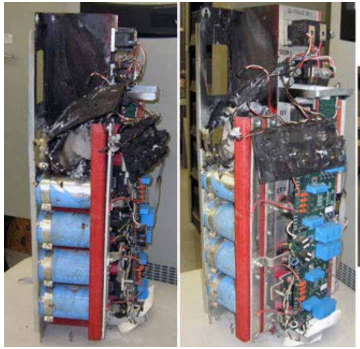
- PV panel degradation and cable faults
- Inverter degradation and converter failures
- Interconnect and protection system failures




*YANG et al.: RECENT ADVANCES IN FAULT DIAGNOSIS TECHNIQUES FOR PHOTOVOLTAIC SYSTEMS: A CRITICAL REVIEW*

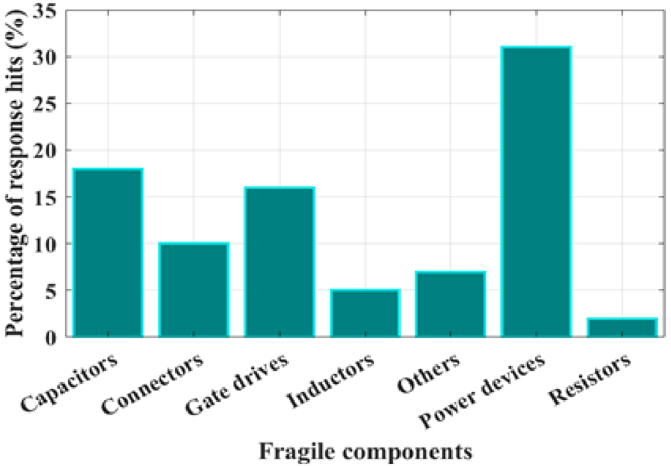
# Energy Conversion Systems and Reliability

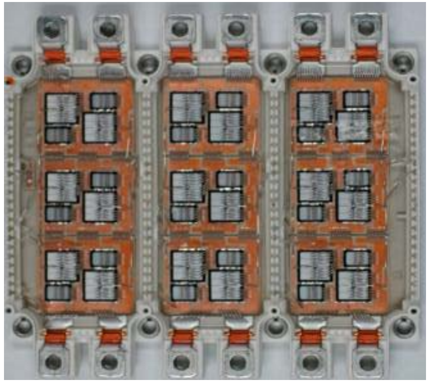


UPS Inverter Assembly

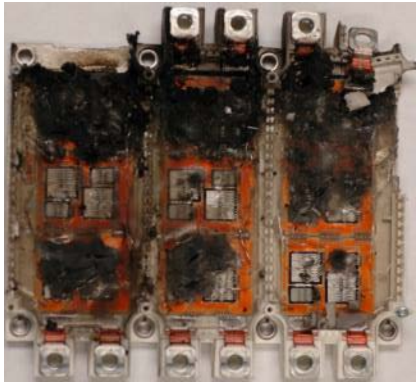
- A modern power conversion system may have components including high-power dc-ac inverters, electric machines such as motors and transformers, renewable energy sources such as wind generators or solar cells and energy storage units in the form of battery banks.
- Most of these power processing units are subjected to electrical and thermal stress resulting in performance degradation.
- In order to ensure a failure free operation, components in a power system employed in critical applications are being operated with redundancy and are needed to go through periodic replacements.
- This periodic maintenance is time and cost intensive, thus shows promise for optimization.

# Degradation in Power Electronic Components and Systems



Healthy IGBT[1]



Failed IGBT due to thermal runaway[1]

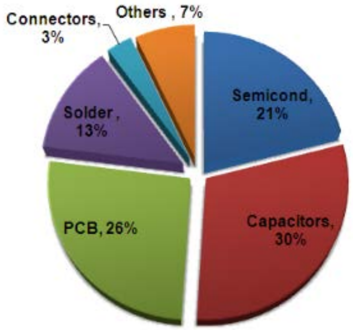
- Power semiconductor devices (MOSFETs and IGBTs) are the most fragile components in power electronic systems.
- When they fail, results can be catastrophic.
- Failure prediction can reduce maintenance costs and potentially save human lives.

