Crosstalk Nuisance Trip Testing of Photovoltaic DC Arc-Fault Detectors

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***Abstract* — To improve fire safety in PV systems, Article 690.11 of the 2011 National Electrical Code (NEC) requires photovoltaic (PV) systems above 80 V on or penetrating a building to include a listed arc-fault protection device. Many arc-fault circuit interrupter (AFCI) devices are currently being listed and entering the market. Depending on the manufacturer, AFCIs are being deployed at the module-level, string-level, or array-level. Each arc-fault protection scheme has a different cost and arc-fault isolation capability. Module-level and string-level AFCI devices tout the ability to isolate the fault, identify the failed PV component, and minimize the power loss by selectively de-energizing a portion of the array. However, these benefits are negated if the arcing noise—typically used for arc-fault detection—propagates to parallel, unfaulted strings and cause additional AFCI devices on the PV array to trip. If the arcing signature "crosstalks" from the string with the arc-fault via conduction or RF electromagnetic coupling, the location of the arc-fault cannot be easily determined and safe PV generators will be disconnected. Sandia National Laboratories collaborated with Texas Instruments to perform a series of nuisance trip scenarios with different PV configurations. Experimental results on a 2-string array showed arc detection on the faulted string occurred an average of 19.5 ms before unfaulted string—but in some cases the AFCI on both strings would trip.**

***Index Terms* — photovoltaic systems, arc-fault detection, series arc-faults, monitoring, power system safety, RF coupling**

I. INTRODUCTION

Arc-fault circuit interrupters (AFCIs) are entering the market to satisfy the 2011 *National Electrical Code*® [1] arc-fault protection requirements. Different manufacturers have elected to provide arc-fault protection at different scales in PV arrays. As illustrated in Figure 1, some of the arc-fault detectors are:

1. module-level devices, such as AFCI-enabled DC/DC converters or microinverters, which provide module-level series and/or parallel protection
2. string-level AFCI devices which monitor and de-energize single PV strings
3. array-level arc-fault protection devices which are incorporated into central inverters.

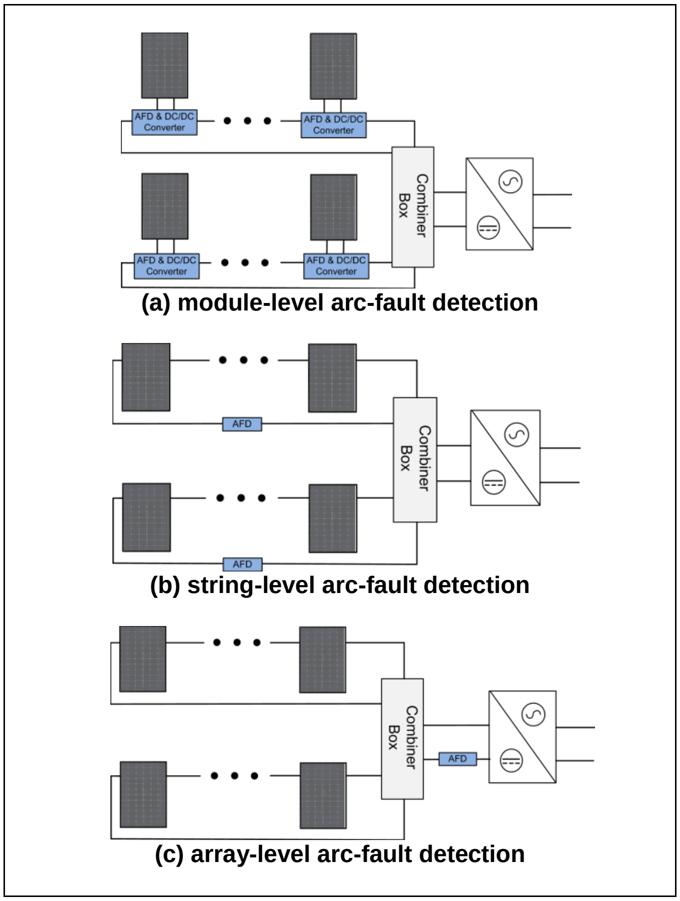

Fig. 1. Arc-fault detection at (a) module-level, (b) string-level, and (c) array-level.

