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USING PV MODULE AND LINE FREQUENCY RESPONSE DATA TO CREATE ROBUST ARC FAULT DETECTORS

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ABSTRACT: Photovoltaic (PV) systems have caused residential and commercial building fires when an electrical arc fault initiates in the conduction path. Article 690.11 in the United States 2011 National Electrical Code requires new photovoltaic systems on or penetrating a building to include a listed arc fault protection device to prevent additional fires. In response, manufacturers are creating arc fault circuit interrupters (AFCIs) using electrical frequencies for detection, but their operation is not fully characterized. Sandia National Labs has undergone a major effort to identify detection difficulties and establish tests for PV AFCI manufacturers to ensure their product can robustly detect arcing conditions while avoiding false trips from noise sources. In previous studies, arc fault signatures have been compared to string noise and frequency-dependant attenuation through PV modules has been quantified. In this paper, a frequency response analyzer was used to measure radio frequency (RF) propagation through arrays of varying irradiance and size. Irradiance did not affect module frequency response, but the length of unshielded wiring significantly affected the frequency response of the system above 100 kHz due to RF effects. Based on the RF affects in PV systems, it is recommended that arc fault circuit interrupter manufacturers select detection frequencies below 100 kHz.

Keywords: Silicon Solar Cell, Characterisation, and Modelling

1 INTRODUCTION

In order to mitigate the risk of series arc fault fires in photovoltaic systems, Article 690.11 was added to the United States 2011 National Electrical Code [1]. The new law requires arc fault protection on new PV systems greater than 80 V on or penetrating a building. Industry is responding to this requirement with different arc fault circuit interrupter designs. Some use the current spectral content [2-3] or voltage frequencies [4] of the string to detect the arc fault signature.

Sandia National Labs is researching the electromagnetic propagation characteristics of arcing signals through PV arrays in order to (a) inform arc fault detector designers of frequency-dependant PV attenuation, electromagnetic noise, and radio frequency (RF) effects within PV systems, and (b) to determine if there are superior frequency bandwidths for detection. To detect the arc fault signature, the AC signal must reach the arc detector located somewhere along the string at the module, combiner box, or inverter. It is important to select appropriate frequencies for arc fault detection, so that AFCI devices are capable of years of reliable operation on a range of technologies while remaining free from nuisance trips.

Unfortunately, the signature can be disturbed a number of different ways as the signal travels through the PV system. Previous work found that normal modules did not attenuate AC signals [5], but damaged modules were capable of squelching some of the frequency content propagating through the module [6]. One study found wind-induced mounting rack vibrations can induce a 1% oscillation in string current due to incident light changes [7]. Further, inverter and RF noise can cause nuisance trips or mask the arc fault signature [2]. As shown in Figure 1, there is 60 Hz, 120 Hz, and switching frequency noise from the inverter on the string during an arc fault, so the arc detector would ideally not use those frequencies to perform arc detection. These challenges are discussed in more detail in [2].

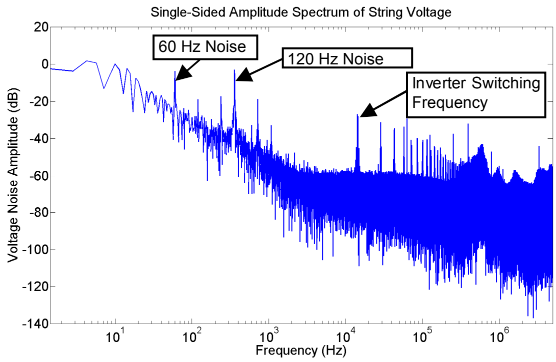

Figure 1: Discrete Fourier Transform of the PV string voltage with 22 80 W polycrystalline Si modules and a 208 V 3-phase inverter during an arc fault event.

This study investigates the difficulties with using high (>100 kHz) frequencies for arc fault detection. At these frequencies, RF phenomenon and antenna effects closely interact with the system and can adversely affect arc detection algorithms.

RF antennas have been studied extensively since the increased use of wireless radio and television communication in the 1920s [8], but in the last 20 years many studies have also investigated electromagnetic reception and emission from PV cells, modules, arrays, and other components. For instance, DC cables running between PV modules and the inverter act as receiving antennas and can transmit power electronic noise [9]. Solar cells were also found to emit RF noise by acting as an antenna for noise produced by the inverter or DC-DC converter [10-11]. Drapalik et al. discovered that PV cells experience nearly the same signal amplification as whip antennas of the same size over the entire frequency band [12].