Wind turbine at fire due to failed IGBT module[1]

[1]*https://www.nrel.gov/pv/assets/pdfs/2015_pvmrw_131_das.pdf*

# Power Converter Failure: Facts



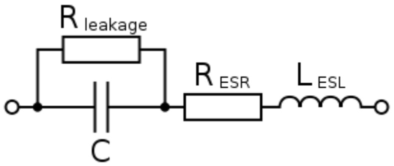

- Electrolytic capacitors and semiconductor switches are two of the most affected components due to aging in power converters.[1]
- Capacitor equivalent series resistance (ESR) increases and capacitance decreases due to aging.
- Accidental high voltage applied at the gate terminal increases the threshold voltage.
- MOSFET ON–state resistance ($R_{DS}$) changes due to thermal aging.
- Degradation at the contact area of bonding wire, such as metallization, and at the die solder layer occur due to thermal aging, which are reflected in the change in MOSFET $R_{DS}$.
- Threshold voltage, transconductance, and collector-emitter ON voltage change due to aging of IGBTs.

[1] U.S. Dept. of Defense. 1995. *Reliability Prediction of Electronic Equipment, Military Handbook 217F.*

# Electrolytic Capacitor Failure

Aging






- **High voltage:** Capacitance value decreases and $R_{ESR}$ value increases.
- **Transients:** Leakage current increases and internal short circuit may occur.
- **Reverse bias:** Leakage current becomes high with loss of capacitance and increase in $R_{ESR}$.
- **Vibrations:** The effects are internal short circuit, capacitance losses, high leakage currents, increase in $R_{ESR}$, and open circuits.
- **High ripple current:** Internal heating occurs and increase in core temperature results in gradual aging of capacitors.

# PV Ground Fault and Corresponding Casualties

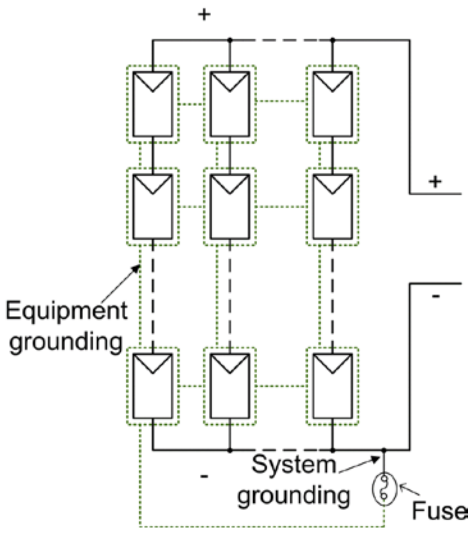
- According to the US National Electrical Code (NEC), PV systems with system voltage more than 50V require both equipment grounding and system grounding .
- A ground-fault protection and interruption (GFPI) device is installed in a PV system to detect the ground-fault, interrupt it and provide a fault indication to protect the system from potential fire hazards.
- Usually ground-fault is detected if the fault current exceeds some predetermines values set by the GFPI device.

**Roof fire caused by ground fault**

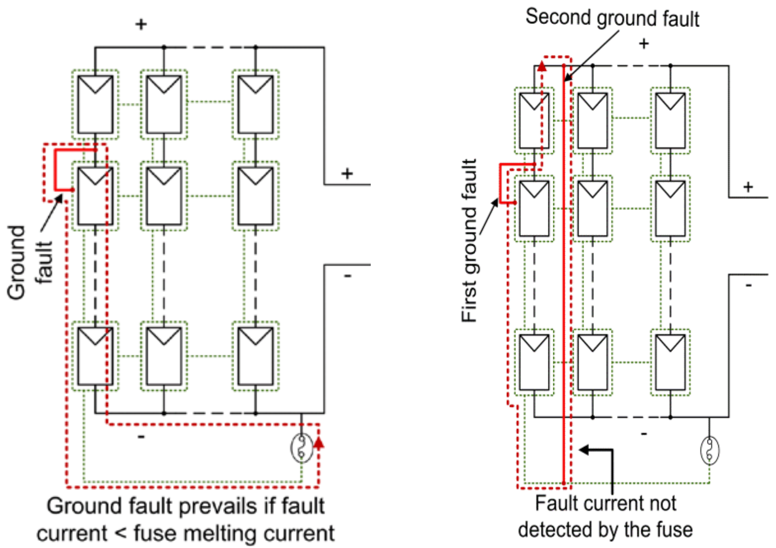
# Possible Ground Faults in PV Systems and the Limitations of Existing Systems

## Limitations of an existing ground fault protection and interruption (GFPI) system

- A ground-fault may occur in the absence of the solar irradiation. (i.e., during night) and remain undetected
- Ground-fault current may be smaller than the GFPI threshold current limit However, the current level may be enough to cause cell damage.
- GFPI may suffer from noise and provide misleading fault indication.
- An undetected ground-fault may pose as a “normal condition” and render to another ground-fault (double ground-fault). This may establish a fault current path without being interrupted by GFPI devices.

