Taking the Nuisance Tripping out of AFCI - Useful Changes to Testing of PV Inverters

2 August 2016

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Introduction

The ability of a PV inverter to detect and interrupt series arcs (AFCI, or Arc Fault Circuit Interrupter) is a useful safety feature. In the US the National Electrical Code (NFPA 70) requires PV systems to be capable of detecting high voltage DC arcs, whether through functionality built into the inverter or by other means. However, the testing of this has been a controversial topic.

1. The NEC requires series arc detection functionality, but does not dictate how the AFCI should be measured and certified. UL1699B OOI (Outline of Investigation) describes some suggested test methods, but is not a standard and is not directly referenced by the NEC.

2. The test methods described in UL1699B are not optimal as we'll see later

3. Real installations are suffering nuisance tripping, which is leading to frustration and wasted time and money. Some installations even have the AFCI functionality switched off to prevent such issues from reoccurring.

We'll take a brief look at the issues with arc detection, and the progress being made in changing test methods to improve the situation. We will also look at how HiQ's TrueString inverters are uniquely engineered to solve the issues of AFCI functionality.

Code Requirements

The National Electrical Code (NFPA 70) specifies the required functionality of an arc-detection capability in 690.11. Note that in the 2011 edition this applied to rooftops, but in 2014 this was extended to include all arrays, not just those mounted on buildings.

690.11 Arc-Fault Circuit Protection (Direct Current).
Photovoltaic systems with dc source circuits, dc output circuits, or both, on or penetrating a building operating at a PV system maximum system voltage of 80 volts or greater, shall be protected by a listed (dc) arc-fault circuit interrupter, PV type, or other system components listed to provide equivalent protection. The PV arc-fault protection means shall comply with the following requirements:

(1) The system shall detect and interrupt arcing faults resulting from a failure in the intended continuity of a conductor, connection, module, or other system component in the dc PV source and output circuits.

(2) The system shall disable or disconnect one of the following:

> *a. Inverters or charge controllers connected to the fault circuit when the fault is detected*
>
> *b. System components within the arcing circuit*

(3) The system shall require that the disabled or disconnected equipment be manually restarted.

(4) The system shall have an annunciator that provides a visual indication that the circuit interrupter has operated. This indication shall not reset automatically.

The basic methods used to investigate products in this category are contained in UL Subject 1699B, "Outline of Investigation for Photovoltaic (PV) DC-Arc-Fault Circuit Protection."

Existing Test Method vs. Real World

Arc fault testing methods are important, and in many ways shortcomings of the methods have lead to the mismatch between compliance and reliable performance in the field. UL1699B was an attempt to specify testing of arc detection in PV systems, which is now being revised as we'll see later. In its current form, the test is not very arduous or representative of real-world arcs. The test as described in UL1699B uses a test fixture that applies a high voltage across a small piece of steel wool. The arc fixture is inserted in series with the DC input near the inverter DC input terminals. See Figure 1 (a).

