ARC-FLASH RELAYS

A Valuable Detection Solution for Photovoltaic Systems

TECHNICAL PAPER

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Use of Arc-Flash Relays in Combiner Boxes

Photovoltaic (PV) systems are being installed in the field at an increasingly fast pace, and the size of each installation project is growing quickly as well. Large-scale utility projects have crossed the 2- and 3-gigawatt mark, which often require several million solar panels.

These impressive power levels are obtained by combining solar modules in a series to a target system voltage to form a string. These strings are then connected in parallel in a combiner box. This dc power is converted to ac using an inverter and fed into the grid. The more solar modules, combiner boxes, and inverters that are paralleled together, the larger the system's power generation capability. When these systems expand from one megawatt to a couple thousand megawatts, the number of cable/wiring connections (and failure points) increases substantially.

Many of these cable connections occur inside the combiner boxes where each string of PV modules is usually connected to a fuse block on both the positive and the negative buses if the system is ungrounded, or only the positive bus for grounded systems. A surge protective device (SPD) is typically connected to the bus in each combiner, and the bus may be connected to an overcurrent protection device or another interrupting device. A standard-size combiner box of 20 strings usually has 88 connection points at a potential 1000 V dc. Therefore, large-scale utility projects, which usually have thousands of combiner boxes, could have millions of connection points inside the combiner boxes alone.

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Associated Risks and Sources of PV-related Fires

Fires in PV installations are on the rise [Firetrace][1] [Usenergy][2] and the number of PV-related fires is historically underreported [Pvmagsylvia][3] [BRE National Solar Centre][4]. These fires are typically categorized into a few probable root causes including problematic system design, faulty product, and poor installation. The fires and associated losses have even caused some organizations and countries to pause large-scale solar projects, asking regulators to consider what actions may be necessary to mitigate the risk.

Fires involving PV systems are "serious fires" and are "difficult to extinguish and spread beyond the area of origin." [BRE National Solar Centre][5]. A loose connection in a combiner box or an inverter can cause arcing or a fire. Wires can become loose during the initial installation or after maintenance is performed if they are not properly tightened. In some cases, loose wires can occur months or years later due to ambient heating and cooling cycles or from vibration caused by high winds or earthquakes.

Loose wires are sometimes difficult to detect. If a loose conductor is resting against its intended connector, it may pass initial continuity tests and even conduct current appropriately. However, if small vibrations cause the wire to separate from the metal contact and create a high resistance point, an arc or significant heating may occur. Also, if there is a fault in the branch circuit, then the high current will cause the loose wire to arc almost immediately.

Using thermal imaging to check for hot spots in various panels can potentially detect a loose wire connection that is generating heat. However, with so many combiner boxes and inverter panels installed throughout a PV system, thermal imaging is impractical from a cost or a labor-hour standpoint. In addition, panels are typically opened one by one during inspections, which is very labor-intensive. Smoke detectors or temperature sensors installed inside a panel could potentially detect a resistive connection that is smoking, burning, and producing significant heat. However, smoke detectors and temperature sensors often take a long time to react to these events so they will not be responsive to an arc event in a timely manner. Furthermore, various environmental conditions, such as high humidity, can pose a challenge for some smoke detector systems.

