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

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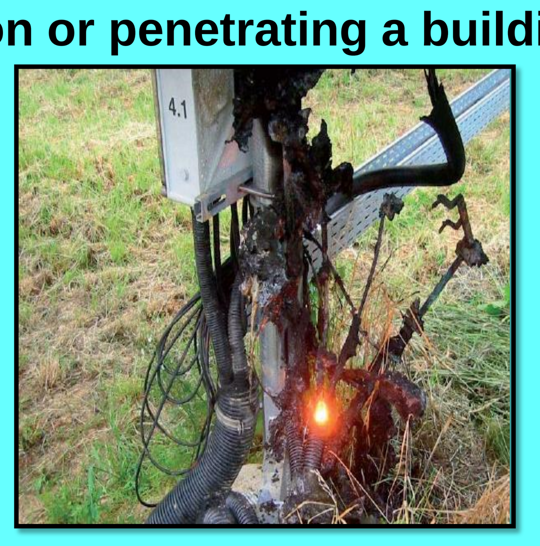
Arc Fault Frequency Propagation through PV Strings Simulated with Equivalent Dynamic PV Circuits

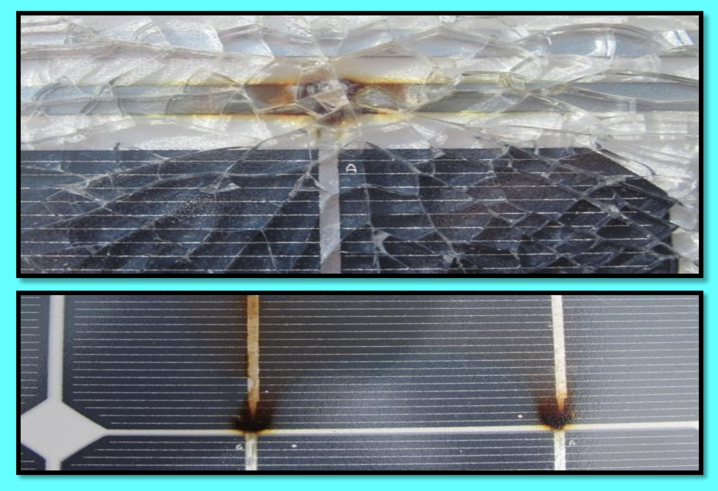
Background

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.

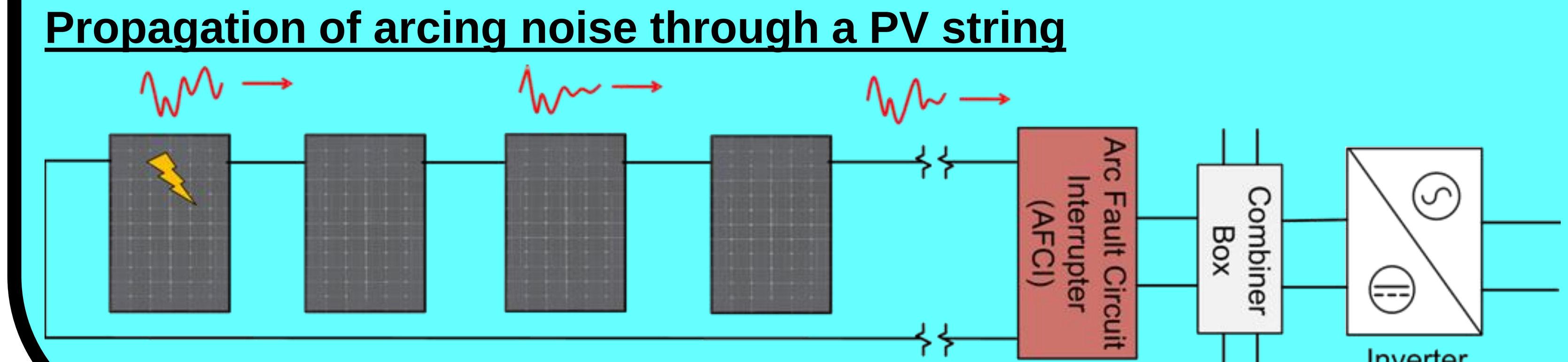
PV arc fault-initiated fire on a warehouse in Buerstadt Germany.