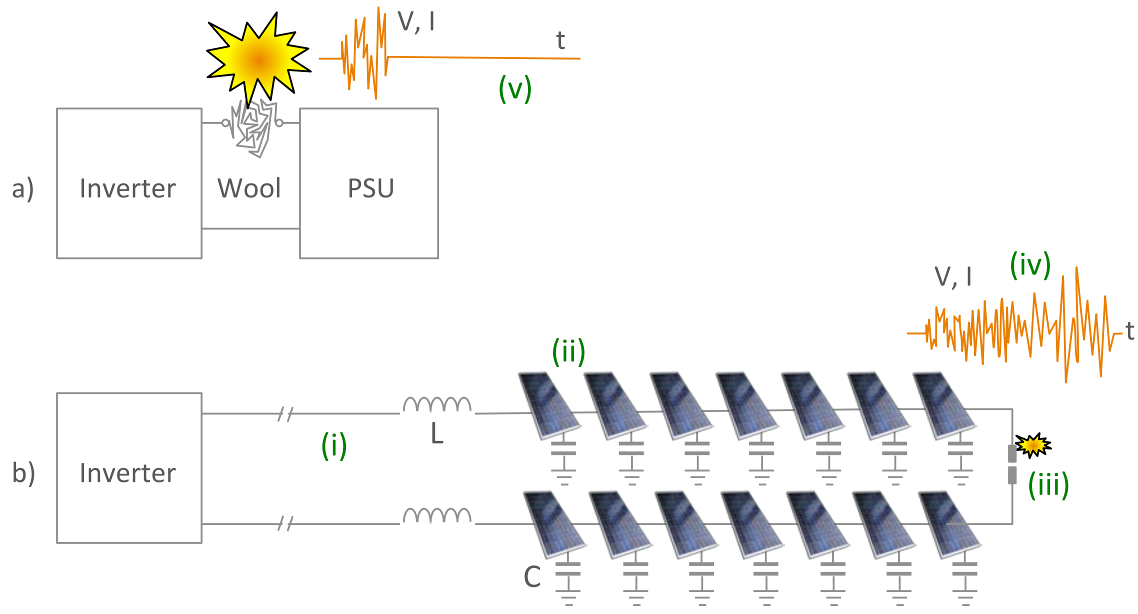

Figure 1: Test practice (a) vs. real-world conditions (b)

Figure 1 (b) shows the kind of situation an inverter AFCI system might see in the field. It is mounted some distance from the array (i), and the PV modules in the array are a series string (ii). The wires and modules add significant inductance and capacitance to the picture. The arc might occur at any point in the string or wiring, the worst case being at the mid-point of the string (iii). It is also likely to have much lower amplitude than the test arc. In addition to all of this, the initiation of the arc is quite different from an arc initiated by burning the steel wool (iv & v).

The primary issue is that in the real world, the arc that the inverter is looking for will begin much, much smaller with a different initial signature. As a real PV string presents significant series inductance and capacitance, these reactive components can provide substantial filtering of the arc signature making it more difficult to detect when an arc is present. Add to all of this the fact that most PV systems used in commercial applications connect strings in parallel, and the problem just got even worse.

This starts to explain why inverters struggle to detect arcs even though they pass the test. The logical response from most inverter companies is to increase the gain of the detection circuit to look for those smaller arc signatures. However, this results in a much-increased likelihood of false alarms, while also missing the presence of real arc problems until it is too late.

Changing the Way AFCI Circuits are Tested

UL1699B Task Group 1 is working on updating the test methods to be more representative of real world conditions and more repeatable. This section gives a high level overview of the development of proposals that are in process and are useful to understand. While this is a work in process they are correct as of July 2016.

Problems to be tackled:

1. The old method of testing resulted in listed products that **did not detect some arcs** in real world conditions
2. And, some listed products suffered from unwanted **nuisance tripping**

Objectives:

- Redefine test method and fixture to more closely represent real-world conditions *(discussed here)*
- Develop method to test unwanted nuisance tripping *(not discussed here)*

Task Group Guidelines

- Test should represent real-world conditions
- Test should represent worst-case
- Test must be repeatable
- Shall be test method agnostic

Improving the Test Arc Signature

One change being discussed is to alter the way the arc is created. Instead of a burning filament of steel wool to initiate the arc, the new proposal uses a ball and ring or pair of rods mounted on a track such that the arc gap can be increased at a controlled rate. The idea is that the arc begins at a very low level and increases at a controlled rate, as is common in the real world. Both the available arc current and rate of separation are now specified. In contrast, the steel wool method is not very repeatable, with arc characteristics changing depending upon the type of wool used, the of wool quantity and how it is placed in the gap. Figure 2 shows the old and new methods. 1. Shows the old fixture with steel wool inserted. 2. Shows the fixture generating an arc. 3. Shows the spent fixture. 4. Shows the proposed ball and ring, and 5. Shows it generating an arc.

