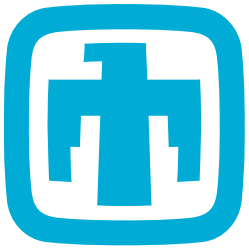

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U.S. DEPARTMENT OF ENERGY

Electrical Simulations of Parallel and Series Arc Faults

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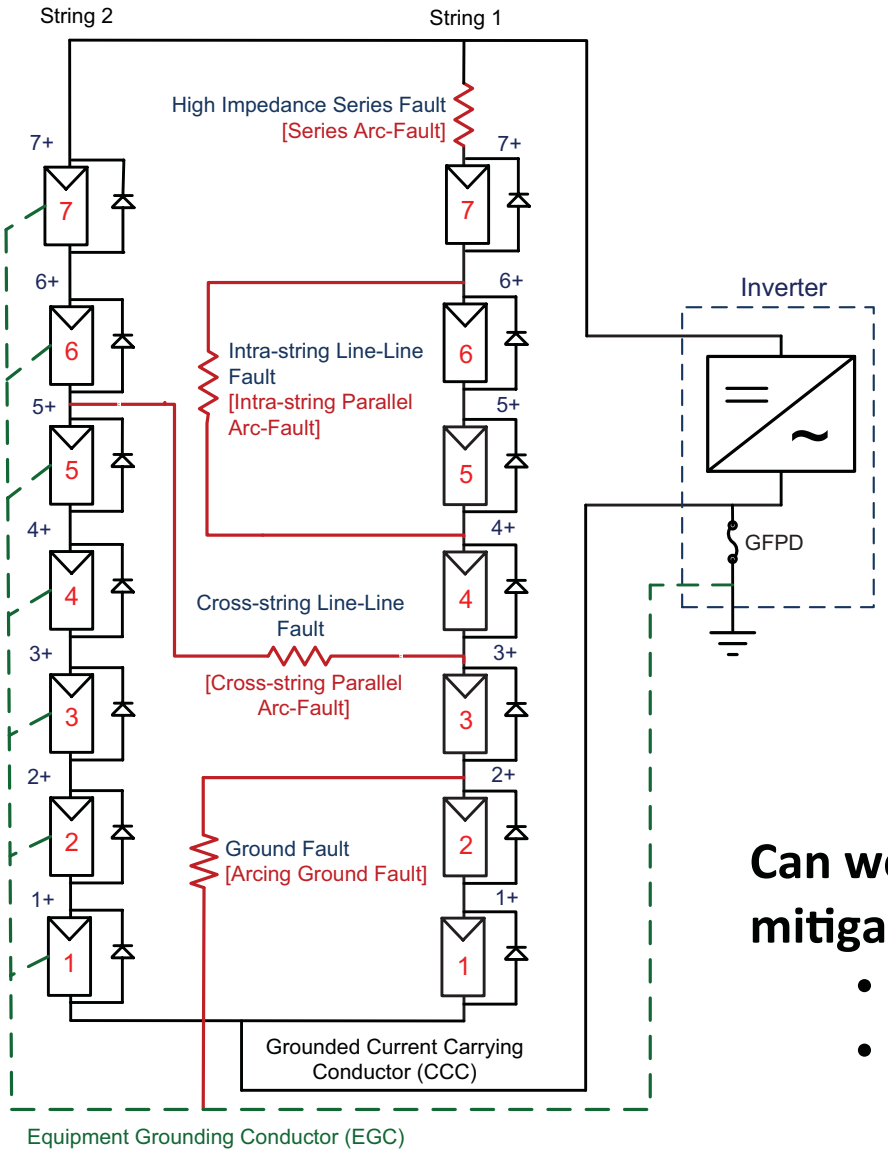
Outline

- Introduction to Arc Faults and SPICE Simulations
- Experimental
  - Constant Resistance Faults with Load Bank
  - Arc-Fault with Load Bank
  - Constant Resistance Faults with Inverter
  - Arc-Fault with Inverter
- Summary and Conclusions

Arc Faults

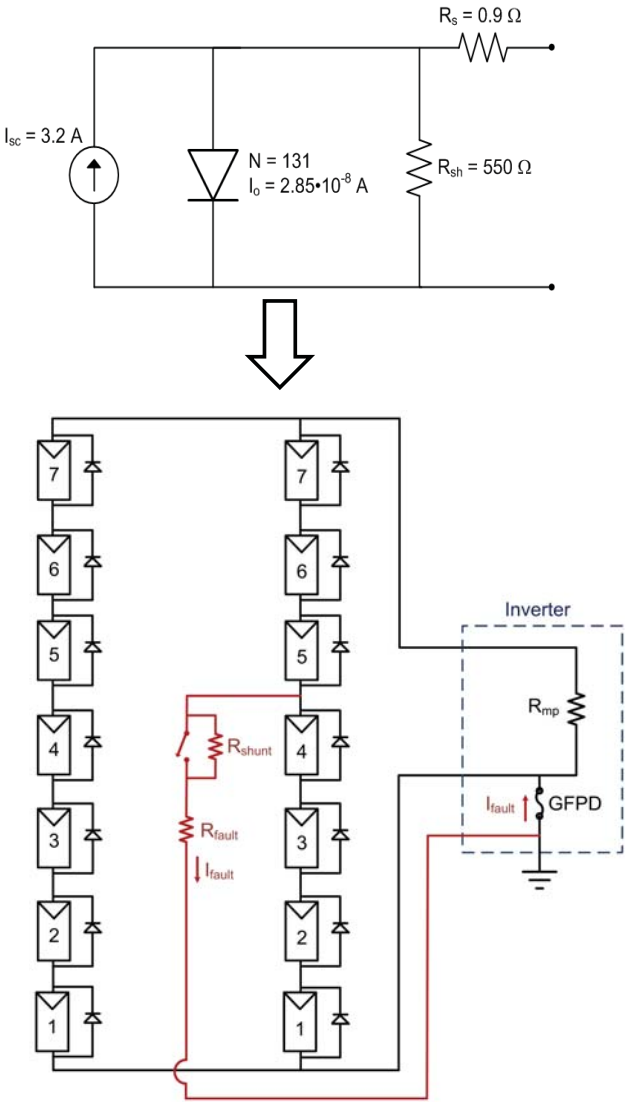


- Types of arc-faults
  - Series Arc-Fault – Arc from discontinuity in electrical conductor
  - Parallel Arc-Fault – Electrical discharge between conductors with different potentials
- 2011 *NEC* requires **series** arc-fault protection in PV installations on or penetrating a building above 80 V
- 2014 *NEC* may require **parallel** arc-fault protection in PV installations

Can we use array simulation techniques to aid in detection, mitigation, and differentiation of arc faults?

