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Next Generation of PV Inverter Technologies

PHOTOVOLTAIC AND DISTRIBUTED SYSTEMS INTEGRATION

Sandia National Laboratories

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

PV System

- PV system designs and capabilities
- Changing Codes and Standards
- Utility interconnection requirements

Reliability impacts

- Implementation of functions
- Mitigation capabilities
- applications

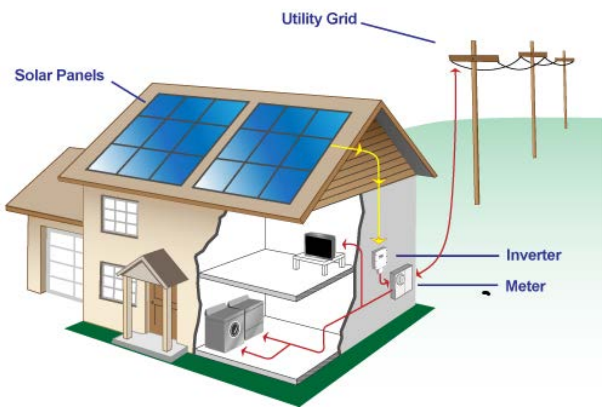
Summary

PV System Design Reliability Challenges

- **Many variations in PV system designs and implementations, each have different reliability concerns. Each design has similar requirements but typically involve different methods of implementation.**
  - **Residential PV systems**
    - **Are typically roof mounted systems – additional safety requirements**
    - **Dc-dc converters, charge controllers, and string single/multi-dc input inverters**
    - **Micro-inverters**
  - **Commercial/Utility PV system**
    - **Roof mount (big box) installation**
    - **ground mound (smart combiner box)**
    - **Large pad mounts (multi-unit devices)**

Residential PV System Reliability Challenges

- **Residential PV systems**
  - **Residential PV systems > 80V require series arc detection**
    - **Detection of dc arc fault for duration of PV system**
    - **Mitigation of dc arc fault for duration of PV system**
    - **Annunciation of arc fault for duration of PV system**
  - **Non-Isolated Inverter Features/Requirements**
    - **Critical Isolation Component-** contactor or relay that isolates the PV array input
    - **Isolation Monitor Interrupter (IMI) -** A device that monitors the insulation resistance of a PV array circuit to ground. Qualifies the array, RISO function
    - **The inverter must cease to export power and open redundant isolation devices upon:**
      - » Ground fault current exceeds a hard limit of 300mA



step changes in ground fault current

converters, charge controllers, and string single/multi-dc input inverters are included in the dc arc fault requirements.

Commercial PV System Reliability Challenges

- **Commercial/Utility PV system**
  - **Roof mount large installation (smart combiner box)**
  - **ground mount (smart combiner box)**
    - **Regardless roof mount or ground mount these PV systems *may* soon be required to have dc arc fault detection, mitigation, and annunciation**
  - **Large pad mounts systems experience thermal extremes created by**
    - **Proximity**
    - **Solar gain**
    - **High dc/ac ratios**

Changing Codes and Standards

NEC 2011 690.11 Arc Fault Protection (Direct Current): as stated
PV systems with dc sources circuits, dc output circuits, or both, on or penetrating a building operating at a PV system maximum voltage of 80 volts or greater shall Be protected by a listed (dc) arc-fault circuit interrupter, PV type, or other system components listed to provide equivalent protection.

NEC 2014 690.11 Arc Fault Protection (Direct Current): [ROP4-251*]
Photovoltaic systems with dc source circuits, dc output circuits, or both, operating at a PV system maximum system voltage of 80 volts or greater, shall be protected by a listed (dc) arc-fault circuit interrupter, PV type, or other system components listed to provide equivalent protection. ***proposed change**

NEC 2011 690.35 (C): Ground-Fault Protection
All photovoltaic sources and output circuits shall be provided with a ground-fault protection device or system that complies with (1) through (3):
(1) Detects a ground fault.
(2) Indicates that a ground fault has occurred
(3) Automatically disconnects all conductors or causes the inverter or charge controller connected to the faulted circuit to automatically cease supplying power to output circuits

NEC 2011 690.35 (C): Ground-Fault Protection [ROP 4–302]*
(1) Determine the PV input circuit has isolation prior to export of current
*** proposed change**

IEEE 1547 Amendment

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The high penetration of distributed energy resources has initiated the revision of the utility interconnection standard IEEE 1547, which allows the distributed resources to have a more significant contribution to the area EPS.