PV owners selecting between these arc-fault protection methodologies must weigh the trade-off in cost, ease of identifying the faulty component, and quantity of power loss during the AFCI trip. Module-level protection requires the largest number of AFCI devices and therefore would likely be the most expensive [2], but it could potentially shut-down the smallest portion of the array—allowing for the quickest identification of the faulty component and lowest reduction in power production. In contrast, the inverter-integrated AFCI devices are much less expensive because there is one per array and they can utilize the DC disconnect in the inverter; but once tripped, they de-energize the entire array. This makes it difficult to identify the location of the arc-fault and discontinues all power production until the fault location is identify and repaired. Inverter-integrated AFCIs also have the advantage of knowing the inverter noise signature (e.g., switching frequency) and, therefore, manufacturers can select detection frequencies to avoid those areas of interference. It should be noted that some AFCI systems may separate the arc-fault detector (AFD) from the circuit interrupter, so some hybridization is possible. For example, arc-fault detection could be performed at the string-level but de-energization performed using the inverter DC disconnect.

The benefits of low-level arc-fault detection are limiting effects of an AFCI trip on power production and improving the speed and accuracy of locating of the arc-fault. In a previous study [3], the attenuation in PV modules between 1-100 kHz was found to be negligible. Previous Sandia National Laboratories (SNL) and utility-scale testing found that the location of the arc-fault detector did not influence detection of the arc-fault signature [4-5]. Luebke, et al. found the arc-fault could be detected at the string, between the combiner and recombiner, and at the central inverter on 500 kW systems [5]. Luebke also noted that the AFD did not nuisance trip on parallel, non-faulted strings.

The arc-fault elevates broadband noise in the radio frequency (RF) spectrum of the DC subsystem. Arc-fault detection can be completed using a number of different techniques, but it is common for AFDs to capture the noise from multiple frequencies using a current transformer and trip the circuit interrupter when all the frequencies reach a threshold for a predefined period of time. The built-in delay avoids nuisance tripping by allowing arc-faults from DC switching and other transitory sources. The Fast Fourier Transform (FFT) of the DC line current from 0-100 kHz with a Hanning window during normal and arcing conditions is shown in Fig. 2. As shown in Fig. 3, the arc-fault broadband noise is elevated when the arc-fault occurs. The low frequency noise and other spikes in the signal prior to the arc-fault were created by the inverter and switching noise while preparing the arc-fault generator.

II. CROSSTALK NOISE MEASUREMENTS

The Distributed Energy Technologies Laboratory (DETL) at Sandia National Laboratories has 150 kW of reconfigurable PV modules, inverters, and BOS components used to test the reliability and performance of different PV technologies. Previously, a series of tests was conducted at DETL to quantify the magnitude of the arc-fault signature and determine if inverter noise would trigger nuisance tripping [4]. In this set of tests we aim to answer questions regarding arc-fault noise propagation through the array. The testing was performed on two different arrays to ensure the noise propagation was consistent between systems. The data acquisition (DAQ) system consisted of one Tektronix TCP303 current transducer connected to a National Instruments (NI) PXI-5922 digitizer and a Tektronix DPO3014 oscilloscope to measure the voltage of the arc-fault. The arc-fault generator was the same design used in [4-5], and was installed on the positive DC conductor of one of the strings.

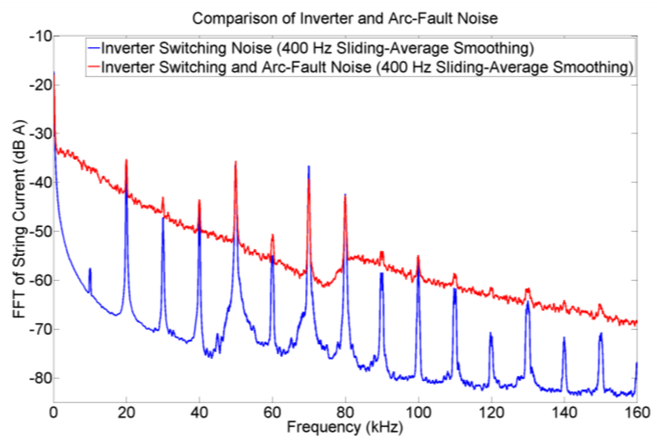

Fig. 2. Comparison of averaged and smoothed inverter "baseline" noise and series arc-fault noise.