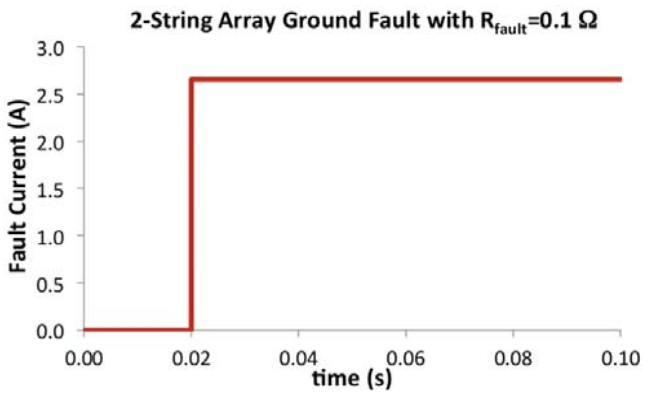
- Mitigation different for series vs. parallel faults
- Location determination critical for large installations

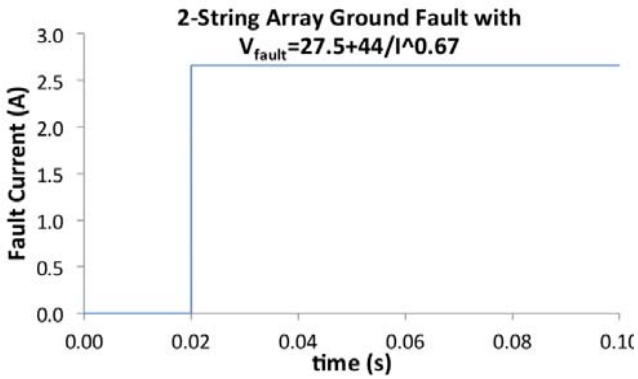
SPICE Simulation



- Simulation Program with Integrated Circuit Emphasis
  - Standard simulation tool for nonlinear circuit effects
- 1 diode model of PV Module (200 W multicrystalline Si),
  - 7 modules series, 2 strings parallel
  - Can be made much larger (~500 strings)
- Inverter modeled as resistor or parallel resistor/capacitor
- Fault modeled as a ~~current varying voltage source~~ resistor

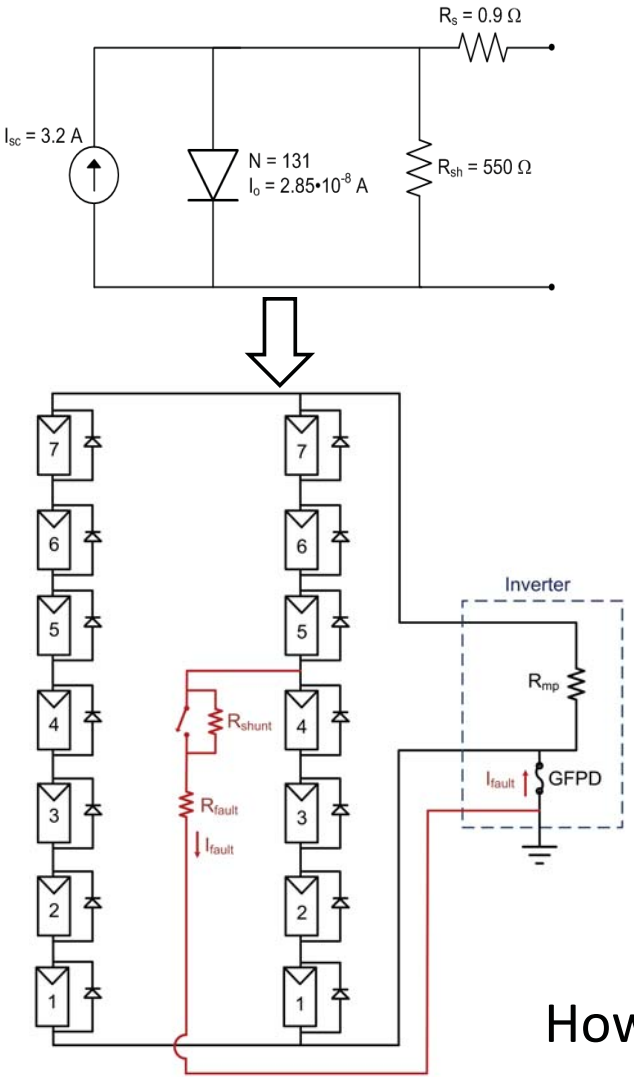
$$V = A + \frac{B}{I^n}$$





J. Flicker and J. Johnson, "Photovoltaic Ground Fault and Blind Spot Electrical Simulations " SAND Report 2013-3459, 2013.
http://energy.sandia.gov/?page_id=2886

SPICE Simulation



- Simulation Program with Integrated Circuit Emphasis
  - Standard simulation tool for nonlinear circuit effects
- Inverter modeled as resistor or parallel resistor/capacitor
  - Does not account for 2nd order non-idealities/ transients due to switching, grid interaction
  - Does not explicitly account for MPPT, must be done manually
- Fault modeled as a current varying voltage source
  - Time dependence of fault resistance must be done manually

How accurately can SPICE predict array operation during fault?