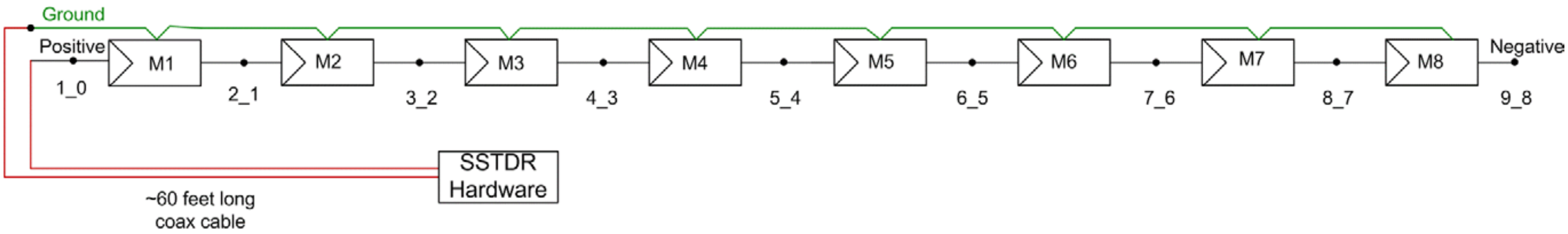


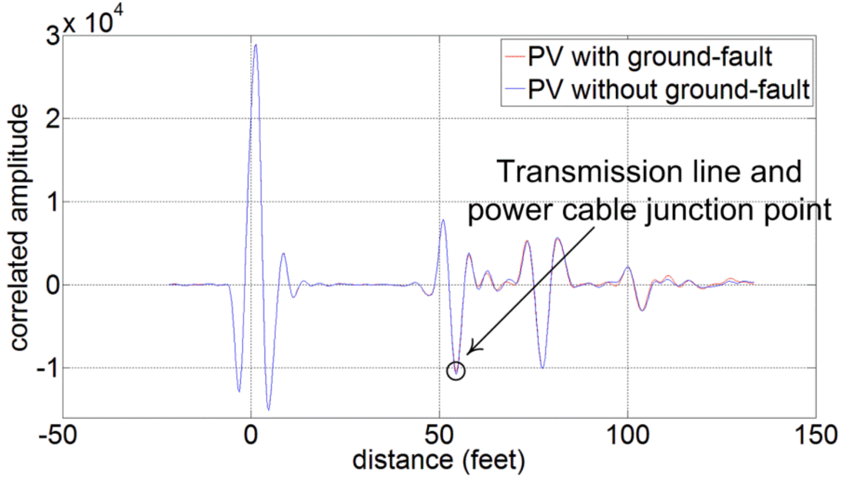
A healthy PV system



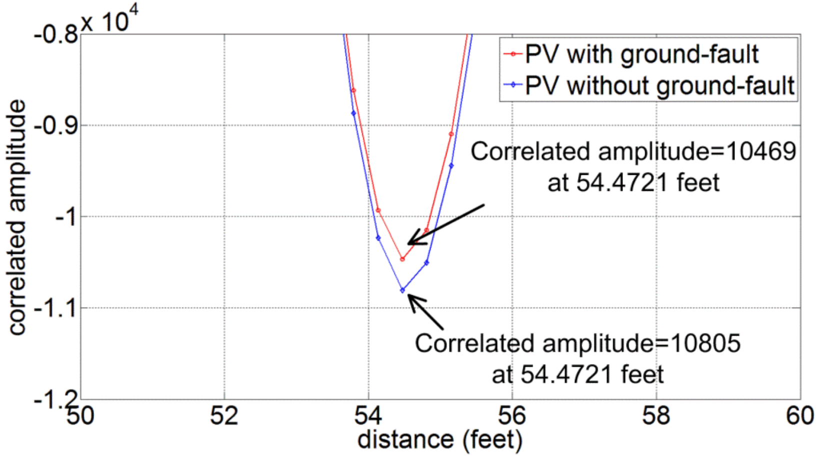
A faulty PV system

# Experimental Results Showing PV Fault Detection Scheme: 1




Correlated amplitude vs. distance curve for a PV panel with and without ground-fault