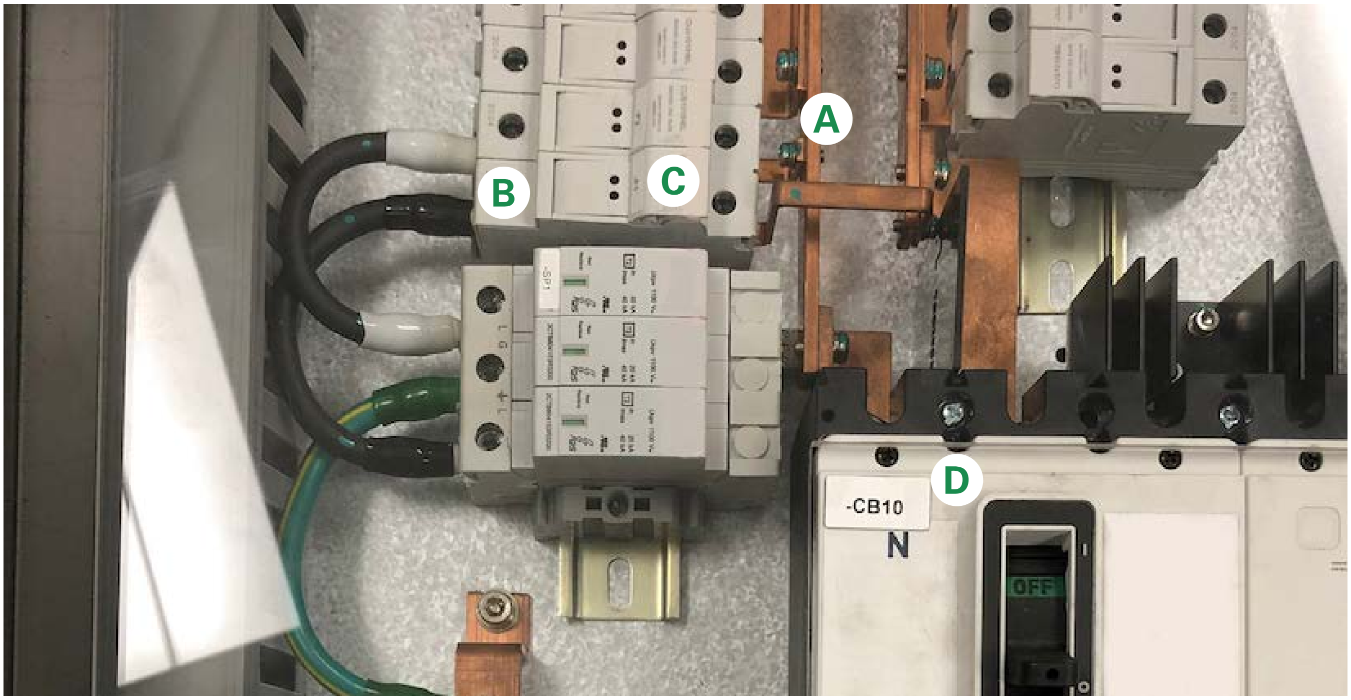


FIGURE 1. Bus connection to interrupting device from a typical combiner box.

A short circuit can also occur in a panel due to a loose cable connection or if debris or dust accumulation accidentally shorts across the positive bus and the negative bus. **Figure 1** depicts a typical combiner box with four points labeled where a short circuit across the 1000 V bus could take place (A – across the positive and negative bus; B and C – across the terminals to the fuse or SPD connections for the main bus; D – across the breaker connection points). Loose connections or faults caused by debris could occur in any of these locations in a typical combiner box installation.

Arc-Flash Relays Stop Arcing in its Tracks

Arc-flash relays provide reliable, ultra-fast reactions to arcing events. These relays use optical light sensors installed inside the panel to sense the light coming from an arcing fault. This triggers the arc-flash relay to quickly operate an output contact that can signal one or more interrupting devices. The interrupting devices then interrupt the current that is feeding the arc and initiate other actions from the control system.

There are several benefits to using an arc-flash relay:

- **Extremely fast acting:** The switching of the output contact occurs in 1 to 10 ms (depending on the relay model) from first detecting the flash of light.
- **Fault location:** The arc-flash relay indicates which light sensor saw the arc, so in installations where multiple sensors are used across large panels or in a large piece of switchgear, it is immediately known which area had the fault.
- **Low likelihood of nuisance trips:** Arc-flash relays have a proven and reliable track record working across wide temperature ranges from -40 up to 70° C; the temperature does not impact its ability to detect an arc as it is looking for the light intensity that will come from the arc.
- **Works even when the current magnitude fluctuates and does not compromise selective coordination:** The available fault current produced by the PV panel can be variable. Overcurrent protection reacts to abnormally high currents while arc-flash relays add further protection by watching for any arc, including resistive ones at or below load current.

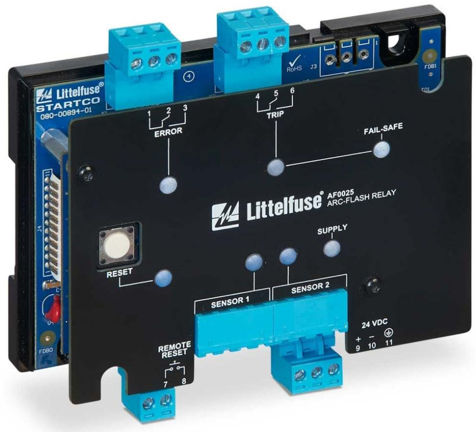


FIGURE 2. Littelfuse AF0025 arc-flash relay.