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http://energy.sandia.gov/?page_id=2886

Experimental

Fault Type

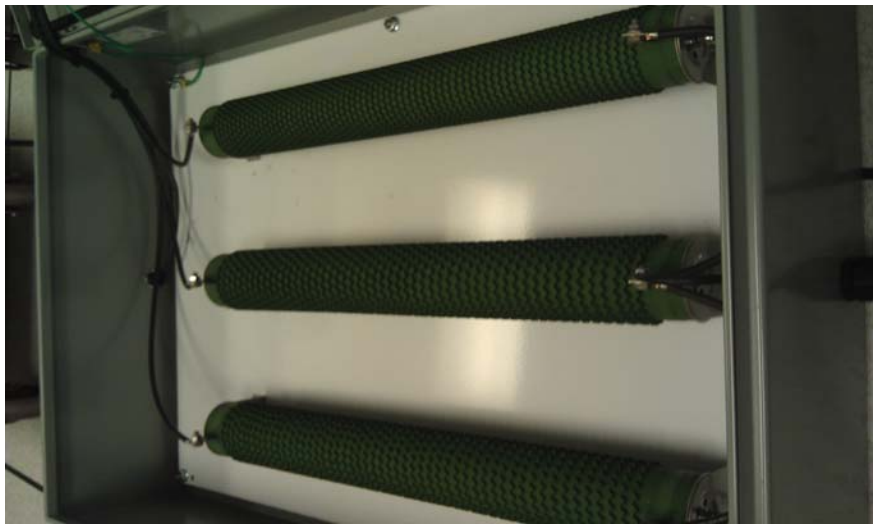
1. Series fault
2. Intra-string parallel
3. Cross-string parallel
4. Ground fault

Array Load Type

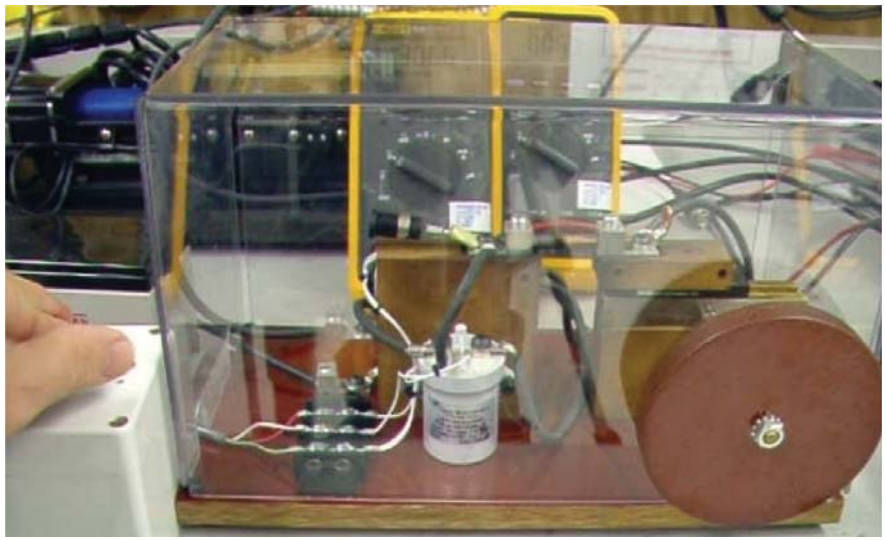
1. Load bank at R_{mp} (~55.6 Ω)
2. 5.0 kW inverter without arc-fault protection

Fault Resistance

1. Constant resistance fault (3.2, 5.2, 10.4, 22.4 Ω)



2. UL1699B-style Arc Fault Generator



Experimental

1. Constant resistance faults with the load bank
   - Find SPICE parameters for the PV modules
   - provide a baseline for the other tests

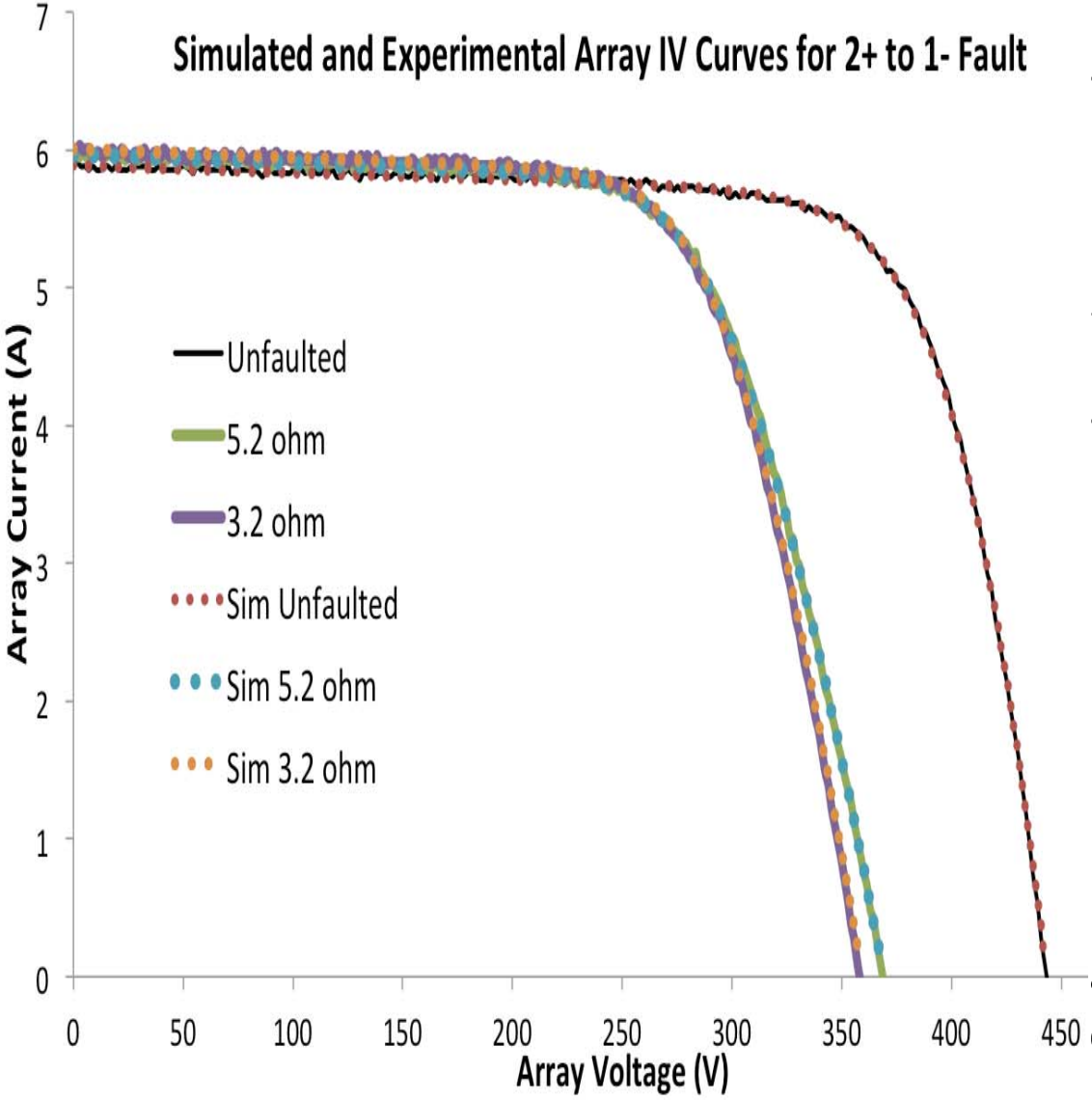
2. Arc-faults with the load bank
   - Ensure SPICE arc-fault model (resistor) accurately simulates dynamic electrical behavior of arc plasmas

