Thought Leadership / 2025

Solar Photovoltaic Systems and Rapid Shutdown: An Introduction to the Configuration, Requirements, and Design

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With the increasing use of commercial-grade solar photovoltaic (PV) arrays in the built environment, the need for protective systems preventing losses has become more prominent in recent years, with changes to the National Electrical Code to address these concerns. A 2016 report by the National Renewable Energy Laboratory (NREL) positions the potential for installed capacity of rooftop solar PV arrays in the US at approximately 1,118 gigawatts (GW) based on available rooftop area and solar irradiance, with the potential to generate roughly 1,432 terawatt-hours (TWh) annually. This equates to about 39% of the national demand in the US of roughly 3,700 TWh per year. This is a testament to the incredible potential of solar PV and its ability to change the energy mix in the US. However, the actual installed capacity across the utility-scale, commercial, and residential solar PV installations is only around 121.4 GW as of 2022, reflective of the room for growth as it pertains to solar PV production in the US.[1, 2, 3]

With the emergence of rooftop solar PV installations, the frequency of fire events resulting from poor workmanship, product failure, and improper designs has increased. The more frequent failures and associated fire events have led to code changes to preserve the well-being of first responders and address some of the safety concerns encountered in commercial solar installations. The present article will discuss the changes of the National Electrical Code with respect to Rapid Shutdown Systems (RSS) and Rapid Shutdown Devices (RSDs) in their application on commercial-scale rooftop solar PV systems.

Due to the combination of size, quantity of components, and reduction of fire risk, ground-based commercial and utility-scale solar PV installations are not governed in the same way as rooftop-mounted systems. As such, ground-mounted systems will be discussed in more detail in future publications.

Halliwell has observed a notable increase in rooftop solar PV fire losses, many of which are alleged to be caused by mismatched connectors and RSDs. While competing opinions in the industry often rely on intuition and anecdotal evidence, our approach is rooted in rigorous scientific analysis. The very technology mandated by the National Electrical

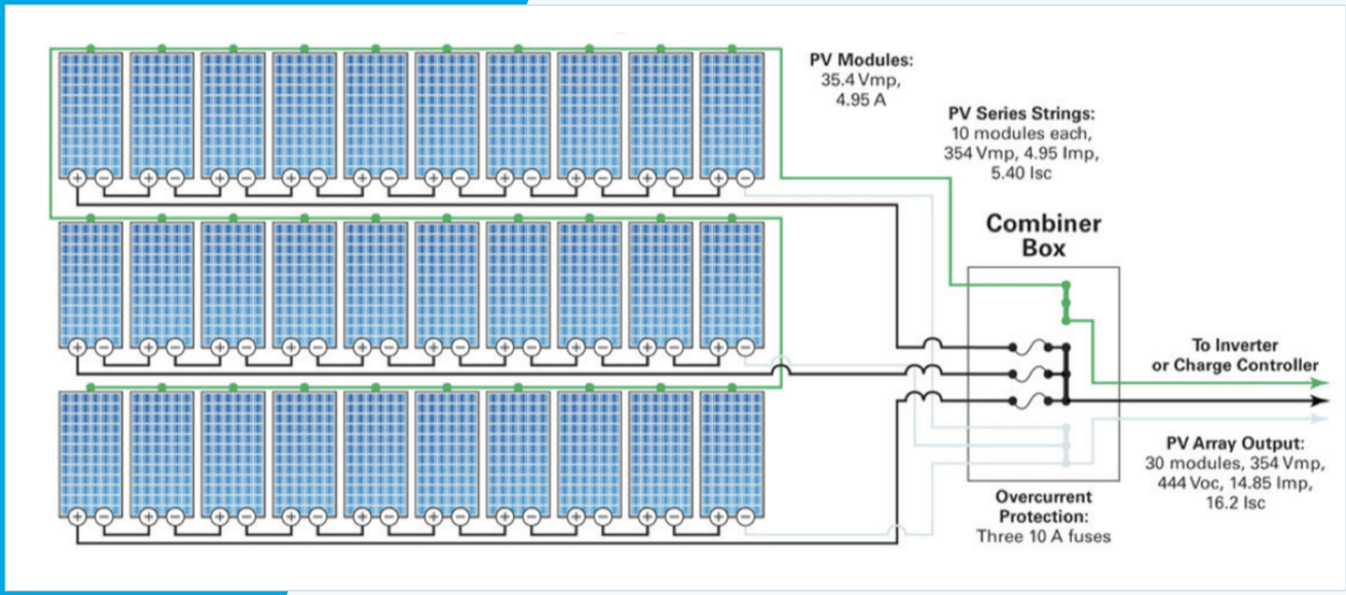


Figure 1: Example of DC String in Three Sub-Array Configuration[4]