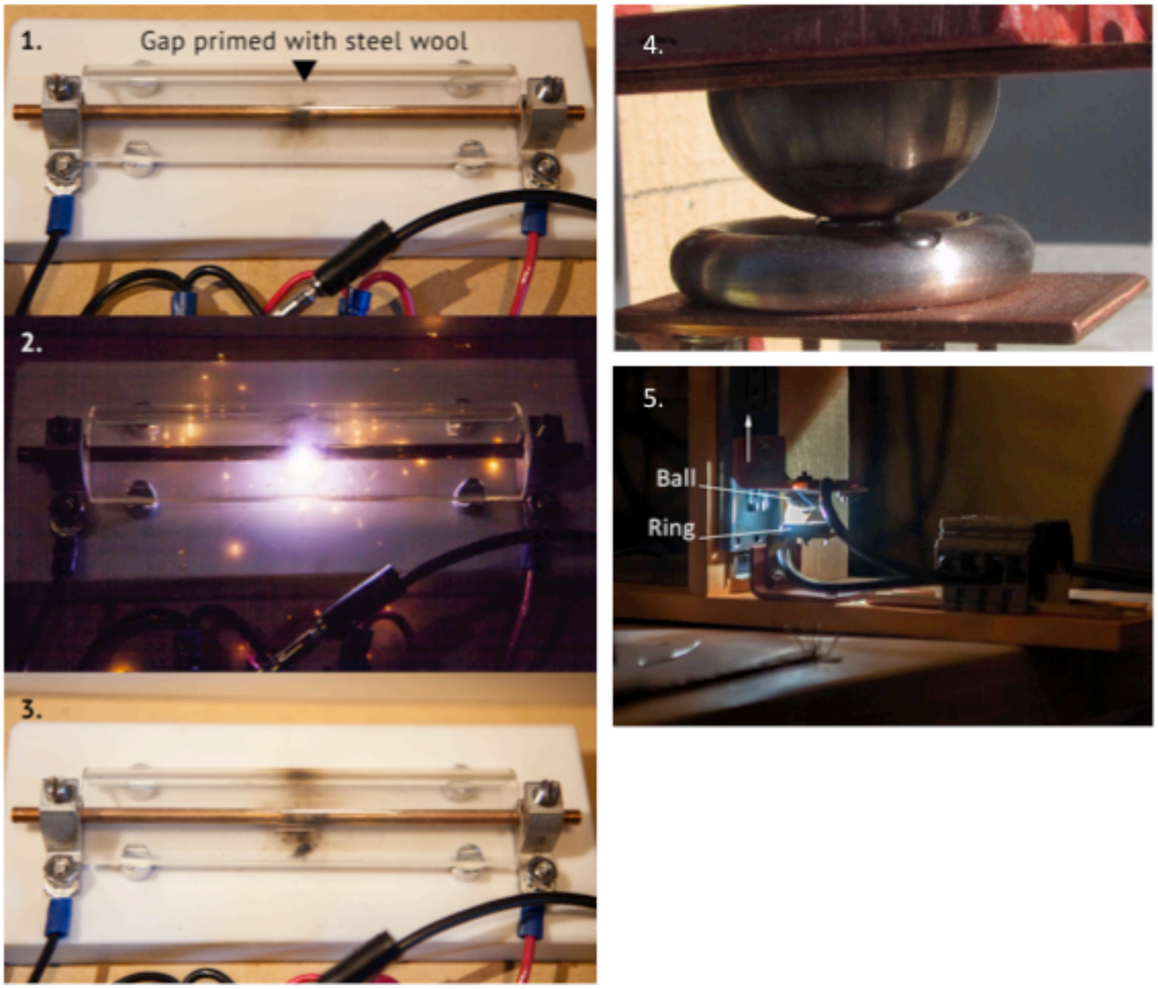

Figure 2: Existing (1-3) and example proposed (4-5) arc generation fixtures

The ball and ring and copper rods with a controlled pull-apart are more representative of a real-world arc, and gives more repeatable test results.

New Methods of Testing

In Figure 1 (b) we saw that the real world is more complex than the test setup being used to test per UL1699B OOI. The block diagram for the original test is shown in Figure 3 (a) and is being eliminated. However, the setup in Figure 3 (c) is being proposed for the testing of AFCI circuits in, for example, string inverters; conceptually it relates back to our PV string as can be seen in (b). While the testing will be harder, the results will be much improved, and the test set-up is discussed further below.