3. Constant resistance faults with inverter
   - Ensure SPICE can accurately describe array/inverter system behavior during fault

4. Arc-faults with inverter
   - Determine any difference in inverter operation between arc-faults and constant resistance faults

Experimental

Constant Resistance Fault with Load Bank



- One-diode module parameters matched to array at Sandia Distributed Energy Technology Laboratory (DETL) array

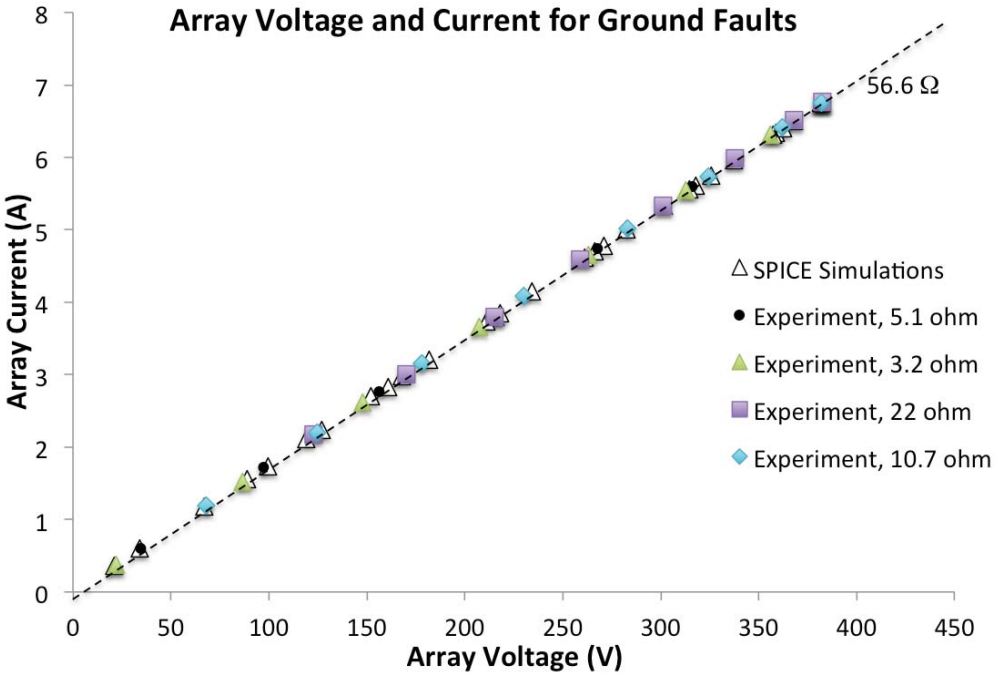
2 string, 7 module, 200 W multicrystalline Si

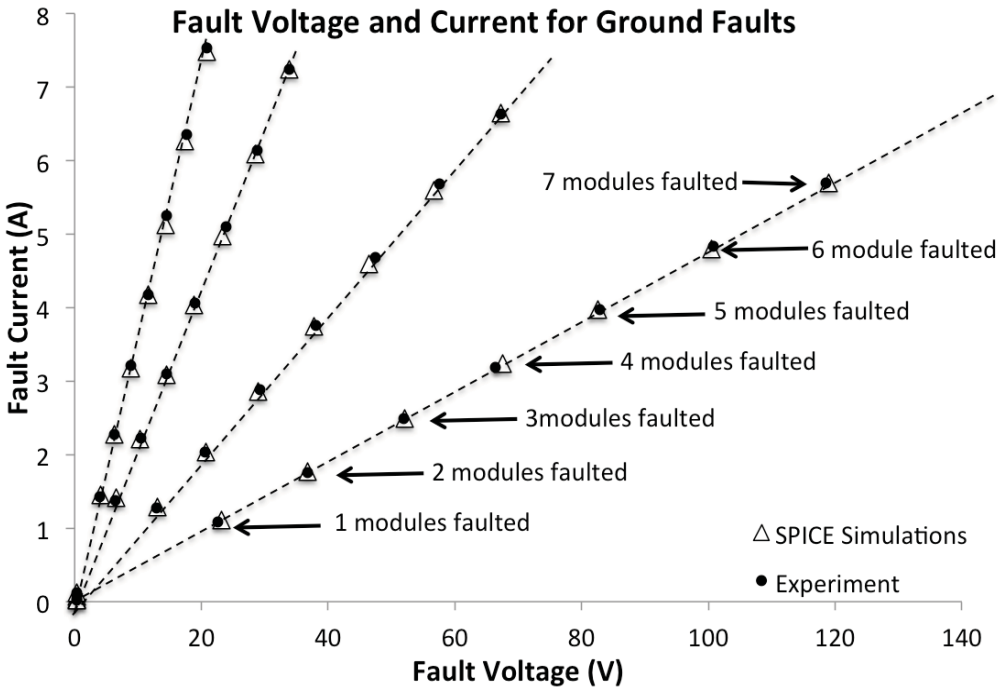
- IV curves with Daystar, Inc DS-100C tracer
  - 900 W/m^2:
    N= 131
    I_{sc}= 3.2 A
    R_s= 900 mΩ
    R_{sh}= 550 Ω