Both the AC and DC sides of inverters produce RF noise and the PV array acts as an antenna to broadcast these frequencies. In the United States, FCC Part 15 [13] covers requirements for RF emissions for consumer appliances and electronic equipment, but solar systems are exempt from this requirement. However, in Europe far more attention has been paid to electromagnetic compatibility (EMC) issues (e.g. [14-16]). Häberlin measured the RF emissions on the AC and DC sides of different inverters from 1989 to 2000. He notes that inverters in the early 1990s produced significant electromagnetic interference (EMI) on the AC side, but by 1994 inverter manufacturers had reduced unintentional RF emittance [17]. On the DC side of the inverter, extensive testing was performed to establish a standardized EMC testing protocol utilizing an inexpensive method of stabilizing the line impedance [14, 18-20]. Yet, even with all these codes and standards, PV systems will still contain electromagnetic noise due to galvanic coupling (generally between 150 kHz and 30 MHz) and will broadcast and receive signals from radiated coupling [19]. PV systems with long DC cabling will experience electromagnetic harmonics at lower frequencies—possibly as low as 150 kHz [19]. These transmissions are picked up by other PV strings and DC cables and induce noise on parallel lines.

In this paper, the influence of line lengths, array size and module irradiance on PV system frequency response is studied. Antenna effects, crosstalk, coupling, and other RF phenomena were found to influence the spectral content of the string significantly between 100 kHz and 500 MHz. It is believed that unshielded and coiled cabling, poor connectors, and antenna effects were responsible for the majority of the RF noise. Unfortunately, this indicates noise from motors (power tools, etc.), meteorological events (e.g., lightning [21]), antenna effects from other power lines, and crosstalk can perturb the string frequencies and potentially mask arc fault signals from the arc fault detector. For this reason, arc detection frequencies below 100 kHz are recommended for arc fault circuit interrupters.

2 RF EFFECTS IN PV SYSTEMS

2.1 RF Frequency Response in PV cabling

To create baseline scans for module and string frequency response tests, the magnitude of RF coupling was determined in different lengths of unshielded high voltage PV wiring. An AP Instruments Model 300 Frequency Response Analyzer was used to measure the attenuation in the PV system by injecting a 250 mV AC signal into the cabling and recording the returning voltage amplitude, as shown in Figure 2. The magnitude of the signal is calculated by V_{output}/V_{input}.

As shown in Figure 3, below 500 kHz there was little attenuation, but at larger frequencies RF effects significantly affected the frequency response of the cabling. Longer wire lengths, more connectors, and coiling increased the signal amplitude and shifted the effects to lower frequencies. The connections between the FRA and high voltage cabling were made with alligator clips (not RF connectors) so this could have resulted in additional RF effects above 500 kHz. The additional connections were high current SUPERCON connectors. The increased amplitude of the signal was unexpected—especially at such low frequencies—but can likely be attributed to either a) coupling in the loop(s) of cabling and/or forming resonant circuitry at those frequencies, or b) the large amounts of far-field RF noise in the Distributed Energy Technologies Laboratory where the testing was conducted.

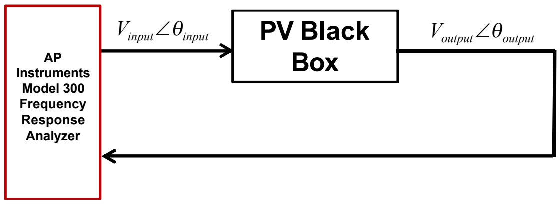

Figure 2: Frequency response analyzer concept.

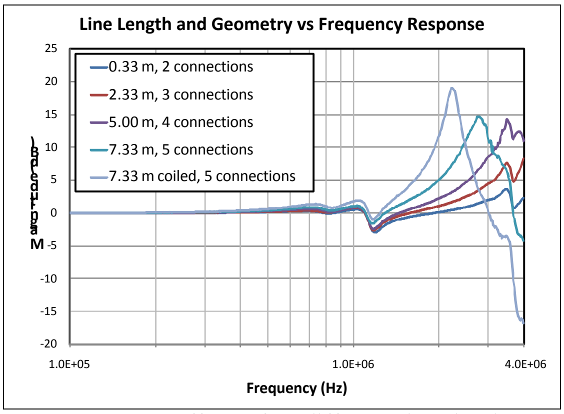

Figure 3: RF effects for different lengths in PV conductors.

2.2 RF Frequency Response in PV Modules

Frequency response tests were completed with 175 W monocrystalline modules in order to determine if PV modules attenuate AC frequencies. The experimental setup is shown in Figure 4. In order to connect the frequency response analyzer to the modules without damaging the instrument, a coupling circuit was designed which filtered out the DC PV current, shown in Figure 5. This circuitry introduced a high pass filter with a cutoff frequency of approximately 120 Hz.