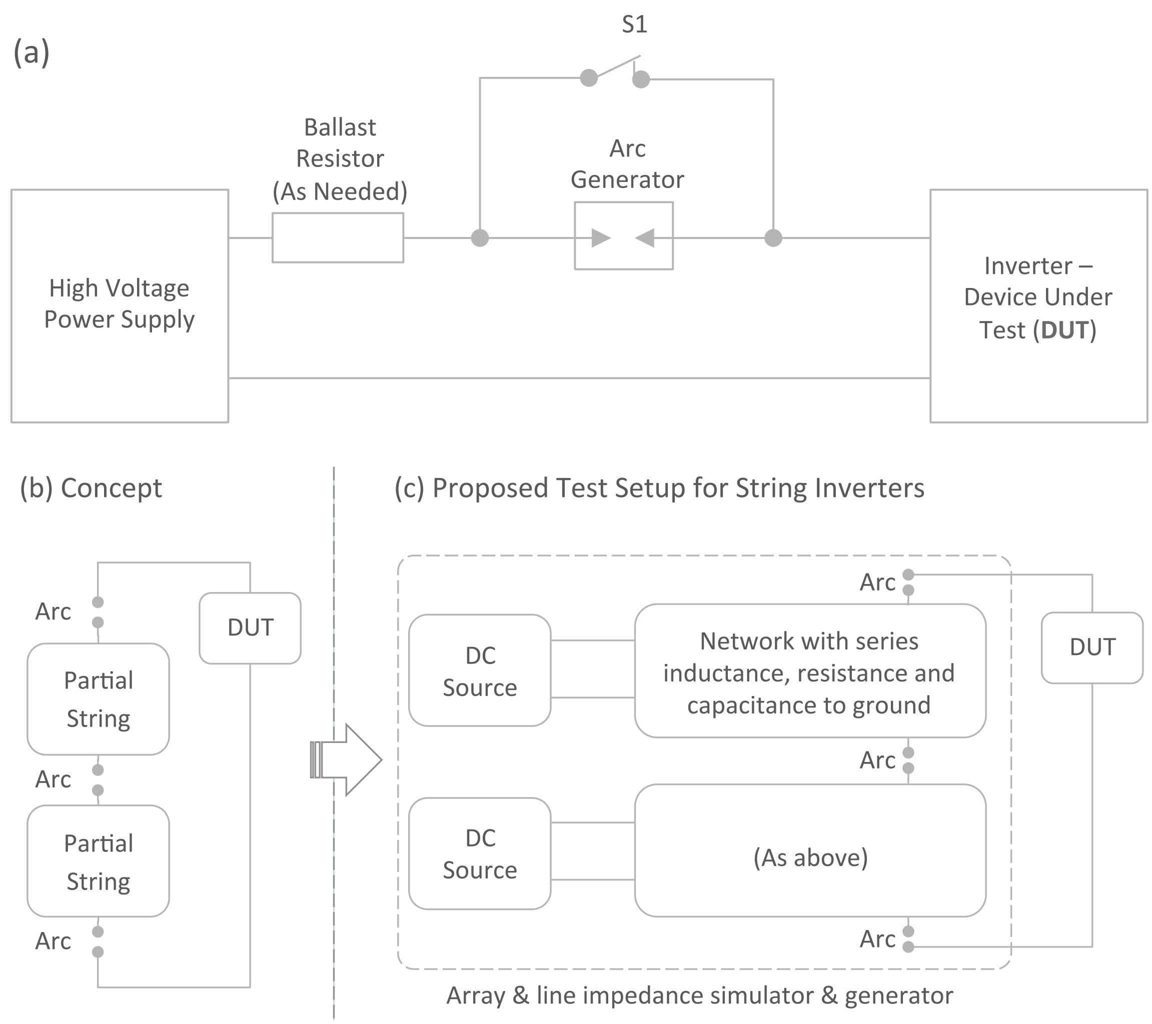

Figure 3: Legacy (a) and new (b & c) arc testing apparatus

In Figure 3 (c) the arc test fixture will be placed at each of three positions, designated "Arc" in the diagram.

The series inductance represents the wire between the AFCI and the PV string. A maximum wire length of 250 feet (80m) was considered reasonable[1], and will probably end up being the default. PV modules have normal mode capacitance between + and – terminals and common mode capacitance to ground. These characteristics can vary widely between module types and installations. Ground mounted modules have very low capacitance (on the order of 150pF); thin film modules can actually be adhesively attached to a structure such as a metal building, giving a capacitance that can be several nF per module. In addition, the wiring will have capacitance to ground that will increase with wire length, and is higher when the wire is in a metal raceway. And, there is capacitance between conductors that varies by wire length, type, and orientation.

[1] It is expected that manufacturers will be able to shorten this distance to make the task of compliance easier; however, they will need to provide a rating of maximum distance in all documentation and accordingly restrict how customers install their product in order to maintain AFCI compliance.

For inverters with a single string per AFCI circuit the situation is simple, and the component values in the electrical network reflect this. For inverters that parallel strings into a single AFCI circuit the component values in the network reflect this, with more capacitance, parallel inductance and resistance shrouding the arc signal, making the test commensurately harder to pass.