Zoomed-in view of the correlated amplitude vs. distance curve

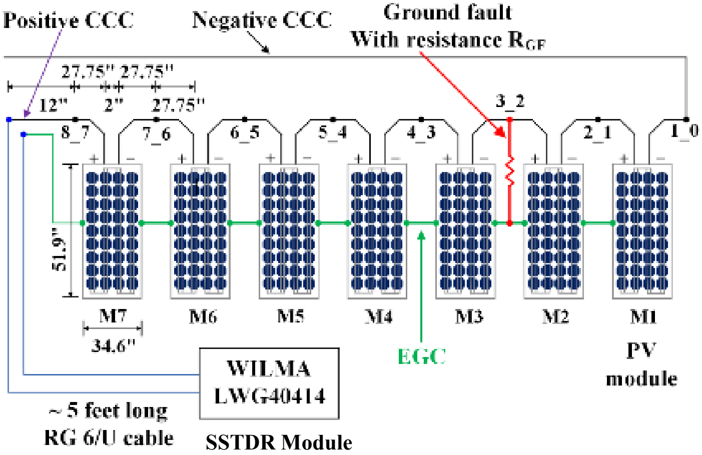
# Experimental Setup

Test set-up used at DETL of SNL

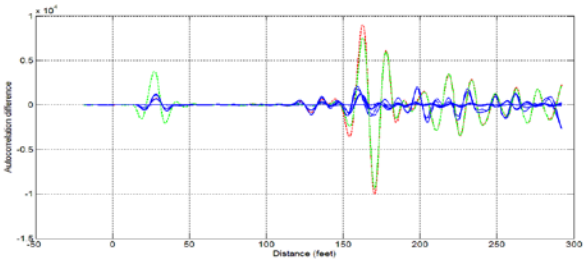
| Maximum power ($P_{max}$) | 200 W |
|---|---|
| Short circuit current ($I_{sc}$) | 3.83 A |
| Open circuit voltage ($V_{OC}$) | 68.7 V |
| Maximum power current ($I_{pmax}$) | 3.59 A |
| Maximum power voltage ($V_{pmax}$) | 55.8 V |

**Challenges:**

- Hundreds of interconnections and impedance mismatches exist inside a single PV string.
- Multiple reflections occur at different mismatches
- Interpretation of the SSTDR reflection is extremely difficult to detect the fault in PV array.



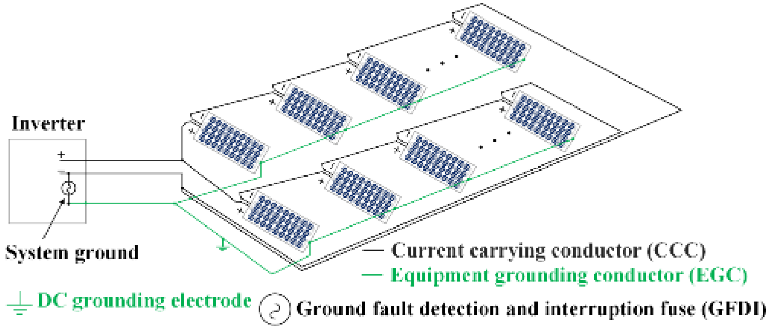
# Experimental Results Showing PV Fault Detection Scheme : 2