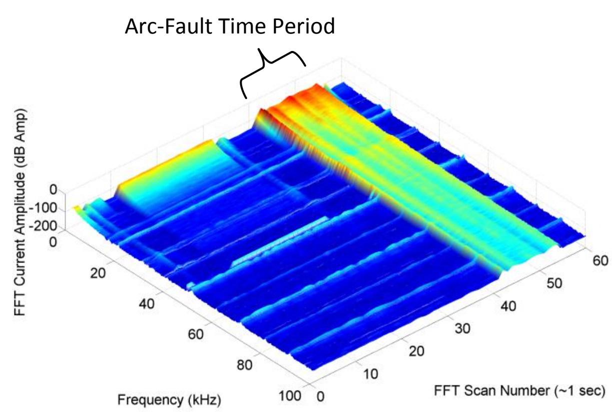

Fig. 3 Arc-fault noise from 0-100 kHz compared to normal operating noise.

The RF spectrum was measured with the NI system for two different inverters to determine propagation behaviors of the current noise on the DC-side of the PV system. The first system consisted of two strings of seven 200 W crystalline Si modules joined within a combiner box connected to a 2 kW inverter. The noise on the two strings was captured 10 consecutive times with the inverter running normally and 10 times with a series arc-fault. These data are shown in Fig. 4 after being smoothed with a 200 Hz rectangular sliding average. Only one Tektronix TCP303 probe was available for the tests, so different arc-faults were measured in the faulted and unfaulted results. Therefore a direct quantitative comparison of the noise values for the two arc-faults cannot be performed, but the qualitative results clearly show elevated noise across the spectrum for both strings when the arc-fault occurs. Note that there are some frequencies where the arc-fault noise is indistinguishable from the inverter switching noise and its harmonics. It is important for the arc-fault detector algorithm to avoid monitoring these frequencies in order to provide robust arc-fault detection.

A second PV system was constructed with the same 14 200 W c-Si modules, but the array used T-branch MC4 connectors and a 3 kW inverter. The crosstalk test from the first array was recreated, but in this case the noise differed by ~20 dB between the two strings during the arc-fault, shown in Fig. 5. Since the arc-fault generator electrodes were separated by hand, the electrode gap was most likely not the same distance for the two tests. As a result, the voltage drop across the gap could have differed for the two tests. However, like the first test, the arc-fault noise was elevated on both the faulted and unfaulted strings and significantly above the inverter "baseline" noise, except for a few specific inverter switching frequency components. This means that arc-fault detectors on either string can trip on the arc-fault. The reason for the slight roll-off of noise below 10 kHz is unknown but may be the result of the inverter absorption or the connections inhibiting coupling in that frequency band. It is also possible the roll-off could be a function of the DC cabling routing.

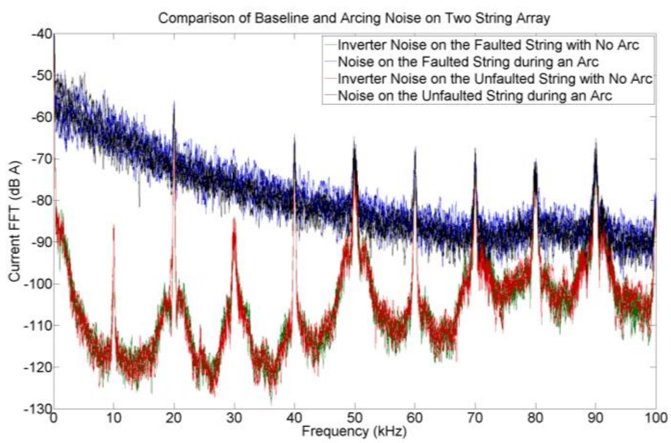

Fig. 4. Inverter noise and arc-fault noise on faulted and unfaulted strings of a PV array with two different arc-faults.

