CHARACTERIZING PV ARCING CONDITIONS WITH IMPEDANCE SPECTROSCOPY AND FREQUENCY RESPONSE ANALYSIS

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ABSTRACT: Photovoltaic arc faults have led to a number of rooftop fires that have caused significant property damage and threatened the safety of building occupants. In response, Article 690.11 was added to the United States 2011 National Electrical Code, requiring new PV systems on or penetrating a building to include a listed arc fault protection device. Many proposed arc fault detectors utilize frequency content on the PV string to remotely determine if an arc fault is occurring. A frequency response analyzer was used to measure the AC frequency and impedance response of an 80 W polycrystalline module with degradation similar to those which have caused arc fault. The module had intermittent electrical connectivity in the junction box because of a failed solder bond, and the quality of the connection could be manipulated by adjusting the external wire orientation. By reorienting the wire, the impedance profile changed and the frequency response transitioned between high-pass, low-pass, and no filtering behavior. This indicated (1) certain module conditions can filter arc fault noise frequencies, and (2) the frequency response or impedance spectroscopy of PV components could be used to identify conditions that cause arc faults in PV systems. The implications for the former are serious because if the detection frequencies used by the fault circuit interrupter (AFCI) are sufficiently filtered, the device will not trip and the arc will not be extinguished. Finally, infrared images were taken of the intermittent module to identify the area of damage and corroborate the impedance spectroscopy results.

Keywords: Silicon Solar Cell, Characterisation, and Modelling

1 INTRODUCTION

Photovoltaic arc faults generate high temperature plasmas which ignite surrounding materials [1]. In rooftop systems, this is particularly dangerous because the fire spreads to the building and can destroy the structure [2-4]. Firefighters have additional challenges extinguishing fires on buildings equipped with PV systems [5], thus delaying the firefighting response. In order to mitigate the dangers to homeowners, firefighters, and building occupants, Article 690.11 was added to the US National Electrical Code in 2011 [6]. The code requires PV installations above 80 V on or penetrating a building to have series arc fault protection.

Industry has responded to the new NEC requirement by creating arc fault circuit interrupters (AFCIs) [7-10]. Some of these arc fault detectors use the spectral content on the string to determine when an arc is initiated. Unfortunately robust arc detection can be difficult due to the wide variety of PV technologies and possible system configurations. Further, the arc fault detector must operate for years without nuisance trips from inverter noise or RF sources (e.g., local electrical devices, radio signals, etc.).

An example of the frequency content on the string during an arcing event is shown in Figure 1. The AC string spectrum is generated and manipulated by the following sources:

1. An arc fault initiates at a connection in a module and generates AC noise on the PV conductor. This signal travels down the line through the PV system. See [7] for characteristic arcing signatures.
2. As the signal passes through the modules and connectors, some of the frequency content of the electrical AC arc noise may be attenuated. Typically there is negligible attenuation in undamaged modules [11], but results from this report show different behavior.
3. Depending on the system line lengths, antenna effects and other RF phenomena, the spectral content of the arc signature will change [12].
4. The modified arcing signal reaches the arc fault detector within the arc fault circuit interrupter. Detection of either the current content (e.g., [7]) or the voltage content (e.g., [13]) can be performed by the AFCI. Depending on the cell technology, system topology, meteorological conditions, and health of the modules, the signal reaching the AFCI will be different than the original arcing signal—possibly allowing an arcing condition to go undetected.
5. In addition to these hurdles to arc detection, inverter switching generates noise in the system at a few kHz to 100 kHz [7-8, 14], which the AFCI must filter.

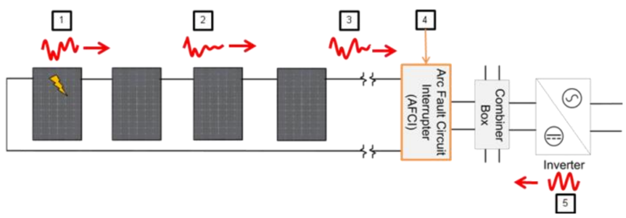


Figure 1: Arc fault signal propagation and detection.

To better ascertain the potential for missing an arc fault, Sandia National Laboratories is investigating the effect of module degradation on string arcing frequency content. In this paper, the arc fault frequency characteristics through an intermittent 80 W polycrystalline Si module are studied. The intermittent module failed from a solder joint in the junction box. An x-ray image of the junction box shows the failed bond in Figure 2.