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

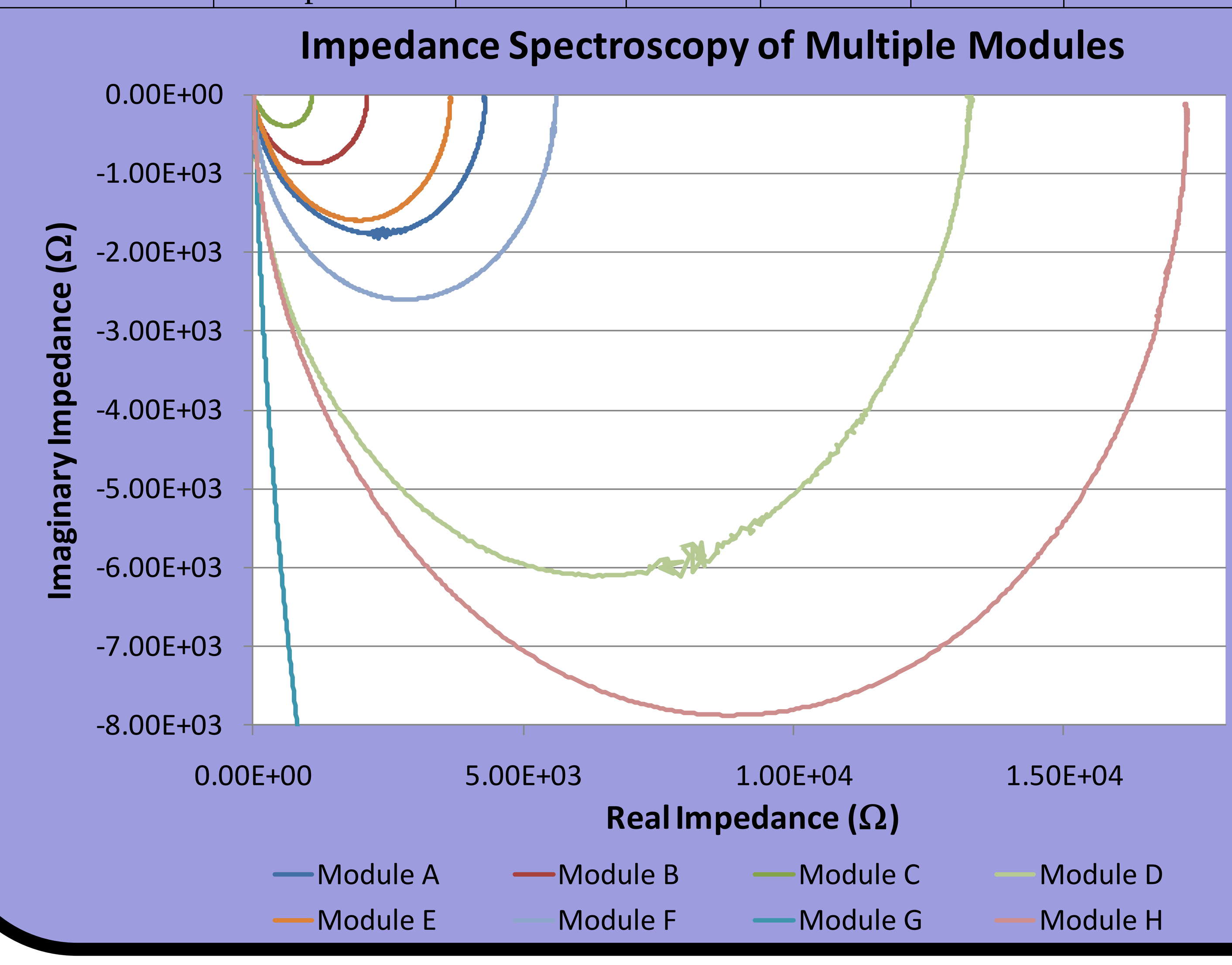


Concern: AC frequencies used for arc fault detection may be attenuated through PV components before reaching the AFCI.