P1547a Draft Standard for Interconnecting Distributed Resources with Electric Power Systems – Amendment 1

The three main sections of IEEE 1547 the amendment addresses are:

- **Clause 4.1.1 Voltage regulation**

  "~~The DR shall not actively regulate the voltage at the PCC.~~ Coordination with and approval of, the area EPS and DR operators, shall be required for the DR to actively participate to regulate the voltage by changes of real and reactive power. The DR shall not cause the Area EPS service voltage at other Local EPSs to go outside the requirements of ANSI C84.1-2006 [1] ~~1995~~, Range A."

IEEE 1547 Amendment

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The second section the amendment addresses is:

- **Clause 4.2.3 Voltage** *{Response to area EPS abnormal voltage conditions}*

When any voltage is in a range given in Table 1, the DR shall cease to energize the Area EPS within the clearing time as indicated. Under mutual agreement between the EPS and DR operators, other static or dynamic voltage ~~trip levels~~ **and clearing time trip settings**[1] shall be permitted.

Default settings[a] 1		
Voltage range (% of base voltage[b])	Clearing time (s)	Clearing time: adjustable up to and including (s)
V < 45	0.16	0.16
45 < V < 60	1	11
60 < V < 88	2	21
110 < V < 120	1	13
V > 120	0.16	0.16

[a] Under mutual agreement between the EPS and DR operators, other static or dynamic voltage and clearing time trip settings shall be permitted 1

[b] Base voltages are the nominal system voltages stated in ANSI C84.1-2006, Table 1. 1

IEEE 1547 Amendment

The third section the amendment addresses is:

- **Clause 4.2.4 Frequency** *{Response to area EPS abnormal frequency conditions}*

  Under mutual agreement between the EPS and DR operators, other static or dynamic frequency and clearing [1] time trip settings shall be permitted.

	Default settings		Ranges of adjustability[(a)]	
Function	Frequency (Hz).	Clearing time (s)	Frequency (Hz)	Clearing time (s)
UF1	57	0.16	56 – 60	0 – 10
UF2	59.5	20	56 – 60	0 – 300
Power reduction [(b)]	60.3	10	60 - 64	0 - 300
OF1	60.5	20	60 – 64	0 – 300
OF2	62	0.16	60 - 64	0 - 10

(a) Unless otherwise specified, default ranges of adjustability shall be as stated.
(b) When used, the DR power reduction function settings shall be as mutually agreed to by the area EPS and DR operators.

Achieving these New Inverter Requirements

- **NEC 2011 690.11 Arc Fault Protection (Direct Current):**
- Residential applications of dc arc fault
  - New capabilities are being developed in power optimizers
  - New capabilities integrated into inverter
- Commercial applications of dc arc fault
  - New capabilities being developed in smart combiner boxes
  - New capabilities integrated into inverter

Sandia is working with various manufacturers to help develop and validate the capabilities to meet this requirement but what is not known is

***How will degradation in system performance effect the performance of the ability to detect, mitigate, and annunciate the occurrence of an arc*.**

Achieving these New Inverter Requirements

- **NEC 2011 690.35: Ground-Fault Protection**
- Residential applications for ground fault protection
  - Residual ground current monitoring
  - Array qualification capability *(isolation measurement of array)*
- Commercial applications ground fault protection
  - Residual ground current monitoring at the smart combiner box
  - New capabilities integrated into inverter or *(communication between inverter and smart combiner box)*

How will degradation in system performance effect the performance of the ability to detect and can the faulted string be isolated before a lock out condition occurs?