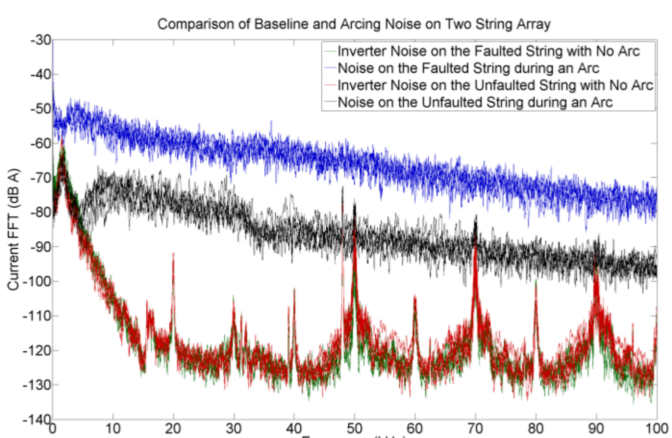

Fig. 5. Inverter noise and arc-fault noise on faulted and unfaulted strings of a PV array with two different arc-faults.

III. CROSSTALK TESTING

To measure the effect of crosstalk in the second two-string test setup, arc-fault detectors were attached to each string and set to detect and annunciate the arc-fault event. While the inverter was operating, a series arc-fault was generated on one of the strings by separating two copper electrodes. The test configuration is shown in Fig. 6. The oscilloscope captured the arc voltage along with the trip signal generated by the TI arc-fault detectors at 100 kHz. The test was repeated multiple times to quantify the detection time and repeatability. The RF spectrum was also captured for the faulted and unfaulted strings using a Tektronix TCP303 current transformer (CT).

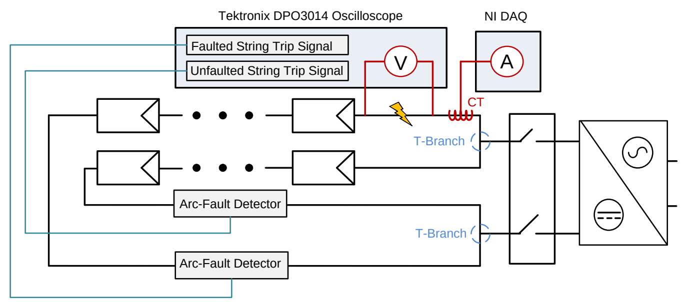

Fig. 6. Crosstalk nuisance trip experimental test setup at Sandia National Laboratories with arc-fault generation on one string.

Texas Instruments arc-fault detectors [6] were installed on faulted and unfaulted strings to determine their susceptibility to trip on unfaulted strings. Typical results shown in Fig. 7. In the test, the arc-fault was generated and the arc-fault detectors both trip due to the arc-fault noise on the two strings. For the case in Fig. 7, the arc-fault detector on the string with the series arc-fault tripped first. This is most likely due to slightly higher energy AC noise levels on this string.

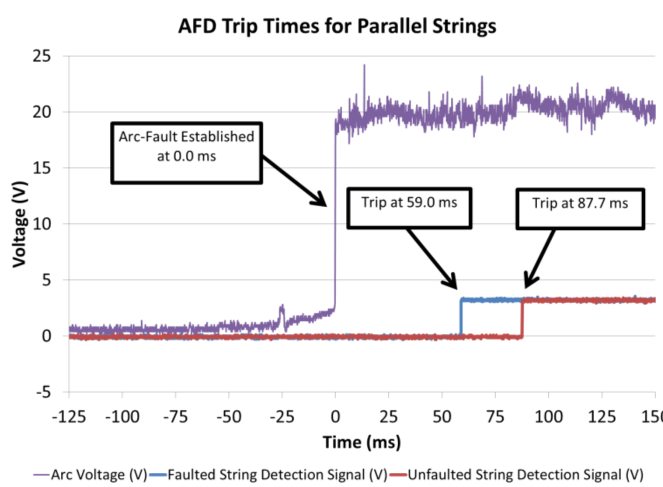

Fig. 7. Experimental trip times for faulted and unfaulted strings in which the faulted string AFD tripped first.

The test was repeated 12 times to identify the repeatability of the faulted string tripping before the unfaulted string. The results are shown in Table 1. The faulted string tripped before the unfaulted string in all except one case. The TI FFT algorithm is performed every 15 ms, so when the difference in the detection times is greater than 15 ms the faulted string AFD would trip off before the unfaulted string. For detection time differences less than 15 ms, it is possible that the unfaulted string could trip on the arc-fault.

In one test the arc-fault detector on the unfaulted string tripped before the faulted string AFD. This test is shown in Fig. 8. During this arc-fault both arc-fault detectors would have tripped and the location of the faulty component would not have been easily identified. Further, for the two-string system, there would be no advantage to using string-level detectors over one array-level detector, because costs could be reduced with a single array-level detector and power generation was terminated for both strings. Yet, based on the trip time differences, in 8 of the 12 tests the AFD on the faulted string would have tripped first and the unfaulted string would not have tripped.