Impedance Spectroscopy Modules

The complex impedance of eight modules was recorded with an AP Instruments Model 300 Frequency Response Analyzer. This data was examined to generate equivalent AC circuit models for these modules.

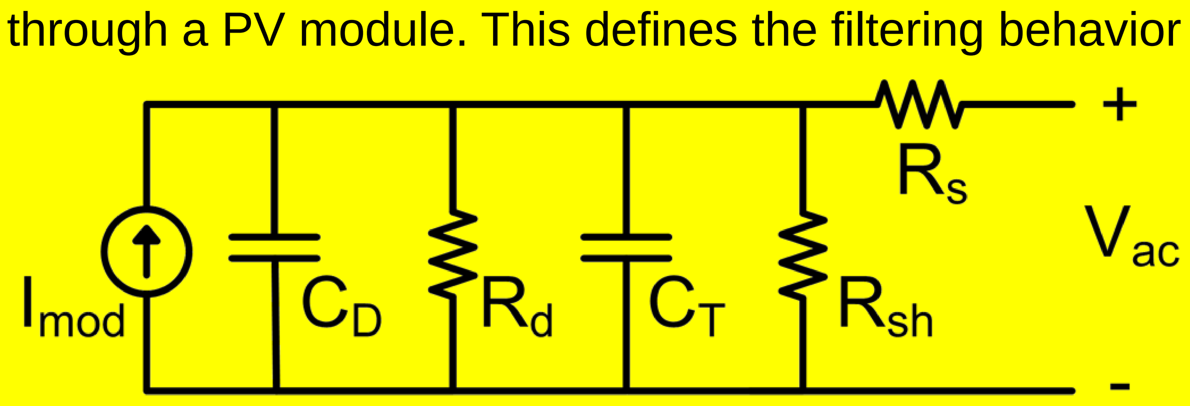
Module	Cell Type	P_{max} (W)	R_P (kΩ)	R_S (Ω)	C_P (μF)	Minimum Reactance Frequency
Module A	p-Si	72.0	4.27	0.50	1.8	355 kHz
Module B	p-Si	47.8	2.10	0.83	1.6	328 kHz
Module C	p-Si	72.3	1.08	1.02	4.0	194 kHz
Module D	c-Si	175	13.2	6.81	0.5	118 kHz
Module E	c-Si	75.0	3.65	0.31	1.8	188 kHz
Module F	c-Si	200	5.60	1.29	2.4	576 kHz
Module G	a-Si	43.0	348	13.8	3.4	666 kHz
Module H	p-Si	93.6	17.3	2.21	2.2	531 kHz



Result: circuit components for different PV modules.

Step 1: Create Equivalent AC Circuit of a PV Module

The equivalent dynamic circuit of a PV module [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.