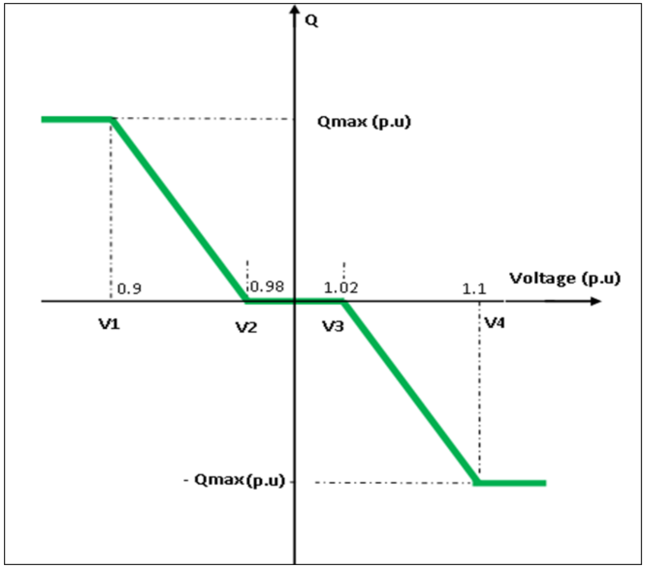
What is needed to Reliably achieve this?

The capability to identify a failing string, isolate that string, and identify the location in the multitude of strings the fault can occurred.

Reliability Concerns implementing Voltage Regulation Capabilities

Autonomous implementation of Volt/Var function

- Voltage is monitored at point of common coupling (PCC)
- Watt or Var priority is determined by controls
- VA/Watt/Var level is dependent on voltage level and ac current limit