Isc, N changed slightly to match MPP and account for irradiance/temperature changes during operation

Experimental

Constant Resistance Fault with Load Bank

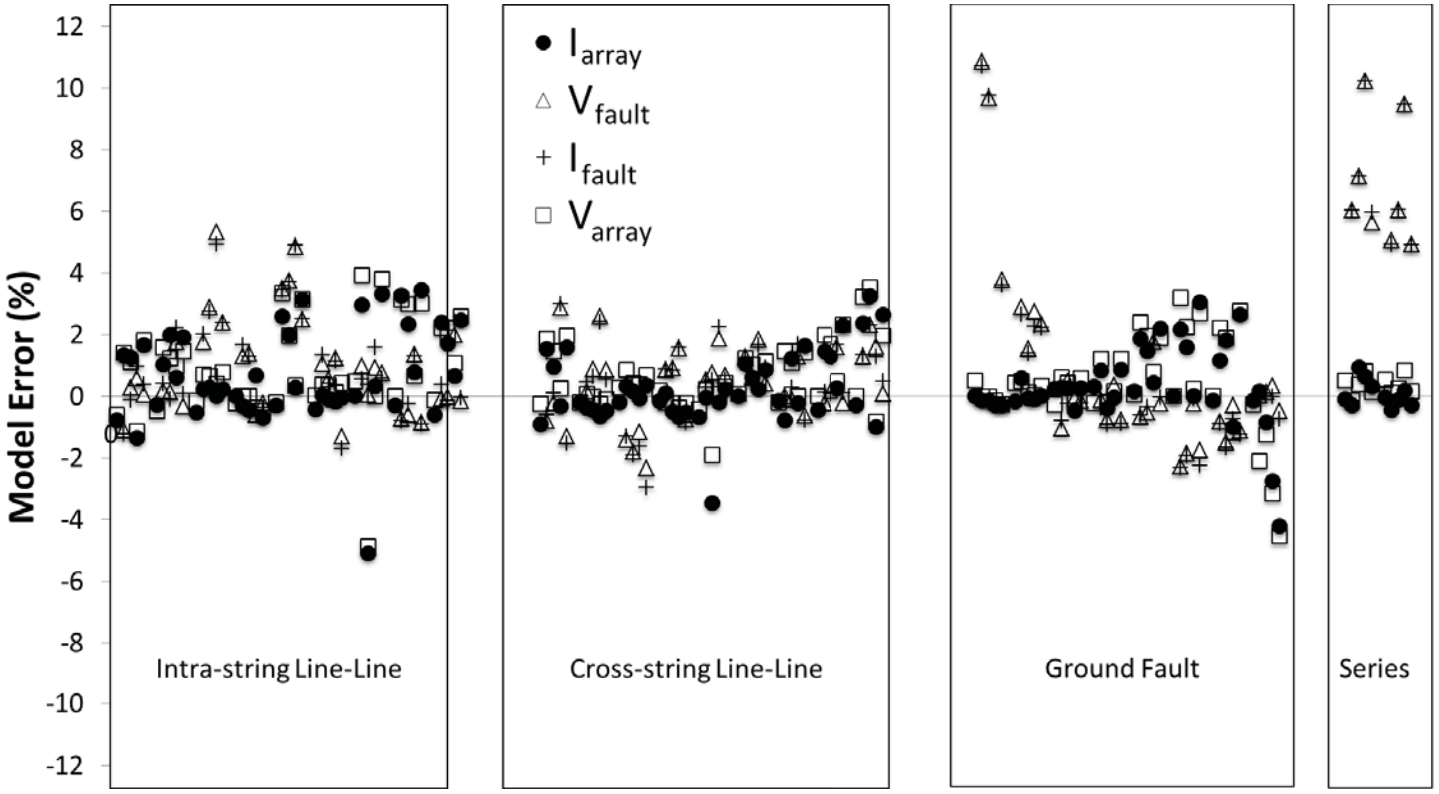




- Good correlation between SPICE simulations and experimental data

Experimental

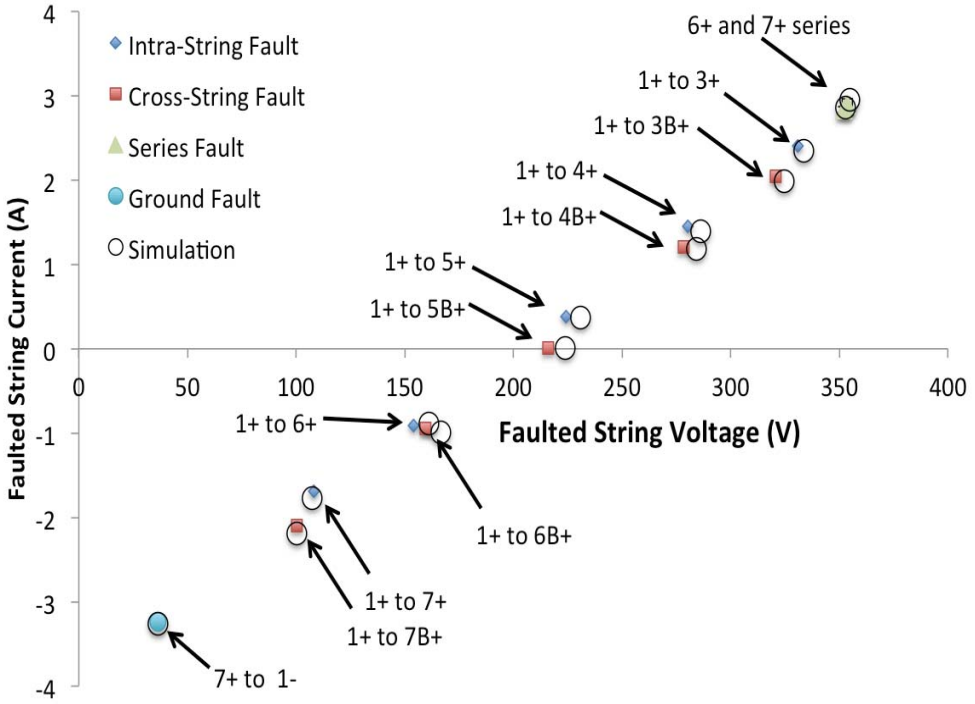
Constant Resistance Fault with Load Bank