The switch shown in Figure 5 is used to test the modules with and without current flow through the load bank. All the tests presented in this paper were conducted with the switch open. This configuration is more representative of a system during a parallel arc when the inverter is off or part of the string is open. Since series arc faults occur in the current path, additional testing with the switch open is required to characterize RF effects in all string configurations where arcing could occur.

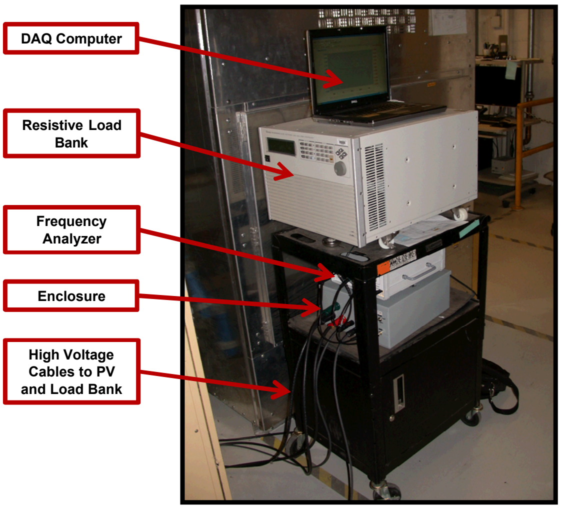

Figure 4: Frequency response system with coupling circuitry, Data Acquisition (DAQ) system, and resisitive load bank.

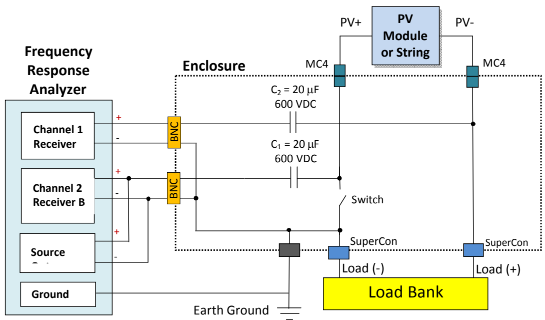

Figure 5: Electrical circuitry with coupling capacitors for frequency response experimentation on energized PV systems. Note: The schematic does not include the circuitry to discharge the capacitors.

Two types of baseline frequency scans were performed. The first connected the MC4 connectors together with a small length of cable (labeled "short at instrument") and the second shorted the ~20 m lengths of cabling running out to the array at the first module (labeled "short at PV"). Frequency response measurements of 1 module and a string of 4 modules are compared to the baselines in Figures 6 and 7. Three scans of all the configurations were taken, but only one of the plots is shown because they were nearly identify for each configuration. The unshielded electrical wiring from the instrument to the modules is the source of increasing amplitude at roughly 300 and 700 kHz and attenuation spike at around 2 MHz. As expected, the peaks shift to lower frequencies as the length of the test loop is increased because the 1st harmonic frequency in the line is decreased. This is consistent with the transmission line effects in the previous cable tests. Based on the heavy influence of RF effects in these results, PV arc fault detectors should avoid the higher frequencies, especially as the length of the array and cabling increases. This is because, depending on the system where these are installed, the content reaching the detector could be highly attenuated or amplified due to near-field coupling (inductive or capacitive) or far-field coupling (radiative antenna effects).

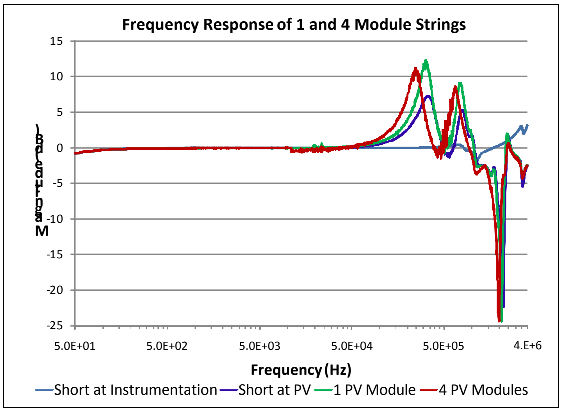

Figure 6: Frequency response of 1 module and a 4 module array with two baseline scans from 50 kHz to 4 MHz.