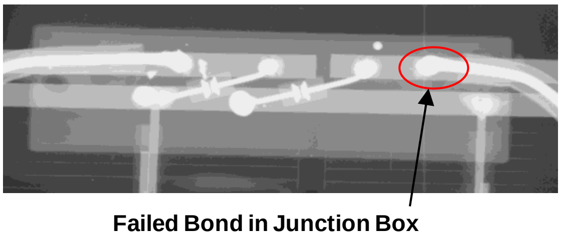


Figure 2: X-ray of the test module junction box.

In previous tests, frequency-dependent attenuation was absent in eight healthy modules [11], but this study found the intermittent module had significantly different behavior. The frequency and impedance response for the module varied drastically depending on the orientation of the external cable connected to the failed solder bond.

This is particularly concerning because AFCI devices use arc fault frequencies propagating along the PV string to determine when to trip. If the arcing signature is sufficiently attenuated, the arc would not be extinguished because the arc detector would not receive the same spectral content produced by the arc. Further, studying the frequency content passing a damaged module is important because these conditions are known to have caused arc faults in the past [15]. Thus, if module damage initiates series arc faults while also attenuating the frequencies used for arc fault detection, it is likely when an arc does occur, the arc signature could be masked. In addition, this intermittent module is representative of the module degradation prior to an arc fault because junction box and bypass diode failures have become more common recently [16].

One potential benefit from this discovery is recognizing the need for preventative maintenance to identify and correct degraded modules prior to an arc fault. Since electrical intermittency is a precursor to arcing in PV systems, frequency response or impedance spectroscopy measurements could be used as a prognostic or health-monitoring technique to identify conditions which lead to arc faults. These scans could be performed regularly on PV strings to identify loose connectors, weak connections, or discontinuities in the PV electrical system.

Similar techniques have been employed in microelectronics packaging to perform prognostic health monitoring. Changes in resistance spectroscopy have been used to predict soldered connection failures [17-18].Kwon et al. [19] found that RF impedance predicts the failure of soldered joints because the skin effect concentrates the signal in the connection surface where soldered connections first fail.

2 EXPERIMENTATION

2.1 Electrical testing setup

In order to determine which arcing frequencies are attenuated in a damaged module, an AP Instruments Model 300 Frequency Response Analyzer (FRA) was used to measure the AC response of the intermittent module under no irradiance. The input signal was a 250 mV AC sweep from 1 Hz to 10 MHz. The FRA recorded the magnitude of the input and output sinusoid, illustrated in Figure 3, and the attenuation of the AC signal was determined by the magnitude of V_{output}/V_{input}. Figure 4 shows the laboratory configuration for the tests.

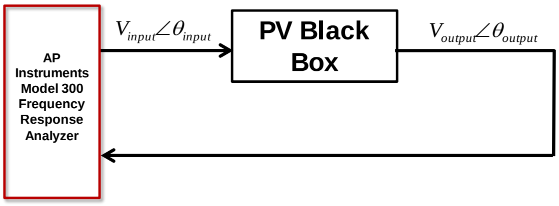


Figure 3: Basic concept of a frequency response analyzer.

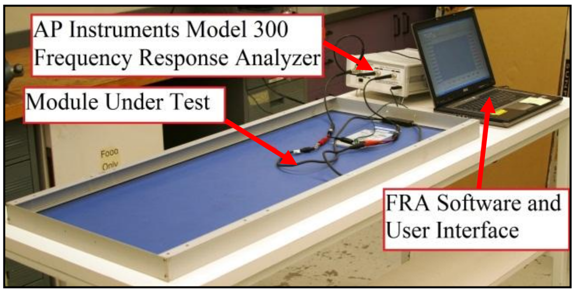


Figure 4: Experimental setup.

2.2 Frequency Response Results

The intermittent module was scanned three times with the loose connection in four different orientations, shown in Figure 5. As shown in Figure 6, orientation 2 (scans 2.1-2.3) made a good connection within the junction box because the frequency response closely matched those of undamaged modules of the same technology [11]. The noisy behavior above 1 MHz is from crosstalk in the cables, RF effects, and noisy connections to the instrumentation [12]. Scans for the 1st and 3rd orientations show the module behaving as a low-pass filter, whereas orientation 4 strongly attenuates low frequencies. Scans 4.1-4.3 are coupled with 60 Hz noise from the instrument or ambient sources, so the change in attenuation is most likely artificial. Arc detection studies have indicated arc faults produce distinct noise signatures between 100 Hz to 100 kHz [7]. An arc detector tuned to those frequencies would miss a portion of the arc signature if the junction box wire was in orientation 1, 3, or 4.