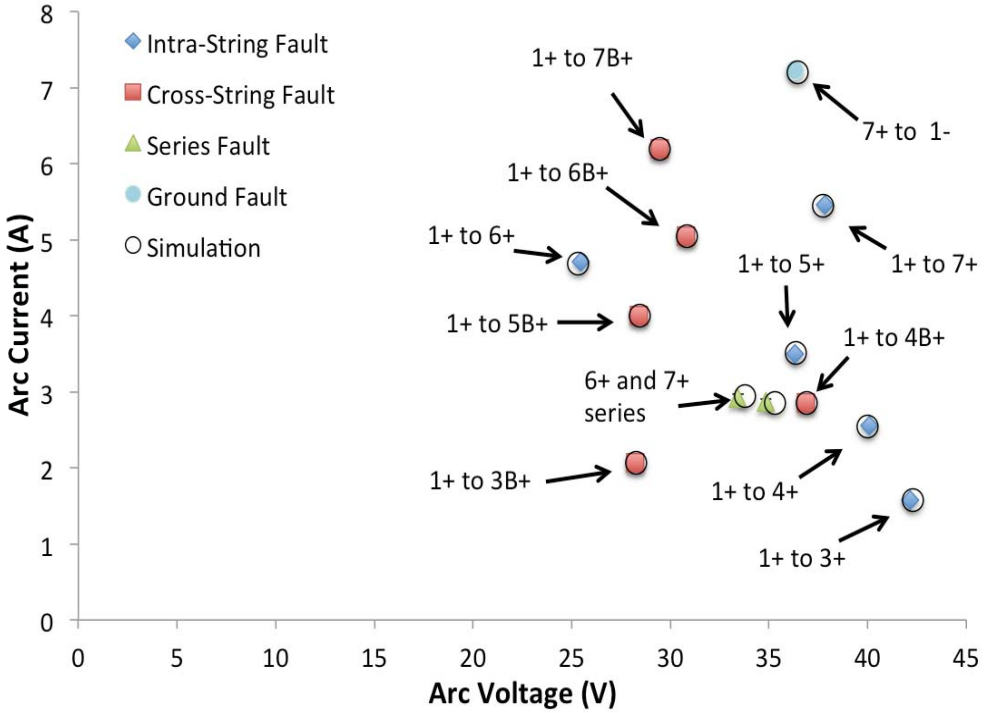


- Good correlation between SPICE simulations and experimental data
- Most simulation within 5% of experiment
- Can the model describe arc-faults as well as constant resistance faults?