Arc-flash relays (see **Figure 2** and **Figure 3**) provide output contacts that can notify the control system of a fault, or where possible, be used in the trip circuit of a breaker, contactor, or other disconnecting means to immediately interrupt the fault current supplying the arc. Many arc-flash relays provide multiple contacts in the case where additional locations need to be interrupted to stop the flow of energy to the arc.

Verification of DC Arc-Flash Relay Detection

FIGURE 3. Littelfuse AF0025 arc-flash relay with two PGA-LS10-01B point sensors.

Ultimately, to understand if arc-flash relays can benefit combiner boxes or other dc applications, you must confirm that an arcing fault can occur and be sustained within the system. It might seem that an arc cannot exist when fuses can clear faults in a matter of milliseconds, but Littelfuse testing confirmed otherwise.

Basic tests were performed to confirm that an arc could be sustained and that an arc-flash relay installed inside the panel could detect this type of arc. These tests used a standard 1000 V dc combiner box built for 20 string inputs with 20 A fuses installed in each fuse block.

Among several tests that were performed at different current levels, there are two tests that best highlight the results:

- Test 1: Loose wire on one string connection, 15 A maximum current
- Test 2: Short-circuit across positive and negative bus at closest point, 1000 A maximum current

Test 1: Loose Wire with 15 A Maximum Current

In this test, one test lead was firmly connected to one side of the fuse block. The second test lead was connected to the other side of the fuse block, with the screw terminal tightened just enough to make light contact with the test lead. A string was tied to a bend in the test lead, which allowed the wire to be gently pulled out from under the load while standing at a safe distance.

A 1000 V dc, 15 A test current was applied through the circuit and then measured to ensure the circuit was stable. The string was slowly pulled until the wire came slightly out of the fuse block. This action generated an arc, and the wire was left in that position. The arc continued for two seconds until the test was manually stopped. **Figure 4** and **Figure 5** show the arc that occurred during the test.

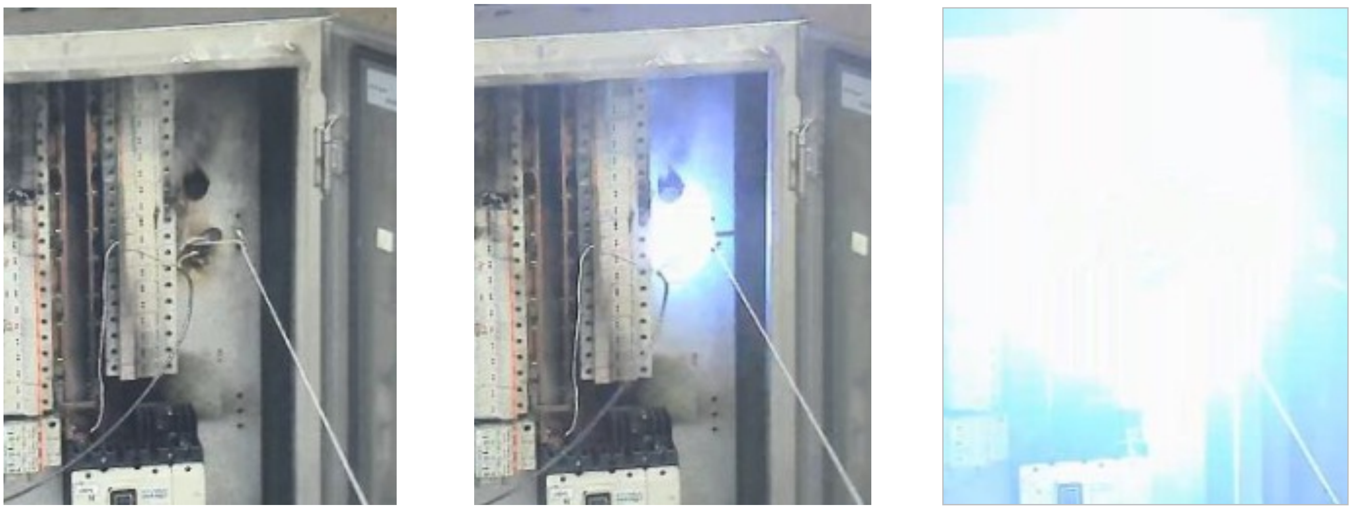


FIGURE 4. Freeze frames from standard video gently pulling wire out of fuse holder with 15 A maximum current.

