

CREATING DYNAMIC EQUIVALENT PV CIRCUIT MODELS WITH IMPEDANCE SPECTROSCOPY FOR ARC FAULT MODELING

Jay Johnson, David Schoenwald, Scott Kuszmaul, Jason Strauch, Ward Bower - Sandia National Laboratories

Arc Fault Frequency Propagation through PV Strings Simulated with Equivalent Dynamic PV Circuits

Background

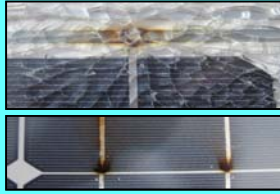
MOTIVATION: PV system arc faults have led to a number of rooftop fires which have caused significant property damage and threatened the safety of building occupants. In response, Article 690.11 was approved for the **2011 National Electrical Code®** which requires new PV systems on or penetrating a building to include a listed arc fault protection device.



Arcing at the combiner box.



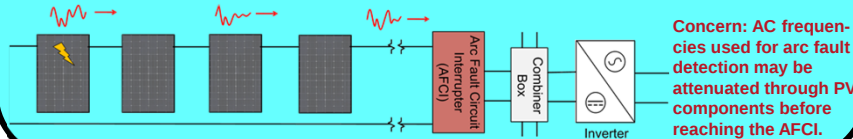
PV arc fault-initiated fire on a warehouse in Buerstadt Germany.



Discoloration indicating arcing at the busbar and collector ribbon.

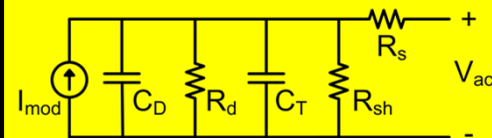
PURPOSE: Sandia National Laboratories is researching the electromagnetic phenomena of PV arcs to inform arc fault detector designers of frequency-dependent attenuation, electromagnetic noise, and radio frequency effects within PV systems.

Propagation of arcing noise through a PV string



Step 1: Create Equivalent AC Circuit of a PV Module

The equivalent dynamic circuit of a PV model [1] describes the behavior of AC signals passing through a PV module. This defines the filtering behavior of the module for arcing frequencies.



- R_s - series resistance
- R_{sh} - shunt resistance
- $R_d(V)$ - dynamic resistance of diode
- $C_D(V, \omega)$ - diffusion capacitance
- $C_T(V)$ - transition capacitance
- V_{ac} - arcing AC voltage
- ω - signal frequency

[1] H.S. Rauschenbach, Solar Cell Array Design Handbook, Van Nostrand Reinhold, New York, 1980.

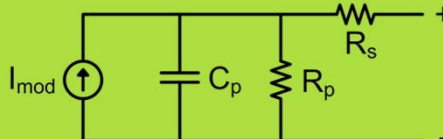
The complex impedance of the equivalent dynamic circuit is calculated based on the circuit model.

Step 2: Find Equivalent Complex Impedance

Chenvidhya et al. [2] determined the equivalent impedance model of AC PV circuits and methods to calculate component values.

$$Z_{PV} = \left[R_s + \frac{R_p}{(\omega R_p C_p)^2 + 1} \right] - j \left[\frac{\omega R_p^2 C_p}{(\omega R_p C_p)^2 + 1} \right]$$

where component values are from the simplified circuit:

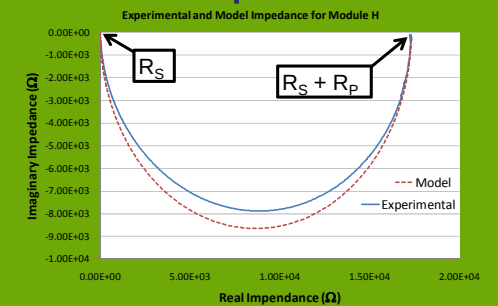


[2] D. Chenvidhya, K. Kirtikara, C. Jivacate, PV module dynamic impedance and its voltage and frequency dependencies, *Solar Energy Materials & Solar Cells* **86** (2005), pp. 243–251.

Result: circuit components for different PV modules.

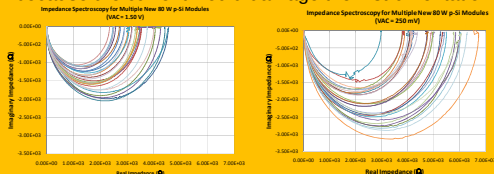
Values for specific modules are determined by adjusting R_s , R_p , and C_p to minimize the error between the Z_{PV} model and the experimental dynamic impedance loci.

Step 3: Experimentally Obtain Circuit Component Values



Module Variability and Challenges

- Manufacturing variability changes AC circuit component values, shown below for identical modules.
- Circuit values are dependant on voltage and frequency, illustrated in the difference in the same 28 modules for different magnitudes of injected sinusoidal voltage.
- Equivalent circuits can only be created for dark conditions because the current would damage the instrumentation.



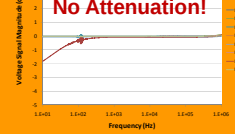
Results

Numerical: MATLAB/Simulink

No Attenuation!

Experimental: Frequency Response

No Attenuation!



Challenges Encountered

- Challenge:** To model the AC arcing signal on the PV string, the well-studied DC diode models were found to be inadequate.
- Solution:** Create dynamic equivalent circuit models of PV modules.
- Challenge:** The nonlinearities present in PV cells from irradiance, temperature, frequency and bias voltage complicate the modeling process.
- Solution:** Develop linearized dynamic equivalent circuits for a range of PV modules to match to the experimental data.

Conclusions

- The numerical simulation results matched experimental frequency response data for the zero irradiance case: **No attenuation from 1 Hz to 100 kHz.**
- The simulations were then expanded to situations with higher irradiances which were not capable of being directly measured: again no attenuation.
- Thus, circuit models determined **arcing frequencies in PV systems will not be attenuated prior to reaching a remotely located arc fault detector.**