Experimental

Arc Fault Generator with Load Bank



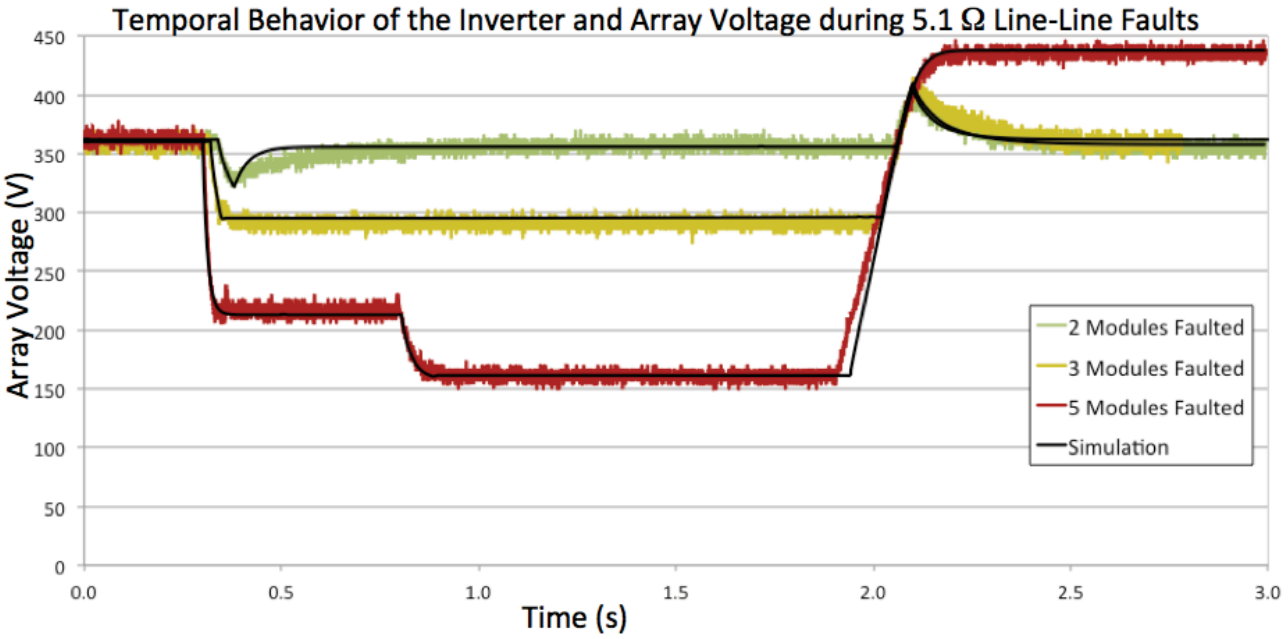


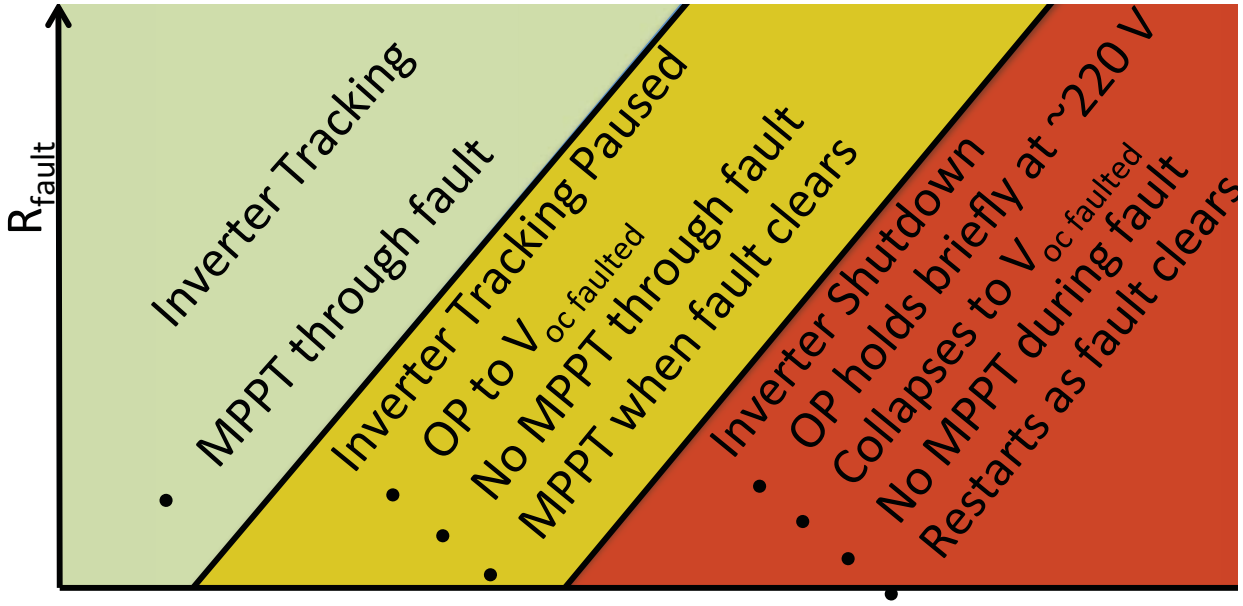
- Good correlation between SPICE simulations and experimental data

- Can the model describe arc-faults as well as constant resistance faults? Yes
- But can it describe inverter behavior?

Experimental

Constant Resistance Fault with Inverter



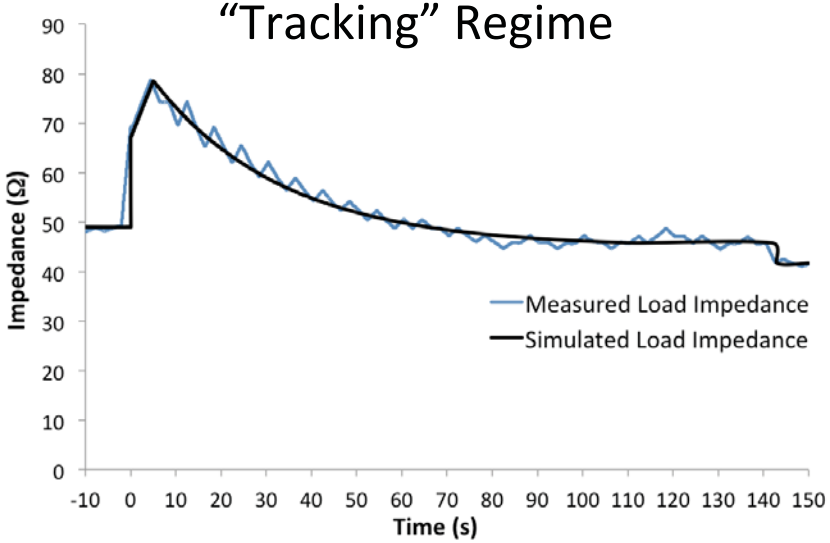


- Three operational modes of inverter depending on "severity" of fault
- Least serious faults, inverter will MPPT before, during, and after fault
- Moderate faults, inverter will go to $V_{oc\ faulted}$ during fault, but will MPPT after fault
- Most serious faults, inverter will briefly hold voltage (~220V) before collapsing to $V_{oc\ faulted}$, restart after fault