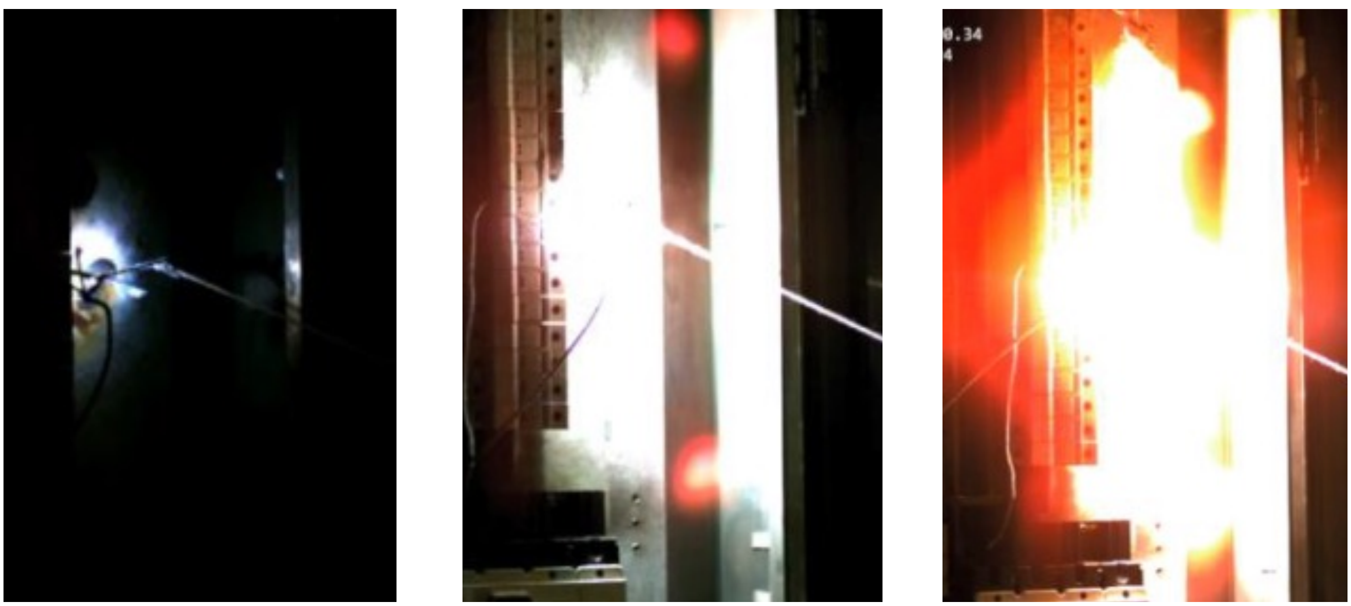


FIGURE 5. Freeze frames from high-speed video with light filter gently pulling wire out of fuse holder with 15 A maximum current.

While this basic test setup does not fully replicate a true field installation, it proves two important concepts: 1) that a dc arc can be sustained at 15 A, and 2) that a loose wire can initiate an arc.

It is important to note that the fuses did not interrupt this arc because their 20 A interrupting rating was higher than the 15 A arcing current.

Even with a 20- to 30-ampere arcing current, the fuse will take a significant length of time to interrupt the arc according to its time-current curve. The arc can ignite and significantly damage the panel before the fuse will act. This is not because of any problem with the fusing, but because arcs can be sustained even at low currents that are similar to normal loads.

Figure 6 shows the initial 15 A of current, which was followed by an arcing period with voltage present across the arc before it was extinguished after two seconds.