The frequency content of the arc reaching the detector is affected by the intermittent module. As cabling between modules swing and change orientation due to wind and weather, the arcing voltage spectrum would appear different to the AFCI. To quantify the difference, a theoretical 1/f voltage signature characteristic of arcing [20] is compared to the voltage reaching the arc detector when the intermittent module is in the string. As shown in Figure 7, the voltage noise reaching the arc detector with undamaged modules is stronger than when the damaged module is in the string and the wire is in orientation 1, 3 or 4.

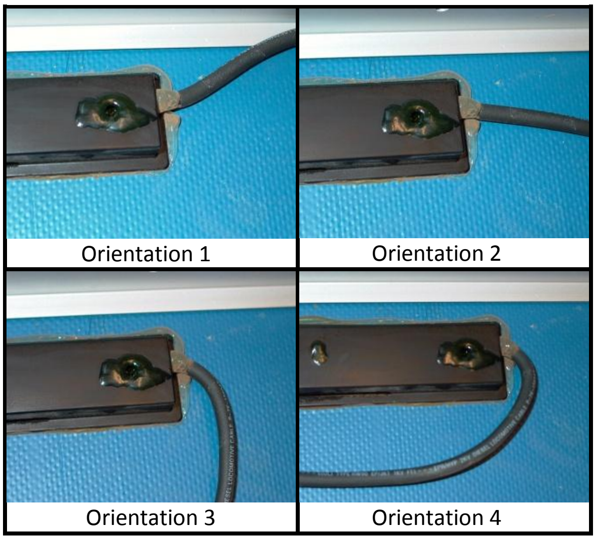


Figure 5: The four orientations of the junction box wire.

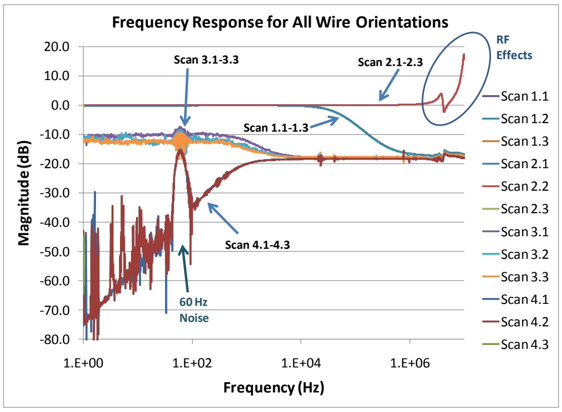


Figure 6: Frequency response of a single intermittent module configured with a loose junction box wire held in four different orientations.

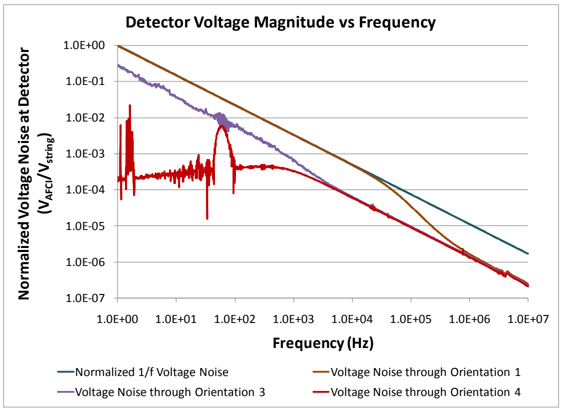


Figure 7: The AC arcing noise, intermittent module attenuation characteristics, and resulting detector signal.