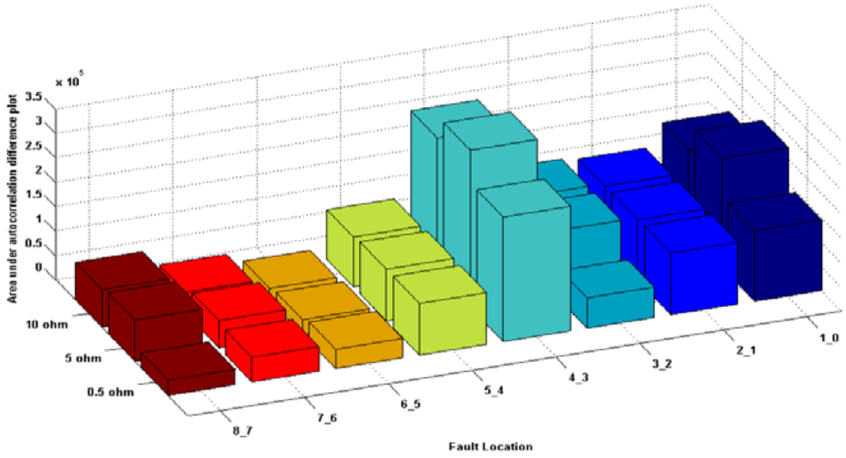


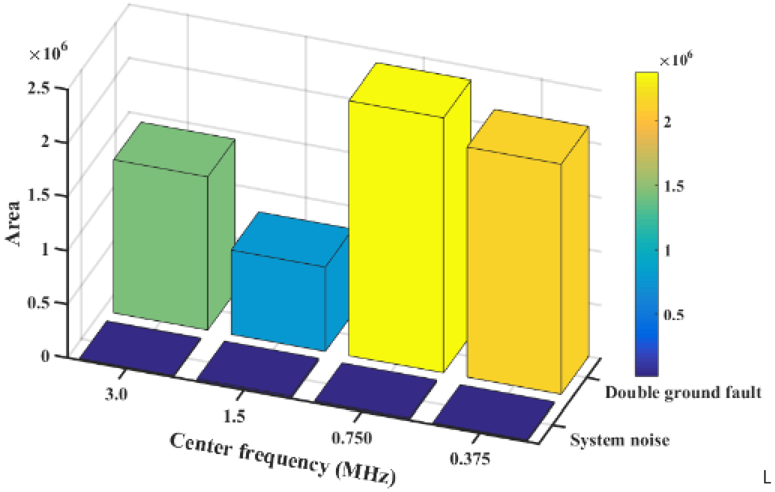

Differential autocorrelation data for faults at different locations

**Limitations of GFDI:**

- Depends on fault current magnitude
- Therefore, suffers from blind spot detection error and can not detect fault at night or low irradiance level