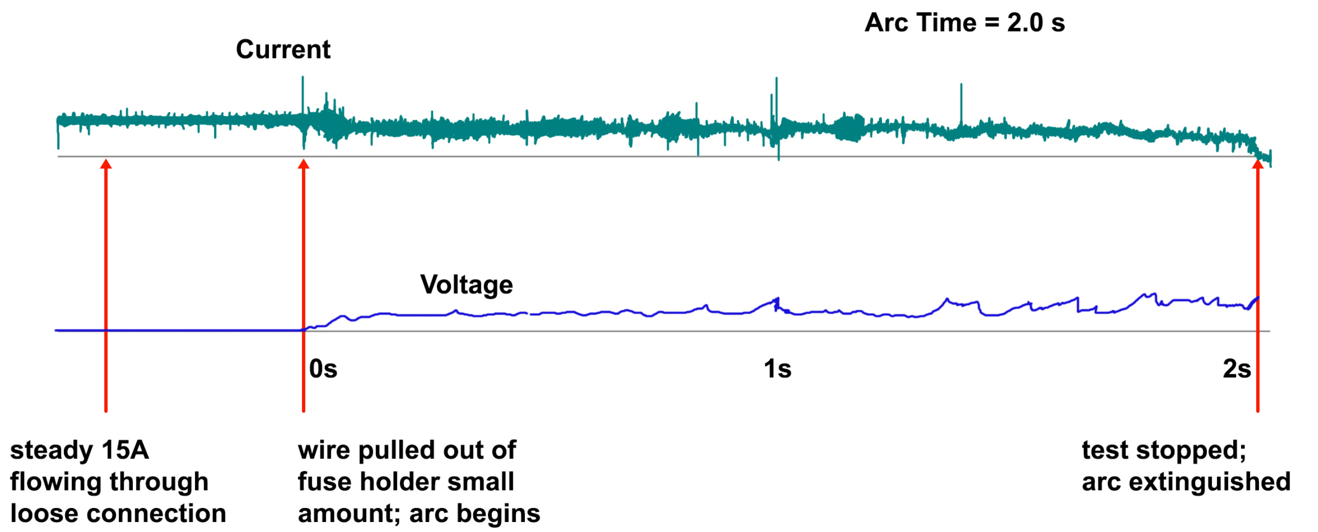
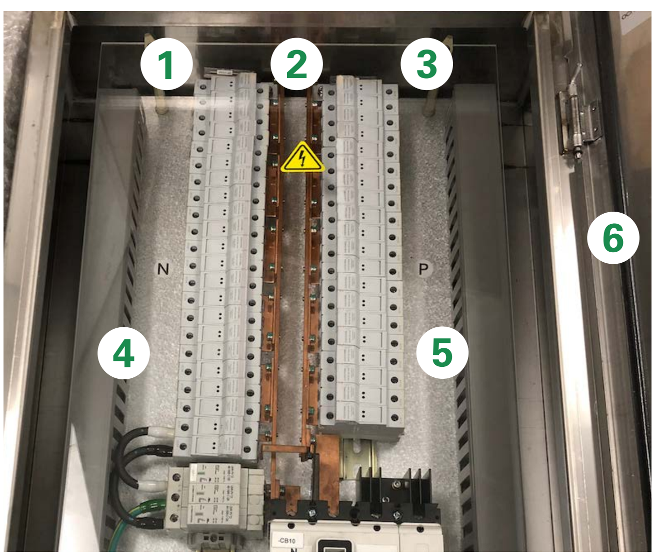


FIGURE 6. Voltage and current waveforms during a 15 A arc test.

The testing also set out to confirm whether an arc can generate light that is intense enough for an arc-flash relay to detect. The test used the Littelfuse PGR-8800 arc-flash relay because of its waveform capturing feature that plots the light intensity measured by its light sensors.

For this test, six light sensors were placed at various locations around the combiner box, including inside the top of the enclosure (left, middle, and right), the sides of the enclosure (left and right), and on the back door (see **Figure 7**). Since other Littelfuse arc-flash relays (including the AF0500, AF0100, and AF0025 series) use the same arc-detection algorithm as the PGR-8800 series, every Littelfuse arc-flash relay will perform the same under these tests.



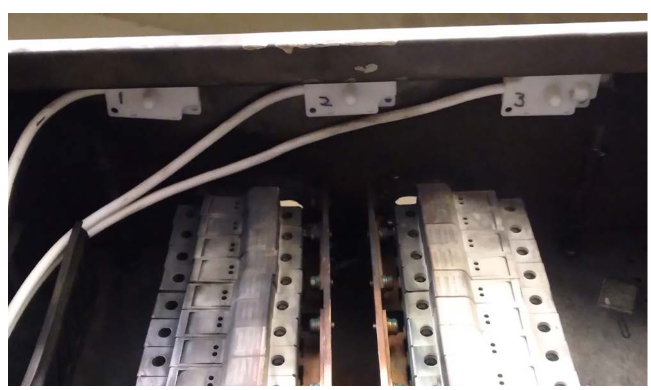


FIGURE 7. Approximate location of the light sensors inside the panel (left) and the light sensors at the top of the enclosure (right).