Other System Topologies

It could be argued that a string inverter with AFCI functionality is one of the more straightforward scenarios to test. System topologies vary widely, and test methods have been created to deal with AFCI circuits embedded in string combiner boxes (see Figure 4), external AFCI circuits, and several dealing with different DC/DC optimizers (an example is in Figure 5). AFCI circuits embedded in individual PV modules are not addressed.

As an example, the configuration of a 1 MW central inverter with string combiners and string re-combiners will be very complex to test, and to design AFCI circuits that will pass.

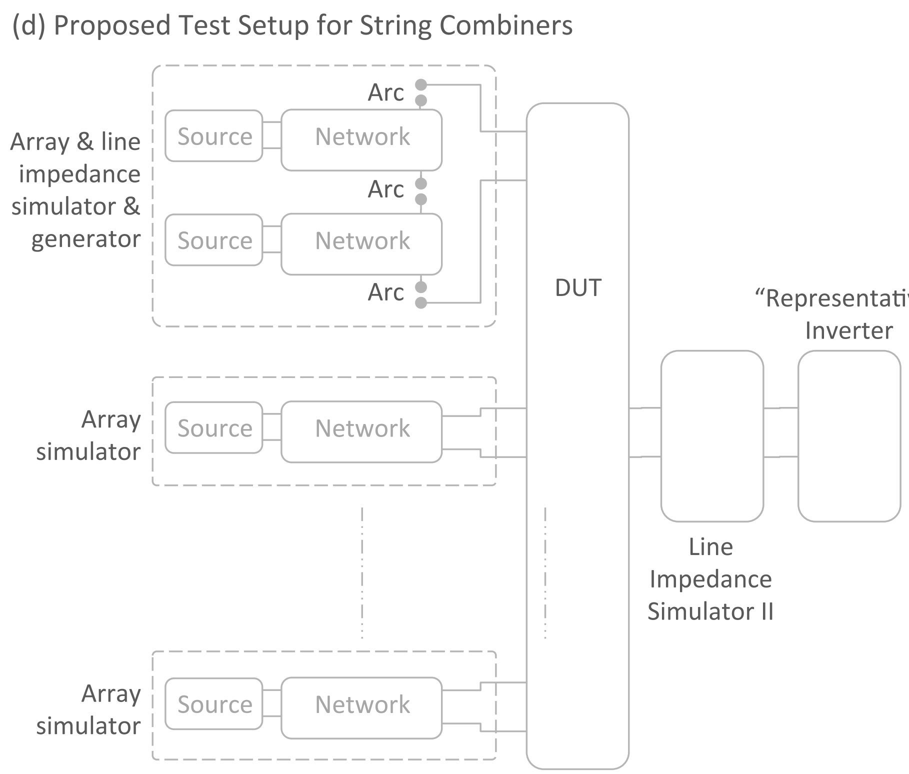

Figure 4: Proposed test set-up for a system involving string combiners

(e) Proposed Test Setup for DC/DC Optimizer System

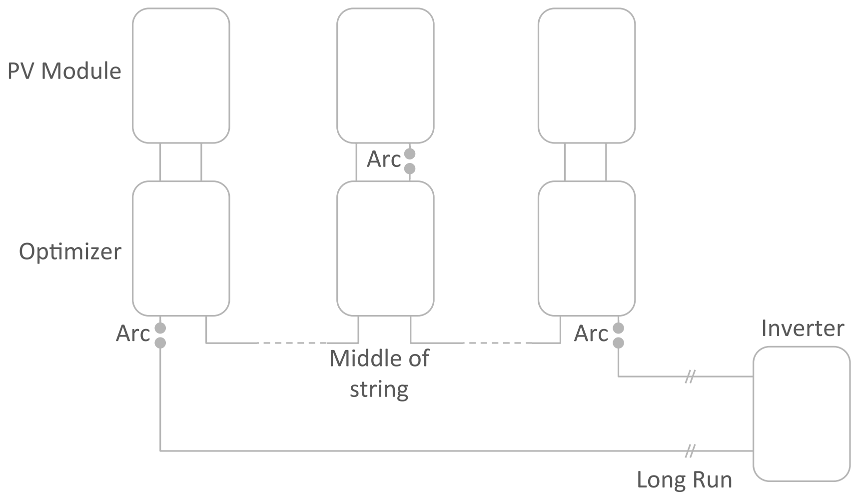

Figure 5: Proposed test set-up for AFCI testing of a DC/DC optimizer system

The 2017 NEC code removes all reference to detecting, annunciating, and manual reset requirements. It is left entirely to the safety standard, which will be UL1699B once it is affirmatively balloted.