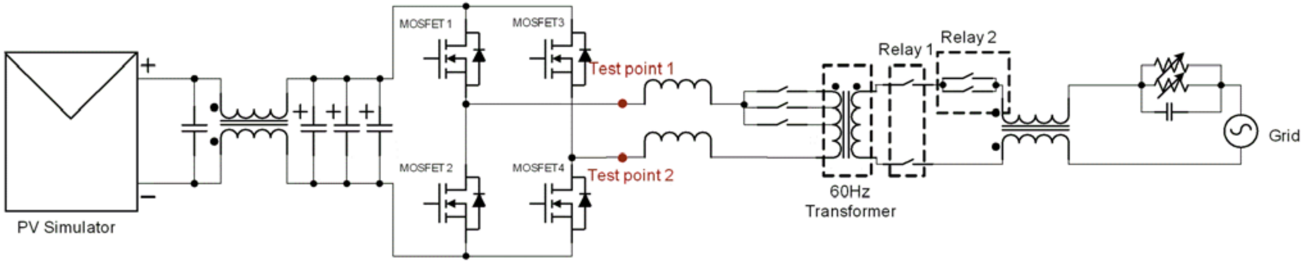


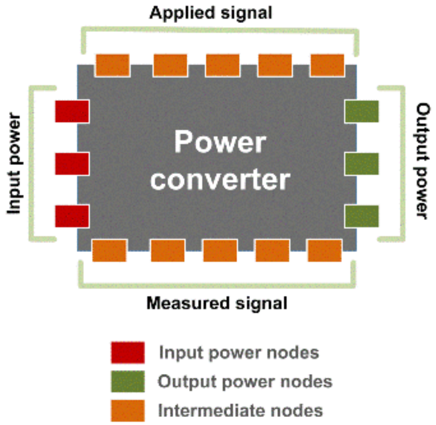



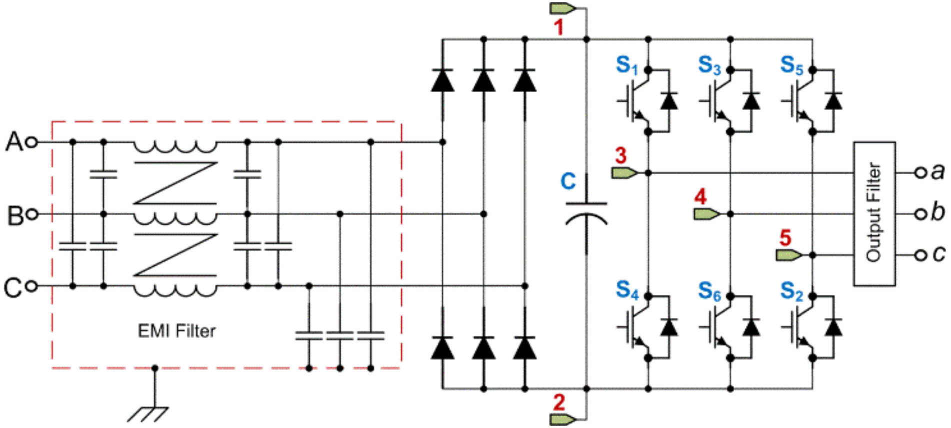



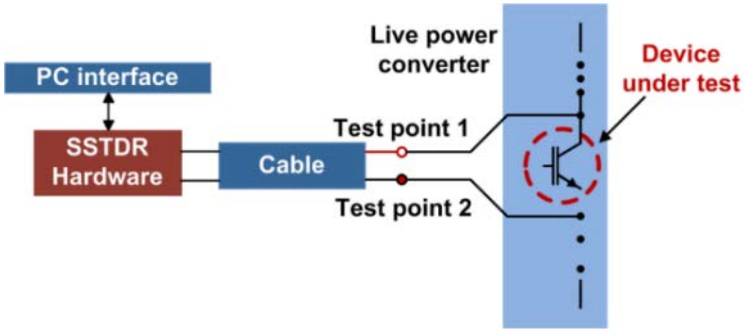

Area under the autocorrelation plot for different fault impedance

# Converter’s Built-In SOH Estimator



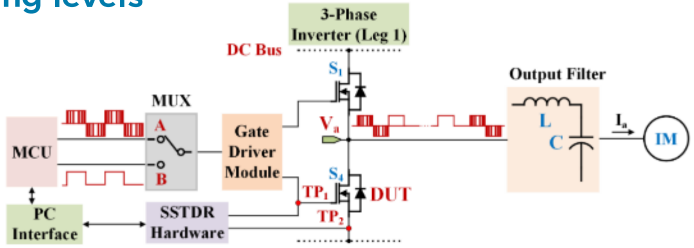



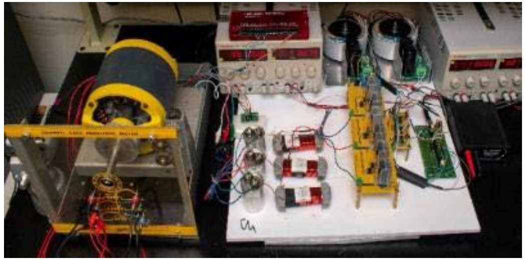



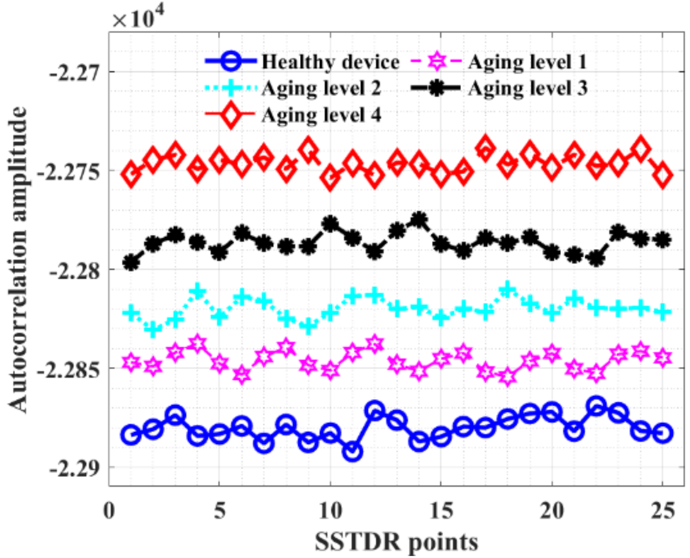



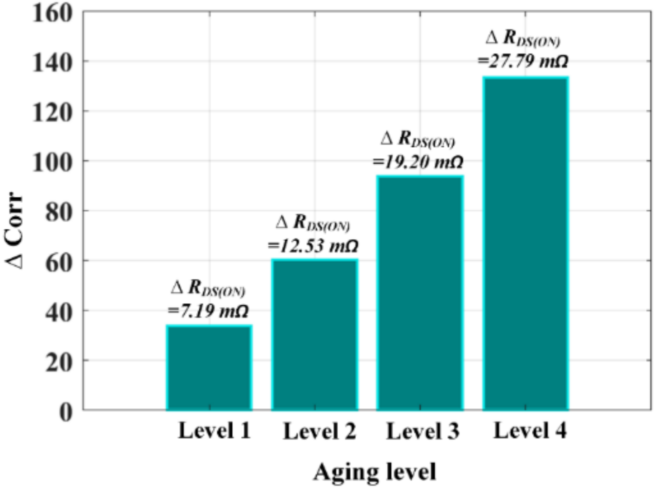
# Live Condition Monitoring in a Three-Phase Inverter: 2019