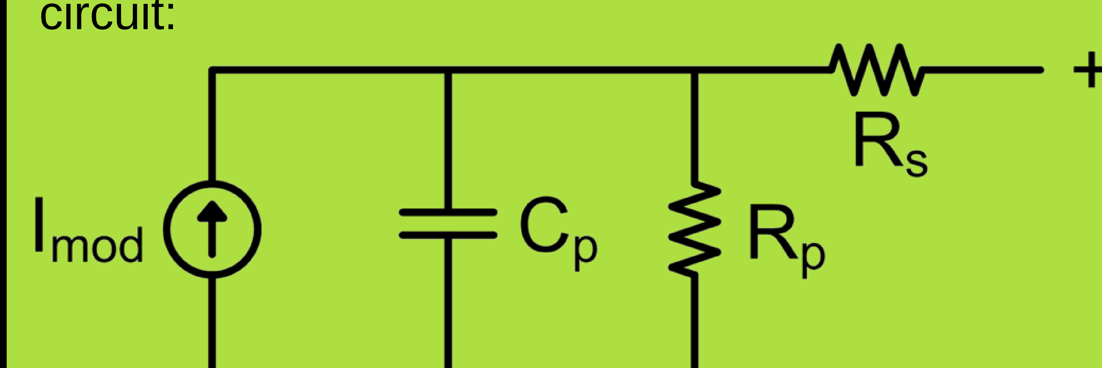
The complex impedance of the equivalent dynamic circuit is calculated based on the circuit model.

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.

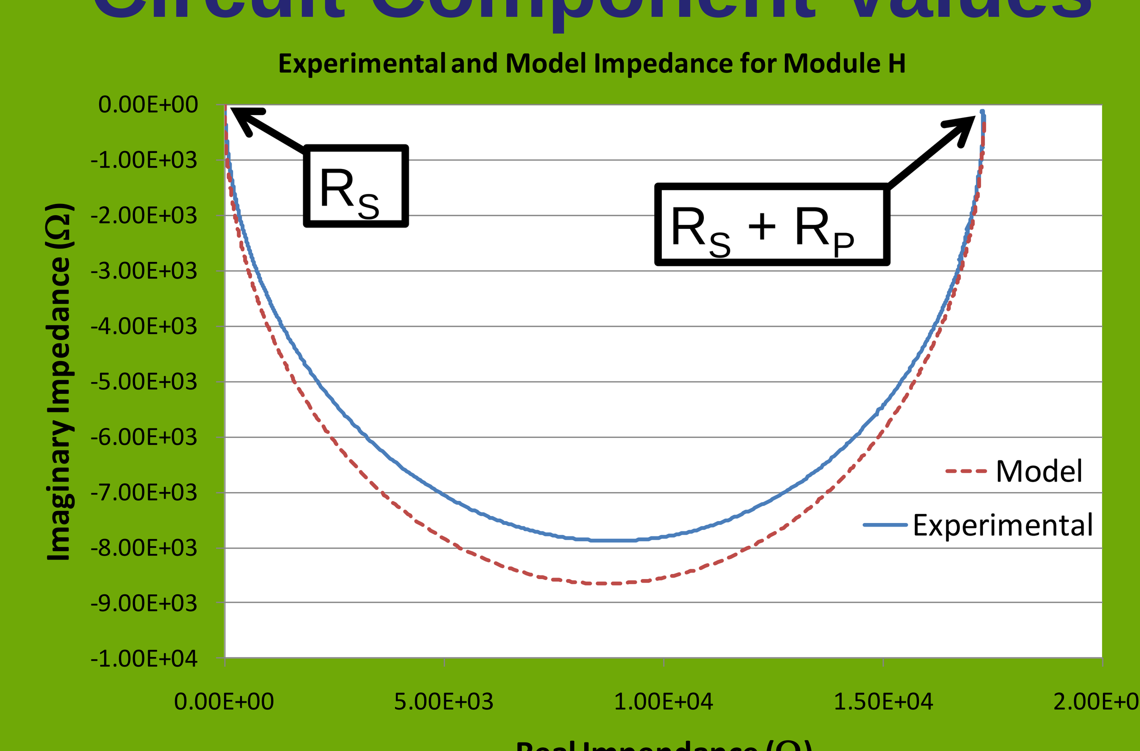
$$Z_{PV} = \left[R_s + \frac{R_P}{(\omega R_P C_P)^2 + 1} \right] - j \left[\frac{\omega R_P^2 C_P}{(\omega R_P C_P)^2 + 1} \right]$$

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.