4 ARC FAULT PROGNOSTICS

4.1 Impedance Spectroscopy

In order to better quantify electrical changes in the module circuitry due to wire manipulation, three impedance spectroscopy scans were performed for the four different wire orientations immediately after taking the frequency response data. The results are plotted from 1 Hz to 200 kHz to avoid the RF effects at high frequencies in Figures 8-11. Orientation 2 was consistent with plots of undamaged modules [11], in which the reactance and resistance asymptotically approach zero, shown in Figure 12. Impedance spectroscopy of wire orientation 1 revealed a 1.5 kΩ shift in the resistance when compared to orientation 2. This is the result of a series resistance increase in the module [11, 21], which indicates the electrical connectivity is reduced due to contact resistance in orientation 2. Orientations 3 and 4 exhibit a significant amount of noise and orders of magnitude more resistance and reactance. Orientation 3 has high resistances at low frequencies but returns to the standard semicircular path at higher frequencies. Orientation 4 contains an especially large amount of noise and is likely not accurately calculated by the FRA. This is because it contains negative resistances which are impossible with passive circuitry.

Based on the frequency responses for the different orientations, the impedance spectroscopy trends are not unexpected. Orientation 2 was not attenuated and produced a "healthy" PV module impedance response; but when the attenuation increased in orientations 1, 3, and 4, the impedance was larger and more chaotic. For this reason, it is believed that either the frequency response or the impedance spectroscopy of modules, strings, or arrays could be employed to monitor the health of the system. If the frequency response deviated from the unattenuated, "healthy" response or the impedance spectroscopy results were uncharacteristic of normal PV systems, this would warn of an impending maintenance problem or potential arcing conditions.

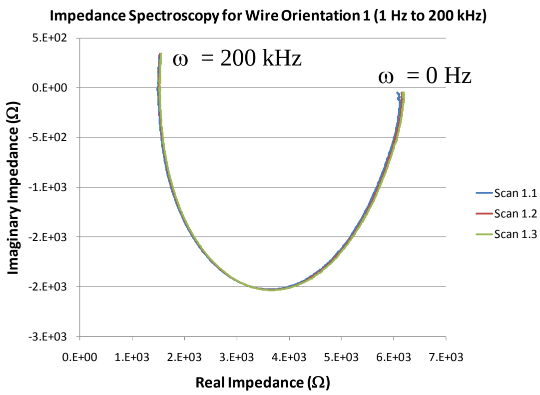


Figure 8: Impedance spectroscopy results for wire orientation 1.

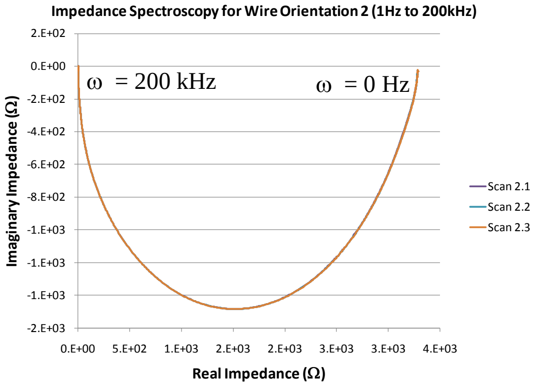


Figure 9: Impedance spectroscopy results for wire orientation 2.

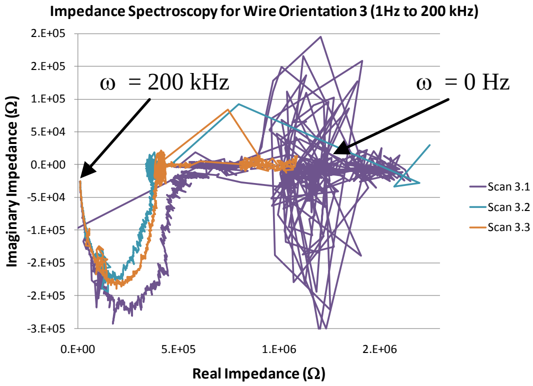


Figure 10: Impedance spectroscopy results for wire orientation 3.

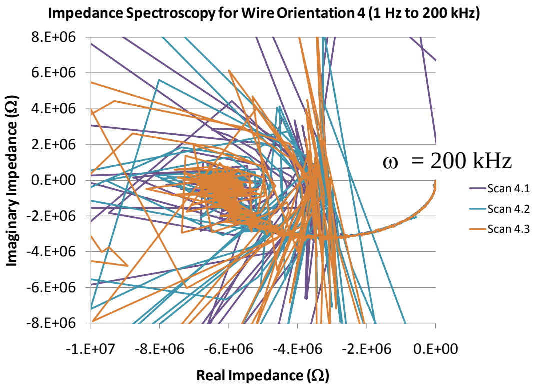


Figure 11: Impedance spectroscopy results for wire orientation 4.