## Single device under test (DUT) with multiple aging levels



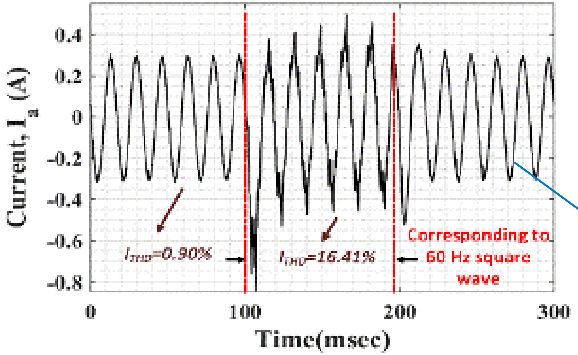


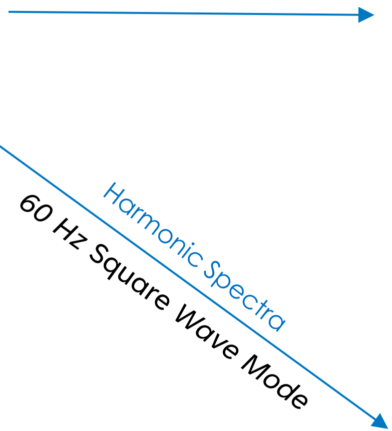

ΔCorr = auto-correlated amplitude – baseline

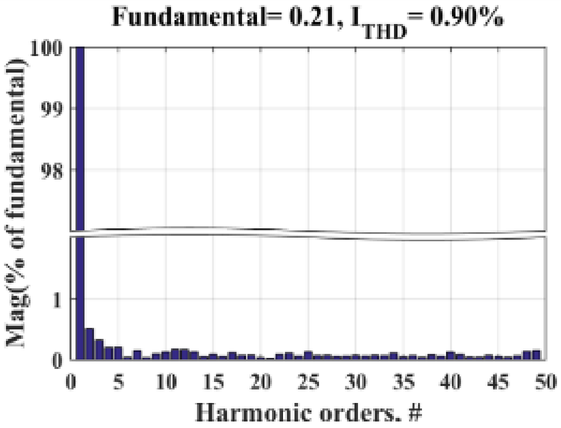
*Aging level 3 > aging level 2 > aging level 1 > healthy device/baseline*

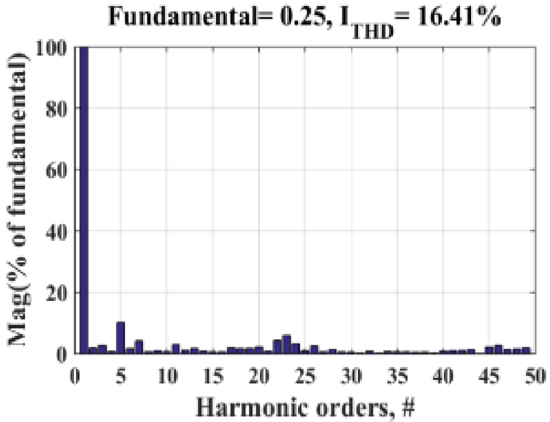
# Live Condition Monitoring

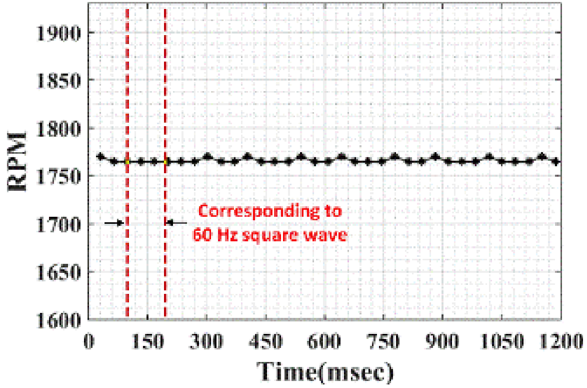



A-phase current



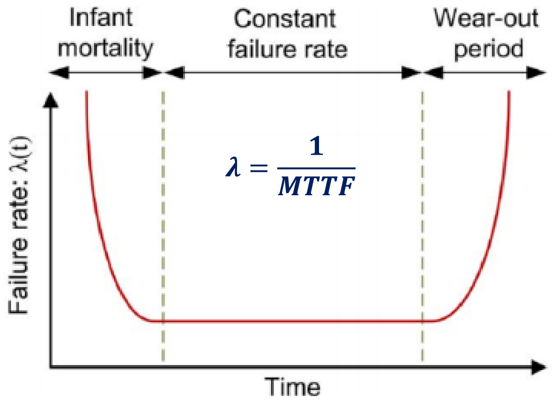

RPM of the Motor

- Current magnitude is high at 60Hz square wave mode, but less than motor start-up current
- Motor Start-up time is way larger than 100 ms time.

# Device Degradation: Dynamic SOA

- Mean time to failure represents the expected life span of the device.
- **Mean time to failure** cannot:
  - Predict unusual circumstances and premature degradation.
  - Answer why reliability of a power switching device drops abruptly beyond a certain time and aging.

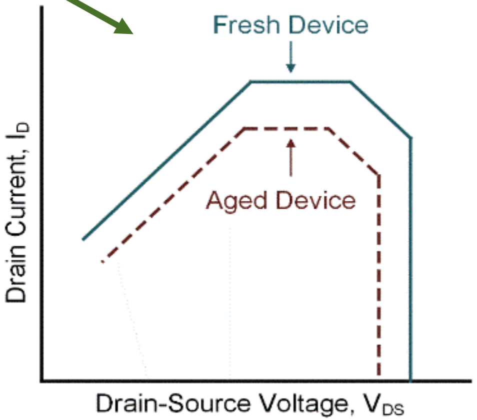
The answer lies in the fact that SOA is an age-dependent parameter rather than a constant value.