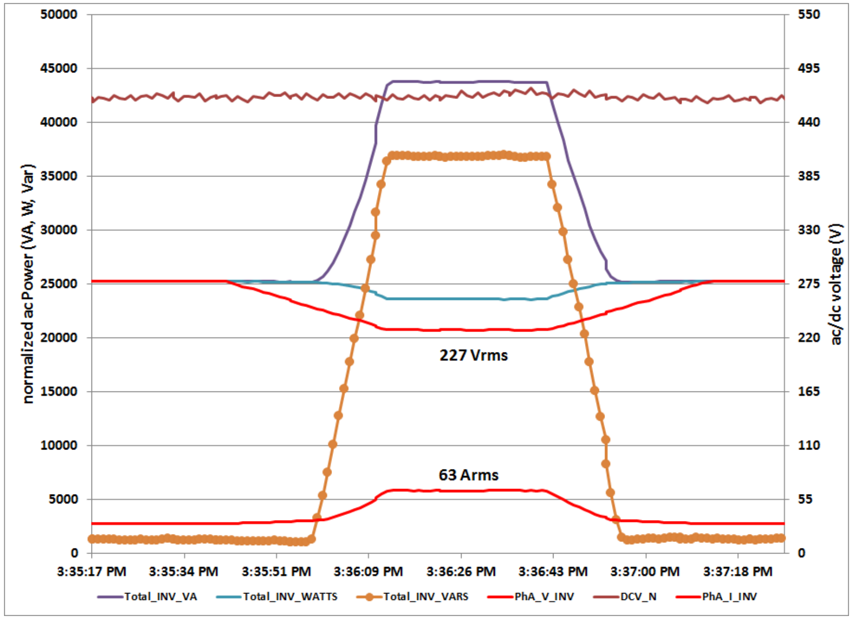
Volt-Var Controls

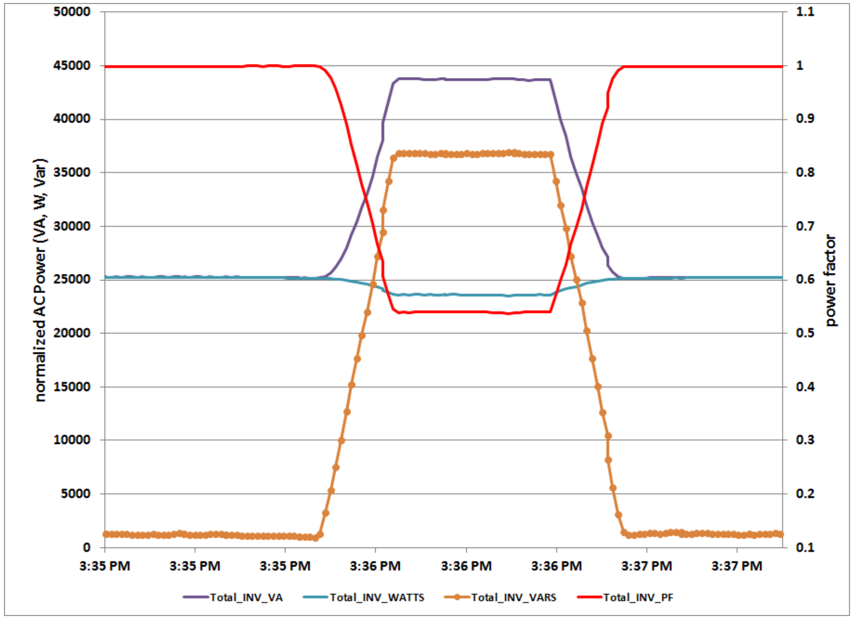
- V1-V4 are all adjustable parameters
- Qmax is determined based on the amount of kVA capability "left over" after the real power needs are satisfied (i.e., real power is prioritized)
- Working to determine what ramp capabilities are achievable while maintaining stability

Autonomous implementation of Volt/Var function (watt priority)

Stimulus: Voltage Sag, Limits adhere to IEEE 1547

- Ac voltage sags below 88% of nominal voltage
- Var generation increases as ac line voltage decrease
- Achievable power factor dependent on watt level





Autonomous implementation of Volt/Var function (watt priority)

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Stimulus: Limits adhere to IEEE 1547

- **Increased inverter losses with volt/var control**

Conduction Losses

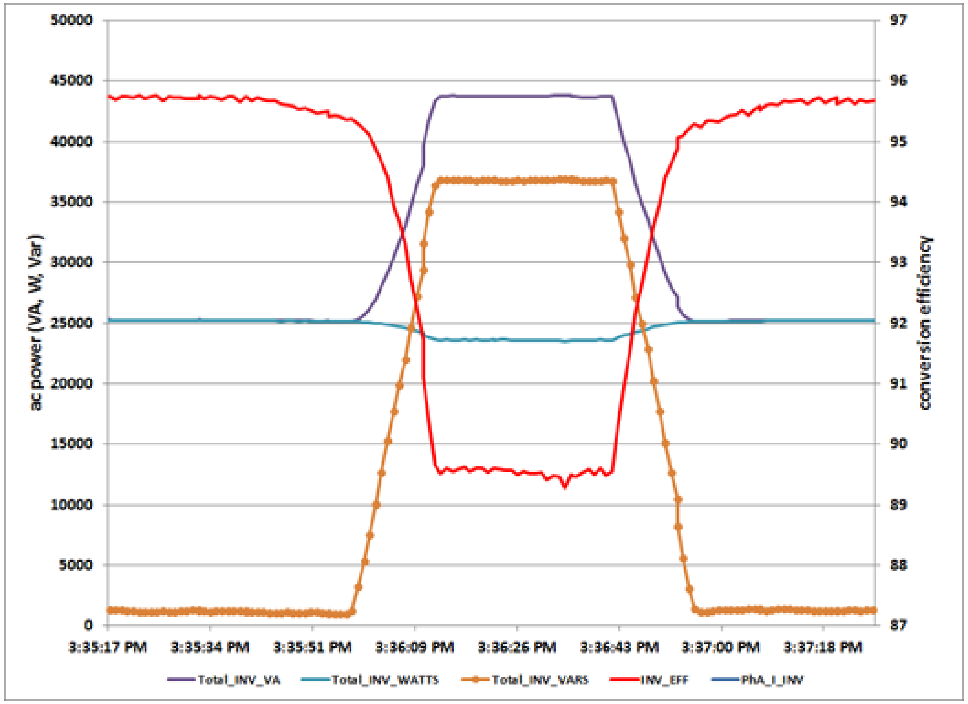
$$\hat{P}_{loss,cond} \cong \kappa_1 I + \kappa_2 I^2$$

$$I_{rms} = \frac{\left(P^2 + Q^2\right)^{1/2}}{3V_{rms}}$$

These losses require additional heat mitigation capability to sustain sufficient design margins on critical components