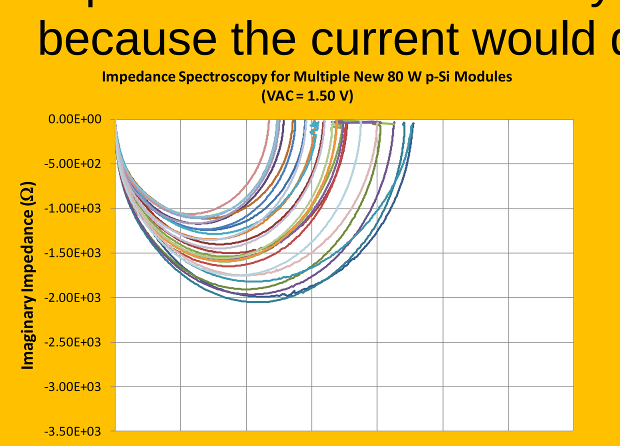
Step 3: Experimentally Obtain Circuit Component Values

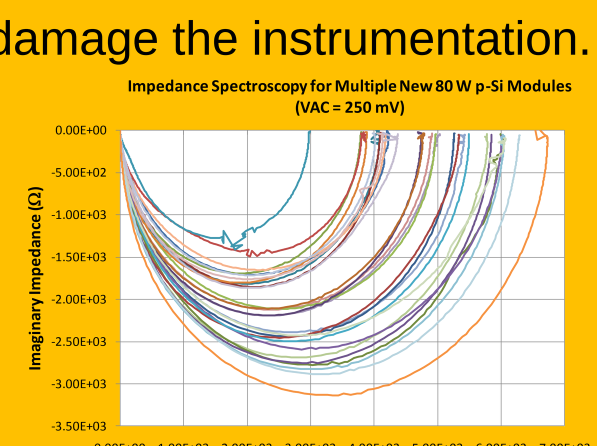


Values for specific modules are determined by adjusting R_s, R_p, and C_p to minimize the error between the Z_{PV} model and the experimental dynamic impedance loci.

Module Variability and Challenges

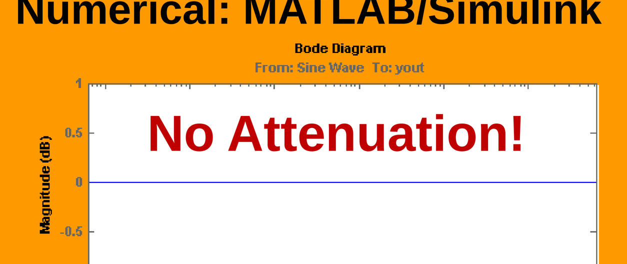
1. Manufacturing variability changes AC circuit component values, shown below for identical modules.
2. Circuit values are dependant on voltage and frequency, illustrated in the difference in the same 28 modules for different magnitudes of injected sinusoidal voltage.
3. Equivalent circuits can only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



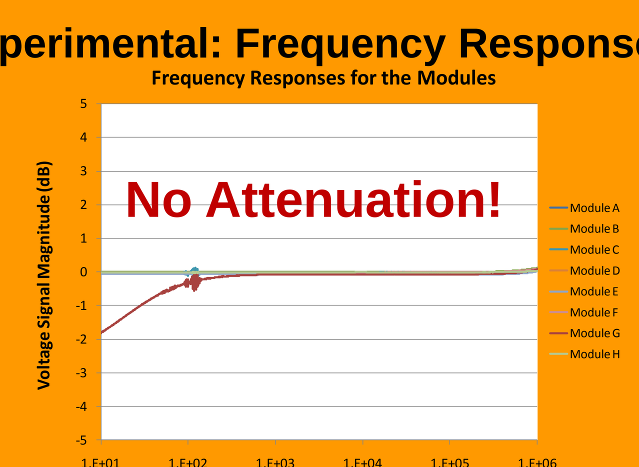


Results

Numerical: MATLAB/Simulink



Experimental: Frequency Response



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

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

National Nuclear Security Administration

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