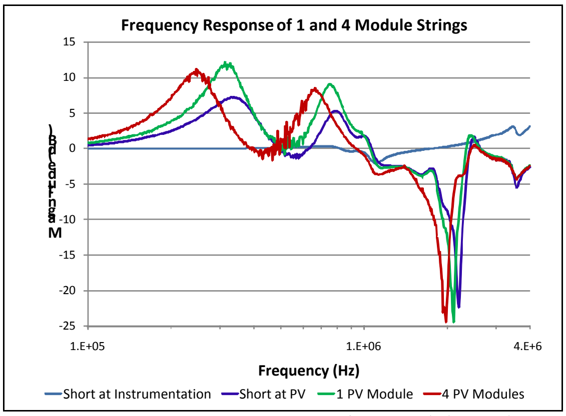

Figure 7: Frequency response of 1 module and a 4 module array with two baseline scans from 100 kHz to 4 MHz.

2.3 RF Frequency Response in PV Modules with Irradiance

It was believed that irradiance would influence the frequency response of the modules because the impedance of PV cells changes with varying illumination and voltage [22-23]. Tests were performed at predawn, early morning, and mid-morning to determine if irradiance affected the frequency response of a single module. As shown in Figure 8, there was only a small change in the response of the module with increasing irradiance, voltage, and temperature. The RF effects seen in the cable tests and the previous baseline scans were still the driving factor in the response profile.

This result has a number of implications for arc fault circuit interrupters:

1. Conducting solar cells do not change the frequency response of modules, so the arc fault signature will travel down the PV string to a remotely located arc fault detector with the same attenuation and RF effects regardless of the solar resource.
2. RF phenomena are responsible for the majority of signal changes in PV systems.
3. Noise primarily exist at frequencies above 100 kHz and may be caused by poor connections, far-field RF coupling with the room electronics or ambient electromagnetic fields, crosstalk with the positive and negative DC cables,

resonance in the PV circuitry, or capacitance toward earth from the PV source [16].

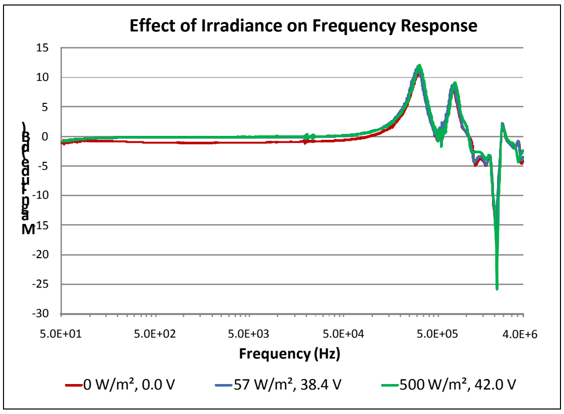

Figure 8: Change in frequency response of a single module with increasing irradiance.

2.4 RF Frequency Response in Different PV Modules

Lastly, to determine if module technology influenced the RF response of the PV modules, five modules with different cell technologies and I-V characteristics were analyzed under dark conditions without the coupling circuitry using a frequency response analyzer and HP 8753E RF Vector Network Analyzer (VNA). A summary of the modules is shown in Table 1.

Table 1: Modules for frequency response analysis

Module	*Cell*	*P_{max} (W)*	*I_{sc} (A)*	*V_{oc} (V)*
1	p-Si	47.8	3.13	21.73
2	c-Si	72.3	5.46	19.1
3	c-Si	75	4.8	21.7
4	c-Si	200	5.4	47.8
5	a-Si	43.0	0.40	194

The characteristics were different for each of the module types, shown in Figures 9 and 10. Multiple scans for each of the modules confirmed results were reproducible, so the variability between the frequency responses of each of the modules was the result of different internal electrical structures and cell technologies. The RF effects began at higher frequencies (~1 MHz) because single modules were tested without the 20 m cable lengths. Unlike the crystalline and polycrystalline modules, the amorphous Si had a small amount of attenuation between 10-100 Hz. The cause of the attenuation is unknown but could be attributed to large resistances and capacitances associated with a-Si modules [5].

The AP Instruments Frequency Response Analyzer is generally not used to analyze very high frequency circuitry so the RF VNA was used to scan the modules from 100 kHz to 500 MHz. Some of the signal amplification and RF noise was believed to be originating from limitations of the FRA. In was observed that the instrument was unable to maintain the 250 mV amplitude at high frequencies. This should not affect results because the instrument calculates the magnitude by taking the returning signal amplitude divided by the original signal amplitude, but to verify the presence of RF effects at higher frequencies, the VNA was used. For each of the modules, the VNA calculated the complex scattering parameter S_{21}, which is defined by network theory as the forward transmission voltage gain—or magnitude of a signal reaching port 2 (output) from port 1 (input) on the device under test [24]. For passive circuitry $20\log_{10}|S_{21}|$ is equivalent to the FRA frequency response in decibels.