TABLE I. SERIES ARC-FAULT TRIP TIMES FOR FAULTED AND UNFAULTED STRINGS

Test Number	Faulted String Trip Time (ms)	Unfaulted String Trip Time (ms)	Difference in Unfaulted and Faulted String Detection Times (ms)
1	29.4	63.3	33.9
2	50.9	82.5	31.6
3	52.6	75.3	22.7
4	35.3	64.0	28.7
5	59.0	87.7	28.7
6	52.2	80.7	28.5
7	40.8	68.7	27.9
8	76.7	79.6	2.9
9	63.8	70.0	6.2
10	82.5	76.1	-6.4
11	63.6	85.1	21.5
12	73.6	81.3	7.7

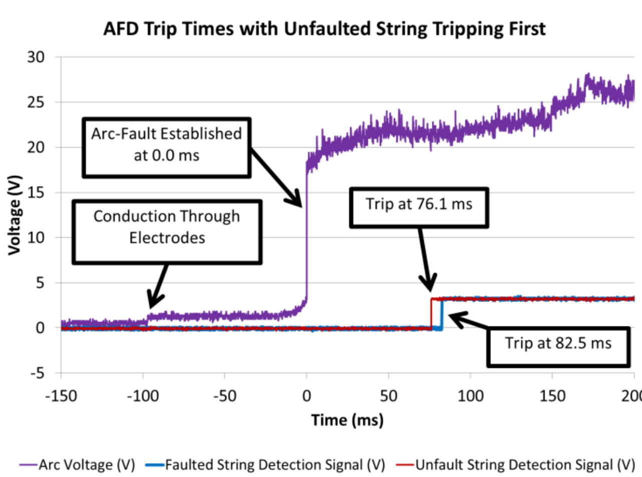

Fig. 8. Experimental trip times for faulted and unfaulted strings in which the unfaulted string AFD tripped first.

Although arc-fault detection algorithms differ between manufacturers, it is unlikely different detection algorithms using string current frequency content would be capable of differentiating the arcing string from the unfaulted string in test number 10. The Texas Instruments algorithm is fairly quick (~15 ms), so it may have an advantage over slower detectors by tripping the faulted string before there is enough noise on the parallel string to trigger the unfaulted AFD. Since the average difference in the trip times was 19.5 ms, the TI design will often prevent the entire array from being de-energized.

While the Texas Instruments (TI) single-string AFD solution used in these tests provided some level of crosstalk effectiveness in a multistring environment, the TI algorithm supports adjustments to the detection parameters which can be used to better address crosstalk induced detection on unfaulted strings. In addition, TI expects to implement additional crosstalk mitigation features for multistring applications. Those modifications were not evaluated in this report.

The susceptibility to crosstalk nuisance tripping may decrease with larger PV systems because the arc-fault noise energy will propagate through a larger branch network. In that case, the arc-fault energy would be distributed to more strings and would be less concentrated on the parallel branches. This may be why crosstalk was not seen in the larger array in [5]. Future testing with a large system is recommended.

V. CONCLUSIONS

Arc-faults in PV systems have caused rooftop fires. The 2011 *National Electrical Code* added Article 690.11 to address this danger by requiring series arc-fault protection on PV systems on or penetrating buildings. New systems entering the market are designed at different levels of protection. While inverter-level protection is inexpensive, it will shut-down the largest amount of power production due to nuisance trips and arc-fault trips. Further, once the AFCI has engaged it is much more difficult to locate the faulty PV component. In order for module and string-level devices to have an advantage over inverter-integrated AFDs, only devices on the faulted string can trip during the arc-fault event. To demonstrate the likelihood of crosstalk nuisance tripping, two Texas Instruments string-level arc-fault detectors were installed on a PV array while an arc-fault on one of the strings was initiated. Results showed that in the majority of cases the arc-fault detector on the faulted string will trip before the detector on the unfaulted string, but there are still times when both detectors will shut down power to their strings. This result does not make it clear which detection methodology is superior. It will ultimately be left up to the PV owner to decide what level of detection they prefer.

ACKNOWLEDGEMENT

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