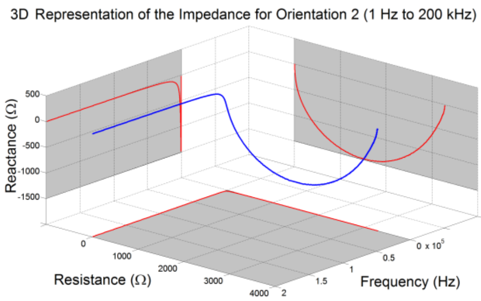
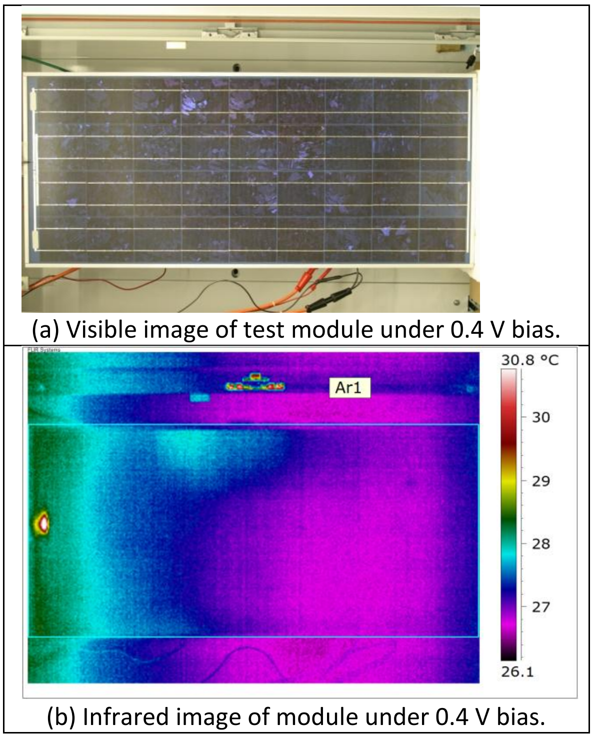


Figure 12: Three-dimensional depiction of the impedance spectroscopy results vs input frequency curve (blue) and projections of the curve on 2D planes (red).

4.2 Infrared measurements of module

To determine if the junction box was the cause of the increased series resistance in orientations 1, 3, and 4, infrared (IR) images were taken of the module. The large series resistance in wire orientation 1, and possibly in orientations 3 and 4, will produce more Joule heating from i^2R losses. Figure 13 shows visible and IR images of the intermittent module taken from the same location. The IR image was taken after 20 seconds of 0.4 amps forward biasing and shows localized heating in the junction box. Although the wire orientation for this test was unknown, the IR results show elevated temperatures in the junction box from high resistance Joule heating. This heating is the result of reduced electrical conductivity from corrosion or poor conductor connections and can lead to arc faults if left unattended.



(a) Visible image of test module under 0.4 V bias.

(b) Infrared image of module under 0.4 V bias.

Figure 13: (a) Image of the front of the PV module after 20 seconds of 0.4 amps forward biasing in a Dark IV chamber, and (b) corresponding FLIR Thermacam P60 infrared image taken with wavelengths of 7.5 to 13 μm. The hot spot (center left) from Joule heating illustrates the high resistance in the intermittent module in the junction box.

4 CONCLUSIONS

Frequency response analysis, impedance spectroscopy and infrared thermography were used to characterize an intermittent PV module. The module electrical response changed based on the connection quality of a failed solder bond in the junction box. The connection quality could be adjusted by orienting the wire in different directions. Four orientations of the wire were tested and produced very different frequency responses and impedance spectroscopy results.

Frequency-dependant attenuation in PV strings could have severe consequences because this filtering may mask the arc fault signature from AFCIs. Furthermore, infrared images indentified a resistance increase in the intermittent module junction box which is characteristic of degradation and conditions leading to arc faults. Therefore, it is particularly concerning that conditions which cause arcs—i.e., discontinuities in the electrical conductors—are also responsible for AC attenuation on the line.

While the module attenuation is a challenge for arc fault detectors, the change in frequency response could be used to identify module damage prior to catastrophic failure. Similarly, impedance spectroscopy, resistance or reactance health monitoring or prognostics could indicate degraded strings or modules before they initiate an arc fault.

5 ACKNOWLEDGEMENT

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