HiQ Solar TrueString Inverters and AFCI

Our TrueString inverter starts off with some advantages compared to common 3-phase string inverters. These include:

- TrueString inverters are commonly mounted under the array. This means that the length of DC wiring between the inverter and the array is minimal, helping to make detection more reliable.
- TrueString inverters have individual string inputs. Reducing the problem to a single string on each input instead of paralleling many makes detection much easier and more reliable.
- Our inverters were tested with both the steel wool and ball and ring test fixtures.
- Our detection method is unique and employs time and frequency domain analysis of the arc signal.
- The detection of arcs is integrated into the inverter, which helps to minimize nuisance tripping.

We meet and exceed the requirements of NEC 690.11 and minimize nuisance tripping while remaining focused on the detection of real-world arcs, as illustrated in the next section.

Customer Testing Example

A good illustration of why mounting a string inverter next to the strings it serves, along with the benefits of an architecture where each string has it's own dedicated AFCI circuitry is shown in this customer-supplied example. The customer wanted to set up validation testing of a group of different string inverters.

The test set-up used an arc generator employing two copper rods steadily drawn apart as described previously; it also placed the arc fixture in the middle of a string of PV modules to be as real-world representative as possible. A variety of well-known string inverters were tested, along with the HiQ TrueString inverter.

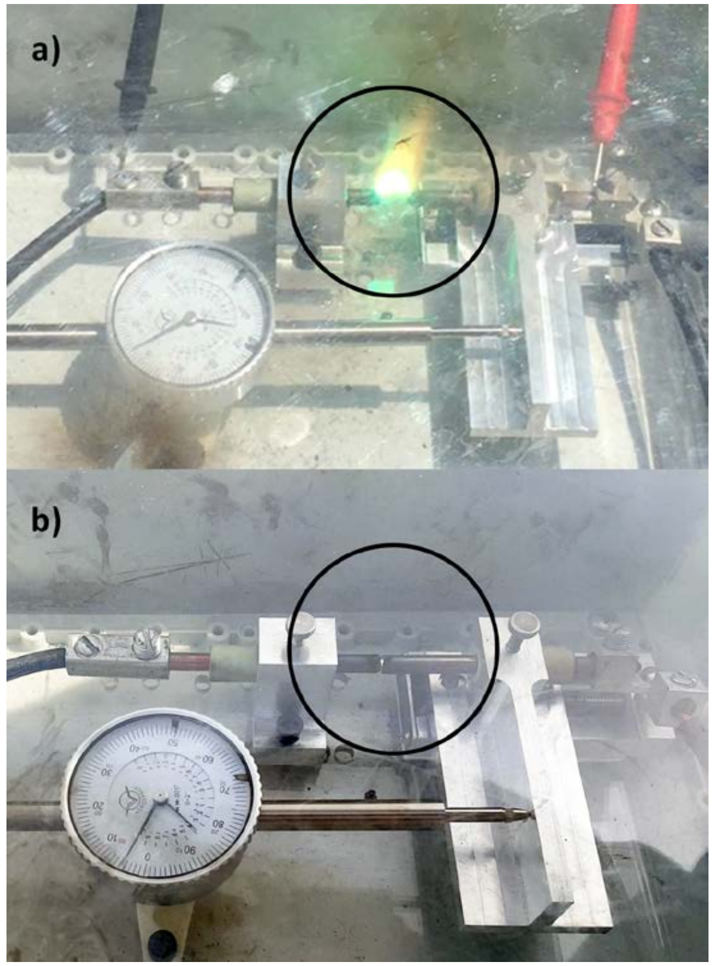

Figure 6: Screenshots of customer AFCI testing

The part of the test set-up with the two copper rods is shown shown in Figure 6. (a) shows a product being tested (note that it passed and is listed to the current UL1699B OOI); the arc burned continuously until the source was removed, with the inverter under test unaware of dangerous arcing. These results were consistent except for the HiQ product. (b) shows an example test performed with the HiQ TrueString – the arc is quickly detected and the string safely shut down as mandated per the NEC.

Summary

Significant improvements to AFCI testing are coming. The result will be more reliable detection of real-world arcs, and the reduction or elimination of nuisance tripping. Nuisance tripping is partly the consequence of the overly simplistic test method recommended in the past.