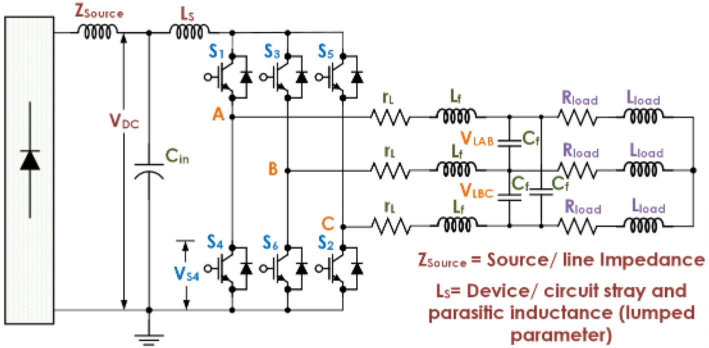

Bathtub curve

25 years old

65 years old

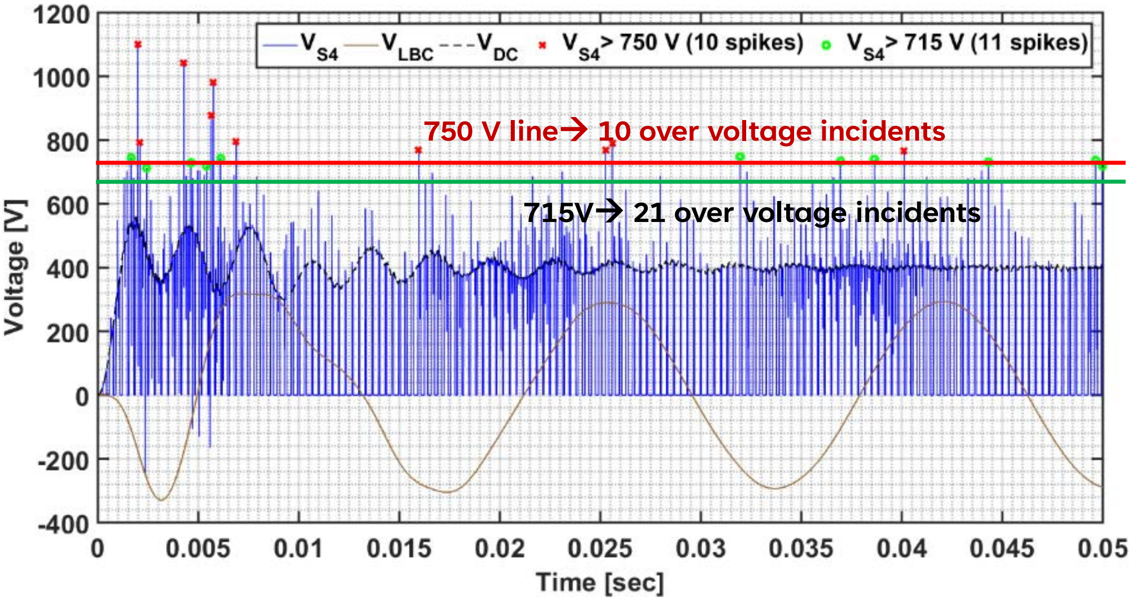


# A Case Study: SOA to Availability




$S_4$ is fresh, $V_{breakdown, fresh}$ = 750 V
$S_4$ is aged, $V_{breakdown, aged}$ = 715 V

- Fresh $S_4$ experiences 10 overvoltage situations
- Aged $S_4$ experiences 21 overvoltage situations




The supply line impedance, along with the circuit/device stray and parasitic inductances, cause considerable voltage spike at the DC bus during inverter operation.

# Summary

- PV ground fault detection using reflectometry is challenging because hundreds of interconnections and impedance mismatches exist inside a single PV string.
- The SSTDR algorithm has been successfully used for detecting ground faults in PV arrays.
- We demonstrated the feasibility of using the SSTDR-based algorithm with any variation in the number of strings, fault resistances and number of faults.
- This technique can test ground faults at night or at low illumination that may remain undetected by standard protection device.
- Various online SOH measurement techniques have been presented with experimental results. The industry is yet to adopt a low-cost solution.
- Each technique has own strengths and limitations.
- Live state of health estimation can predict faults before it happens.
- Knowing the dynamic SOA of a device/module is pivotal.

# Thank You

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