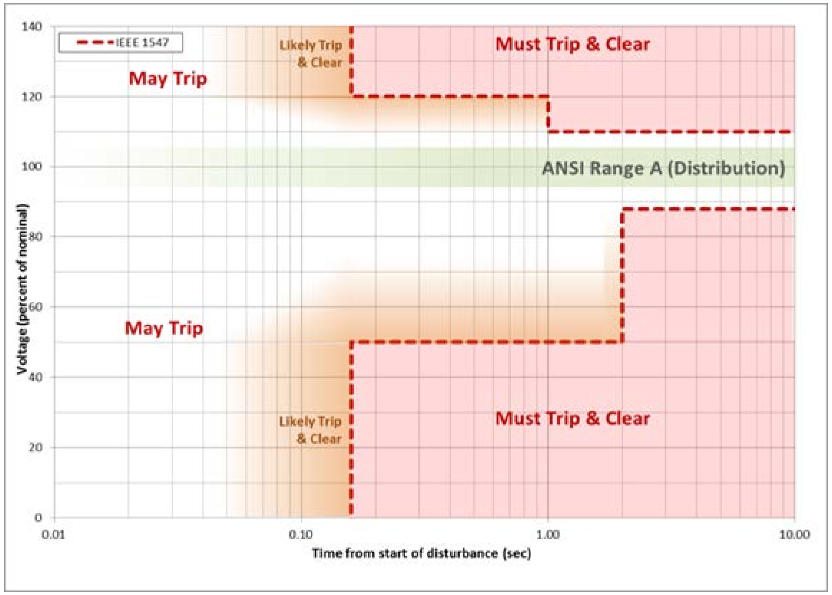
Switching losses

$$\hat{P}_{loss,sw} \cong \frac{1}{6} f_{sw} VI \left(T_{off} + T_{on}\right)$$

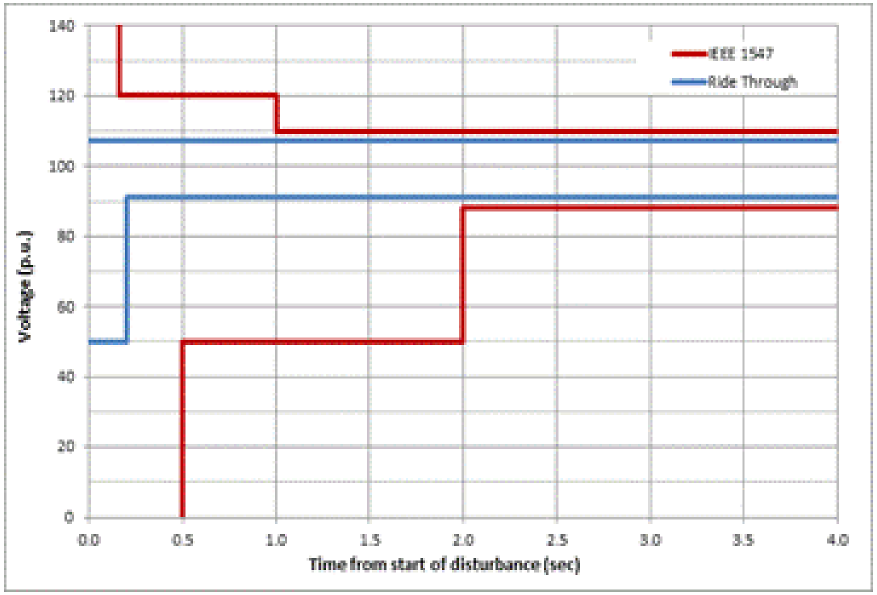


Low Voltage Ride Through Implementation

The high penetration of DER has lead to the desire/requirement for the distributed resources to ride through momentary sag/surge in voltage and frequency. Presently the proposed change in the interconnection standard does not have a ride through requirement. This may change.