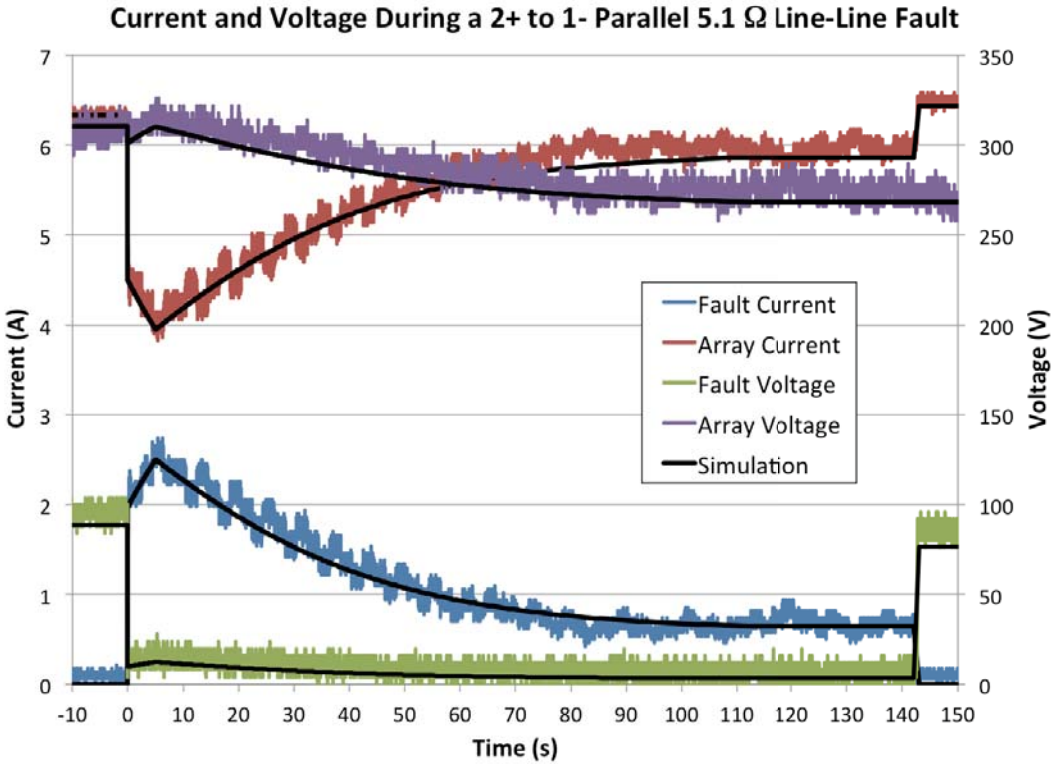
Experimental

Constant Resistance Fault with Inverter

2+ to 1- Parallel 5.1 Ω fault
"Tracking" Regime

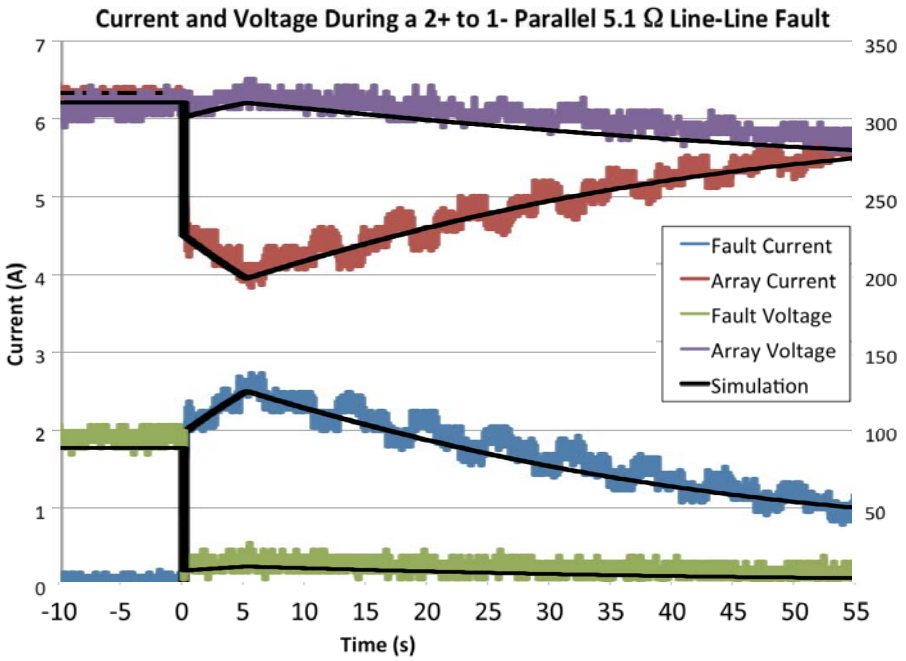


Time (s)	R_{load} (Ω)	Action
-10 to 0	49	MPPT
0	67	OP to V_{MPP}
0 to 4.4	$R = 2.64 \cdot t + 67$	
4.4 to 143	$R = 33.6 \cdot e^{-0.035t} + 45$	MPPT
143 to 150	41.7	OP to V_{MPP}

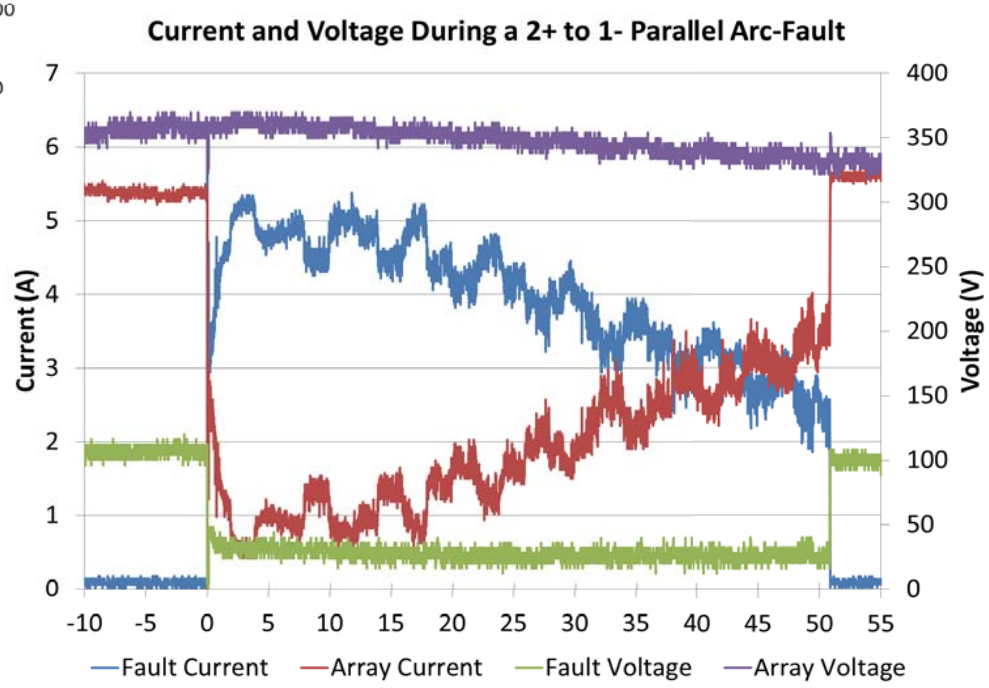


Experimental

Constant Resistance Fault with Inverter



- Inverter treats both constant resistance and arc-faults the same
  - More noise during arc-fault
  - Will not complete tracking
    - Decreased voltage during tracking leads arc to self-extinguish



Summary and Conclusions

- Introduced SPICE simulations of PV arrays to model series and parallel arc-faults
- Experiments conducted analyzing array and fault voltage/current in real faulted arrays
  - Constant resistance faults with load bank
  - Arc-fault with load bank
  - Constant resistance faults with inverter
  - Arc-fault with inverter
- Three fault-dependent inverter modes depending on “severity” of fault
  - “tracking”
  - “tracking paused”
  - “inverter shutdown”
- SPICE simulations completely describe both static conditions with the array connected to the load bank and dynamic conditions with inverter MPPT
- Inverter treated constant resistance faults and arc-faults similarly when MPPT

Acknowledgements

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