SENSOR 1 = TOP LEFT SENSOR 2 = TOP MIDDLE SENSOR 3 = TOP RIGHT
SENSOR 4 = LEFT SIDE SENSOR 5 = RIGHT SIDE SENSOR 6 = DOOR

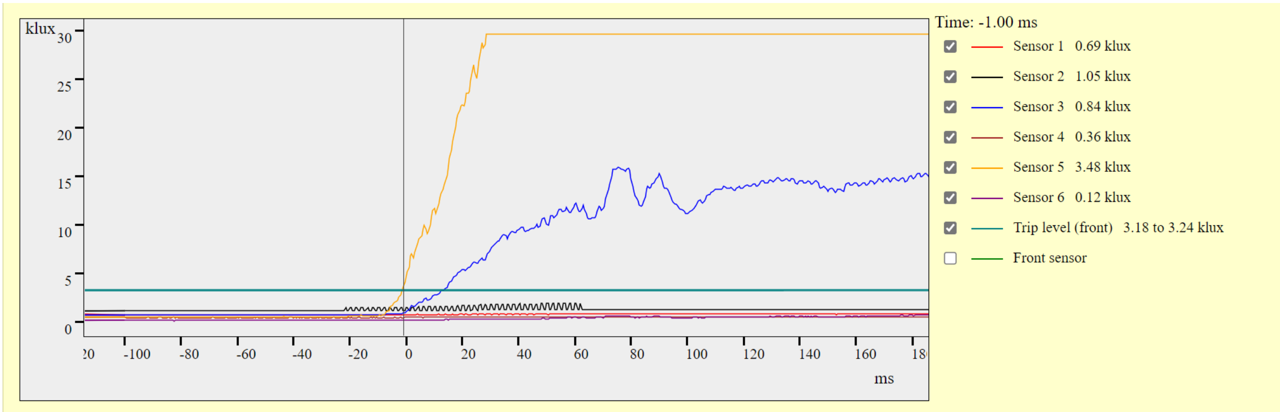


FIGURE 8. Light intensity measured by the arc-flash relay's light sensors during a 15 A arc test.

Figure 8 shows that an arc-flash relay can easily detect a 15 A arc depending on the placement of the light sensors. The two sensors nearest to the fault (Sensor 3 positioned at the top of the panel above the fault, and Sensor 5 positioned on the side of the panel close to the fault) immediately saw light intensity above the 3 klux selected trip level. Sensor 2 positioned at the top of the panel in the middle, did trip after a short time as the arc grew more intense. Note that every design is different and should be individually evaluated to ensure proper arc detection.

Test 2: Short Circuit on DC Bus with 1000 A Maximum Current

In the second test, one test lead was connected to the positive bus and the other lead was connected to the negative bus. A small jumper wire was placed directly across the bus to initiate an arc that simulates a piece of debris, a forgotten tool, or anything else that may drop and land across the bus within a panel.

Upon applying voltage, the arc immediately ignited, vaporizing the wire, and then quickly traveled up to the top of the panel. When the arc continued from the top of the panel across the ends of the vertical bus, the test was quickly terminated to avoid further damage inside the test panel. **Figure 9** shows the arc during the test, and **Figure 10** shows the arc's travel.

FIGURE 9. A short circuit on a dc bus with 1000 A maximum current.