No ride through requirement



Proposed must ride through requirement with must trip level out of way for expanded ride through. *Many curves exist*

Low Voltage Ride Through Implementation

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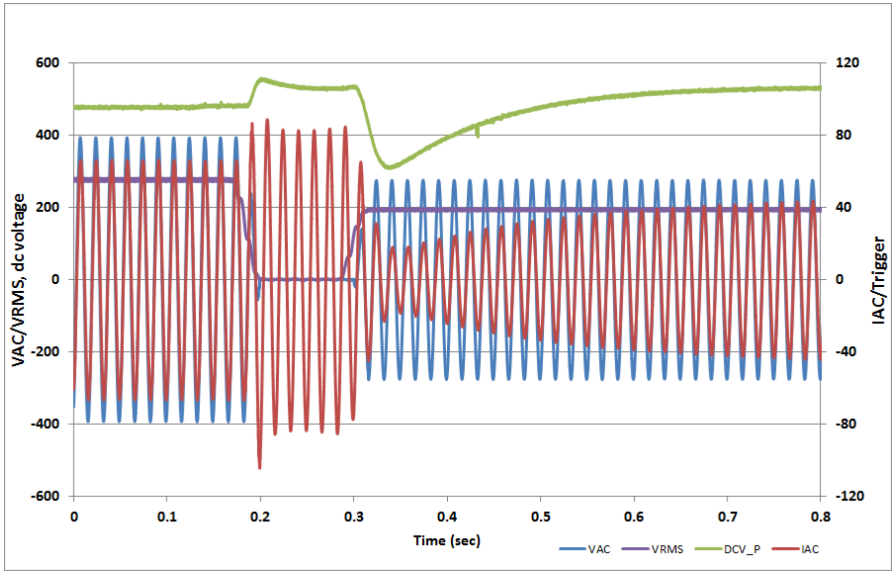
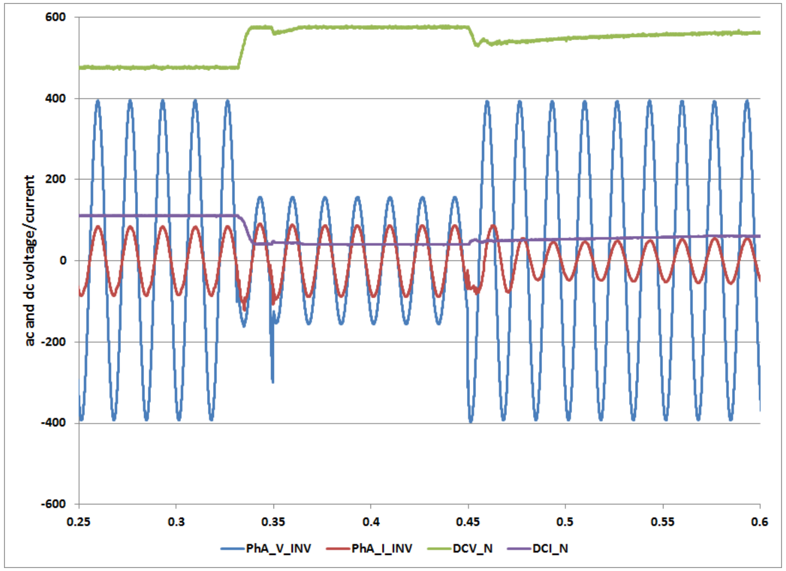
The result of ride through in voltage allows devices to stay on line and assist the EPS meet their load demands during critical conditions. Consequence of implementing this capability are perturbations on voltage and currents.



Dc voltage and ac current perturbations



Dc voltage and re-synchronization perturbations

Summary

New features driven by code and standard changes add safety and value to the PV system installations. These features do add the need to quantify the effectiveness over time and to document the susceptibility to degradation in performance.

NEC changes/proposed changes

- **DC arc fault detection- integrated or combiner box (communications)**
- **Ground fault – residual current monitoring, RISO measurement**

IEEE 1547 Utility interconnection standard changes

- **VRT/FRT capability**
- **Volt/Var**
- **Frequency/Watt**

Thank You

Questions?