To eliminate noise and signal reflections from connectors in the experimental setup, the VNA was connected to the PV modules with RF connectors. The system was calibrated with an input impedance of 50Ω such that there was no attenuation when the probes were connected together without a module. It was noted that adjusting the connectors to the PV modules or manipulating the wires by moving them, twisting them, or creating sharp bends would significantly change the VNA results. Swings of 20 dB or larger could be produced by changing the wire geometry at higher frequencies. This variability means the calibration was somewhat arbitrary and the variability between modules was likely due to connector and cable orientation changes. Moreover, the difference in the FRA and VNA frequency response results between 100 kHz and 1 MHz is the result of connector differences, VNA calibration errors, and the two instruments coupling different RF noise.

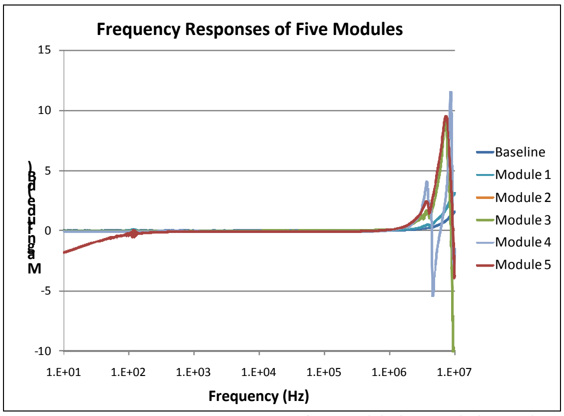

Figure 9: Frequency response for multiple modules using a frequency response analyzer. The baseline was taken without a module.

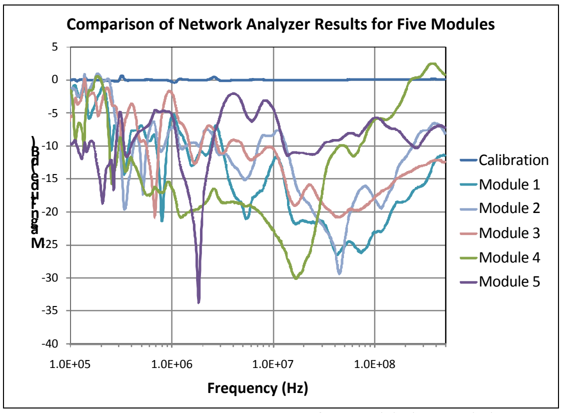

Figure 10: Frequency response for multiple modules using the vector network analyzer. The calibration was performed without a module under test.

3 CONCLUSIONS

Arc fault circuit interrupters designed for protecting PV systems against series arc faults often use string current or voltage frequency content to determine when to trip. Selection of appropriate frequencies is critical for robust arc fault detection because string attenuation or noise will lead to missed arc faults or false trips. This study investigated RF phenomena in PV systems in order to determine the viability of using high frequencies for arc fault detection. Irradiance did not change the frequency response of the PV system, but line length and module type did change the frequency response above 100 kHz. Thus, high frequency detection is expected to be more challenging because DC cables, PV cells, modules, and inverters transmit and induct RF noise; weak or unshielded connections to the PV string lead to high frequency attenuation; and the long cable lengths and metal grids in modules act as antennas. Additionally, the magnitude of arc fault string current and voltage is smaller at higher frequencies (i.e., Figure 1) so the arc signature could be lost in measurement noise.

Based on the RF challenges, arc fault detection frequencies below 100 kHz and above 1 kHz is recommended. Frequencies below 100-1000 Hz are susceptible to solar variability from clouds, trees, toys, and people, incident irradiance oscillations from wind loads, and 120 Hz inverter noise and 60 Hz mains noise. Thus, arc fault circuit interrupters utilizing low frequencies are more likely to have false trips. Switching frequencies of most inverters is between 1-100 kHz, so selecting a single frequency within this range is not advised. Instead—as proposed in [25-27]—multiple frequencies or broadband noise may be used to detect arc fault initiation because the arc fault produces noise across the entire spectrum [28]. This technique is also possible for frequencies above 100 kHz and below 1 kHz, but there is evidence that 1-100 kHz receives more arc fault noise than other frequency bands [2]. Thus, there appears to be a "sweet spot" for arc fault detectors within 1-100 kHz where arc detection is robust and reliable.

4 ACKNOWLEDGEMENT

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