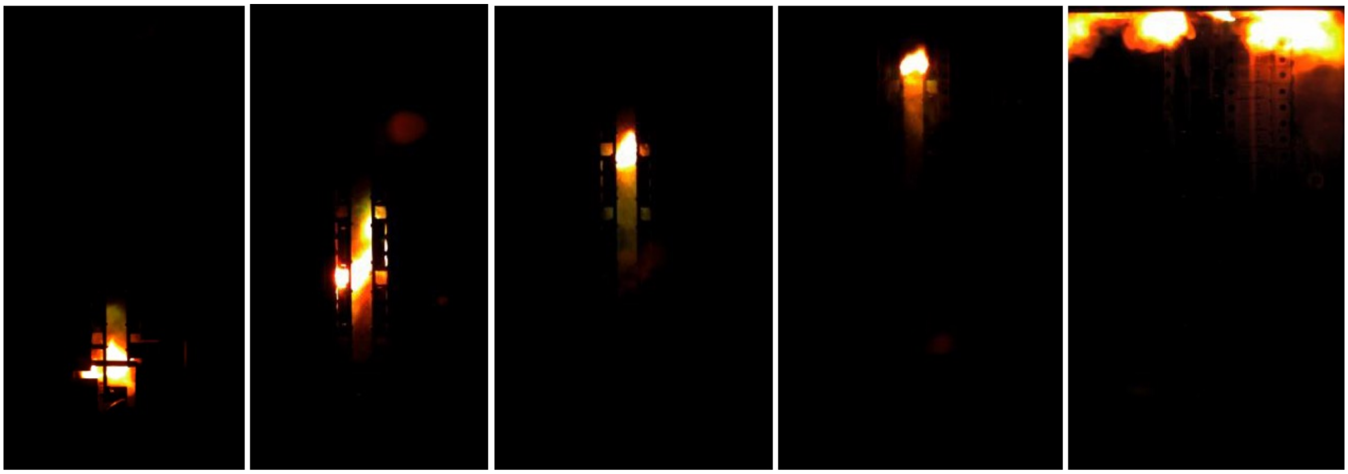


FIGURE 10. Freeze frames from high-speed video with light filter showing short circuit on dc bus with a 1000 A maximum current.

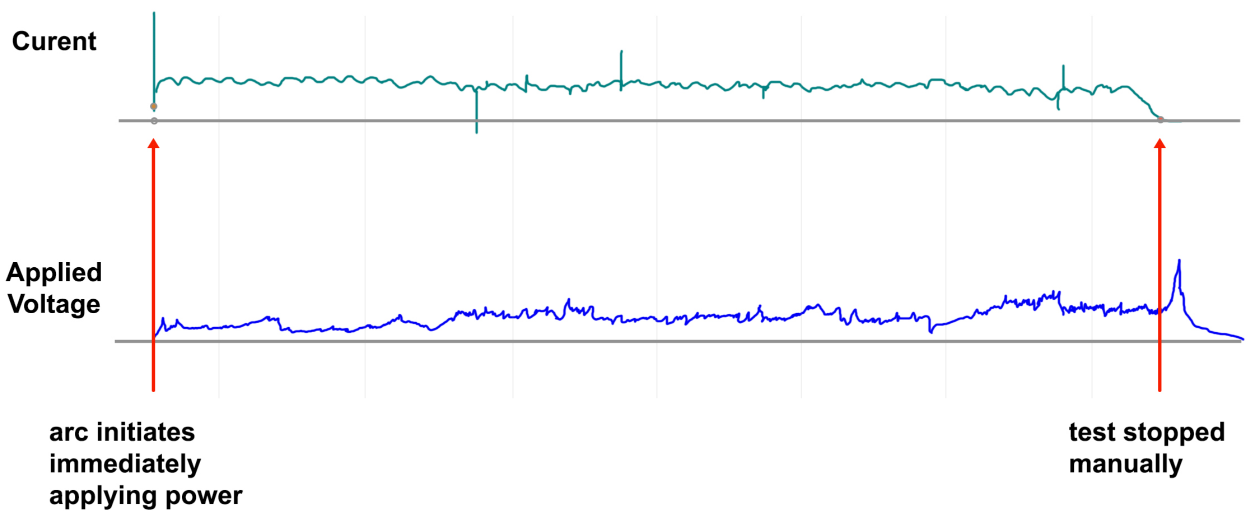


FIGURE 11. Voltage and current waveforms during the 1000 V dc arc test.

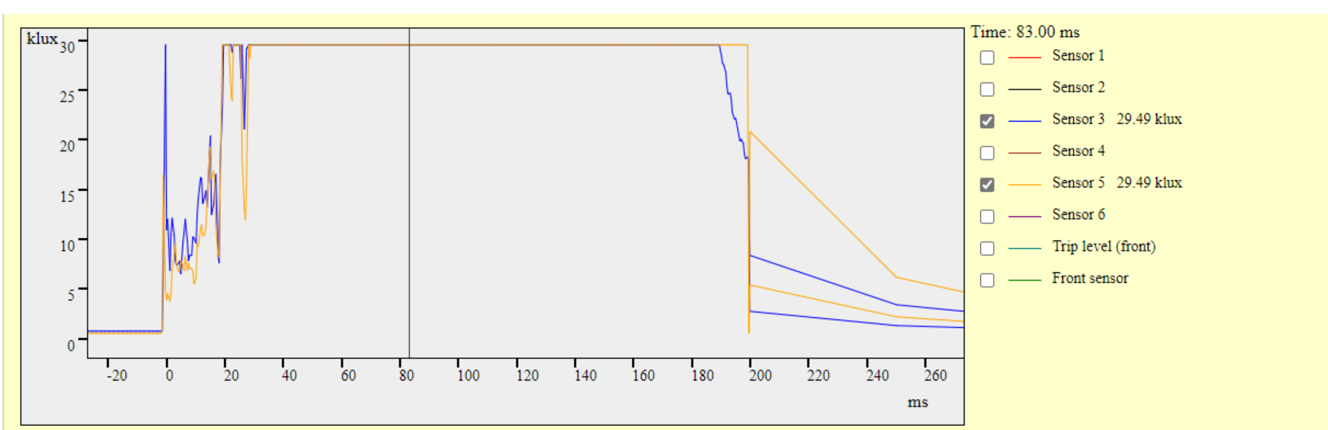


FIGURE 12. Light intensity measured by the arc-flash relay light sensors during the 1000 V dc arc test.

The voltage and current waveforms for the 1000 A arc are shown in **Figure 11**. **Figure 12** confirms that arc-flash relay light sensors quickly detect the 1000 A arc. During this test, two light sensors were installed. Both arc-flash light sensors saw the initial flash caused by the vaporizing of the test wire, which they registered to be more than 30 klux (this is the maximum light recorded by the PGR-8800 waveform capture).

As the arc continued to burn across the air gap on the bus and then travel vertically across the bus to the top, the light intensity continued to increase and go beyond the 30 klux limit. This is logical given the arc was traveling toward the sensors and ended up burning very close to the point sensors.

Even when the arc was burning across the air gap at the very bottom of the bus after the initial flash, both light sensors registered light intensity levels near 5 klux (see **Figure 12**). This means that an arc-flash relay with a set trip level of 3 klux will detect an arc across the bus regardless of how the arc was initiated.

Calculating the arc-flash energy reduction when including arc-flash relays is outside the scope of this initial test. The goal of these simple tests was to understand the ability to form and sustain an arc at 1000 V dc at low current levels and to confirm that light-sensing arc-flash relays could detect these types of arcs.

While IEEE 1584, *Guide for Performing Arc-Flash Hazard Calculations,* is the go-to standard for ac arc-energy calculations, a singular authoritative reference is not yet published for dc calculations. However, there are many excellent published papers discussing various dc arc-flash incident energy calculations—some of these methods are already included and referenced in the arc-flash hazard calculation software tools.

Conclusion

These two tests confirmed that dc arcs can be sustained at low current levels such as 15 A and that the light intensity generated from these arcs is sufficient to trip an arc-flash relay. Since any sustained arc can generate enough heat to ignite a fire, this testing confirmed that the use of overcurrent protection by itself may be insufficient for equipment level protection in dc distribution equipment (such as combiner boxes, inverters, universal power supply cabinets, etc.). Arc-flash relays are a valuable engineering control which, when implemented in dc systems, will mitigate incident energy levels and react to arcs before they escalate and cause destructive fires and irreparable damage.

The goal of these simple tests was to understand the ability to form and sustain an arc at 1000 V dc at low current levels, and to confirm that light-sensing arc-flash relays could detect these types of arcs.

Citations, full reference:

[1]Firetrace International, author unknown, *"Hidden Danger, Why Solar Farm Fire Risk Could be Greater Than You Think."* www.firetrace.com. July 25, 2022.

[2]Energy.gov, Annett Sepanski, *"Guideline: Assessing Fire Risks in Photovoltaic Systems and Developing Safety Concepts for Risk Minimization."* www.energy.gov. June 2018.

[3]PV Magazine, Tim Sylvia, *"Solar System Fires are on the Rise in the U.S."* www.PV-magazine.com. April 23, 2020.

[4]BRE National Solar Centre, Steve Pester, *"Fire and Solar PV Systems – Investigations and Evidence."* www.assets.publishing.service.gov.uk. July 17, 2017.

[5]BRE National Solar Centre: Steve Pester, *"Fire and Solar PV Systems – Investigations and Evidence."* www.assets.publishing.service.gov.uk. July 17, 2017.

Suggested reading:

- DC Arc-Flash Studies for Solar Photovoltaic Systems: Challenges and Recommendations
- Reducing Arc Flash in Common Bus Dc Systems
- Measured Dc Arc-Flash Risk in a Photovoltaic System

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