Code (NEC) to enhance safety for first responders—particularly RSD systems—has now come under scrutiny as a possible contributor to these fires. Understanding the relationship between these components and fire risks requires more than speculation; it demands empirical research, systematic testing, and a comprehensive failure analysis methodology.

To that end, Halliwell has conducted extensive laboratory testing and research to measure the performance of these devices and to determine the conditions under which they fail. By applying a data-driven approach, we have been able to quantify the electrical, thermal, and mechanical stresses that drive these failures. Our investigations go beyond simple visual inspections, incorporating forensic material analysis, electrical testing, and simulations to replicate real-world conditions. This allows us to distinguish between installation-related failures, inherent manufacturing defects, and degradation mechanisms that develop over time.

As a leader in forensic engineering, Halliwell remains at the forefront of root cause analysis for solar PV system fires. Our expertise in RSD technology, connector compatibility, and failure modes has positioned us as a trusted resource in the industry. Through ongoing research and case studies, we continue to refine our understanding of the complex interactions between system components, ensuring that our conclusions are based on scientific evidence rather than conjecture. By advancing knowledge in this field, Halliwell contributes not only to resolving disputes but also to improving industry standards and enhancing the safety and reliability of solar PV systems.

BRIEF OVERVIEW OF A SOLAR PV ARRAY

Before delving into the specifics of RSDs, we will provide a brief overview of how electromagnetic radiation from the sun is harnessed for use as a clean energy source as well as the typical components of a solar PV installation in accomplishing the effort.

A solar photovoltaic (PV) module consists of a collection of many individual solar PV cells that transform electromagnetic energy from solar irradiance to electrical energy as a source for renewable energy.[5] The solar PV module combines the absorbed energy contained within photons striking the surface of the module's surface. These modules are constructed with n-type and p-type silicon layers that are excited by the photons, creating an electric current. The energy transferred in this interaction is captured by the semiconductor material contained within the solar PV cells to facilitate utilization as a source of renewable electrical power. The generation of this electrical power via solar PV sources is becoming more common as the reduction in costs associated with development, manufacturing, and installation is realized.[6]

The Direct Current (DC) power harnessed from a typical commercial-scale solar PV installation generally consists of multiple sets of solar PV modules, DC combiners, and inverters that convert DC power to Alternating Current (AC) for commercial use.[7] As is typically encountered, the solar PV modules are electrically connected in series to form a DC string. The purpose of the series configuration is to minimize voltage drop and power losses over the length of the DC string. While installation designs vary widely, each DC string nominally contains up to twenty solar PV modules and can deliver a maximum output power of approximately 5 and 7 kWDC with voltages between 500 and 1,000 VDC and amperages between 7 and 10 ADC.

These strings are routed to a DC combiner which electrically groups the DC strings into an equivalent parallel configuration in forming a solar PV array. Due to the parallel configuration of the DC strings, typically encountered bus amperages are in the range of 70 to 175 ADC, depending on the number and power rating of Solar PV Modules in each string. Refer to **Figure 1** for a graphical representation of the interconnection between solar PV Modules forming three DC strings and routing to the DC combiner.

As is usually encountered on rooftop-mounted solar PV systems, the DC combiner is directly adjacent to the inverter. This provides a convenient location for both the DC and AC disconnecting means and overcurrent protection devices. The inverter receives the output of the DC combiner and converts the DC power to AC power. As is commonly found on commercial-scale solar PV installations, multiple inverters and DC combiners manage solar PV generation from hundreds or even thousands of solar PV modules. This combined AC power is then routed to the distribution system for use by the facility and inter-connection to the grid. When many DC strings and supplementary inverters are installed on a typical rooftop, the resulting electrical energy can be utilized to supply renewable energy to a facility. This can be monetized in contributing to the US energy grid via net metering programs, Power Purchase Agreements (PPAs), and Renewable Energy Credits (RECs).[8]

THE INHERENT DANGER OF SOLAR PV INSTALLATIONS

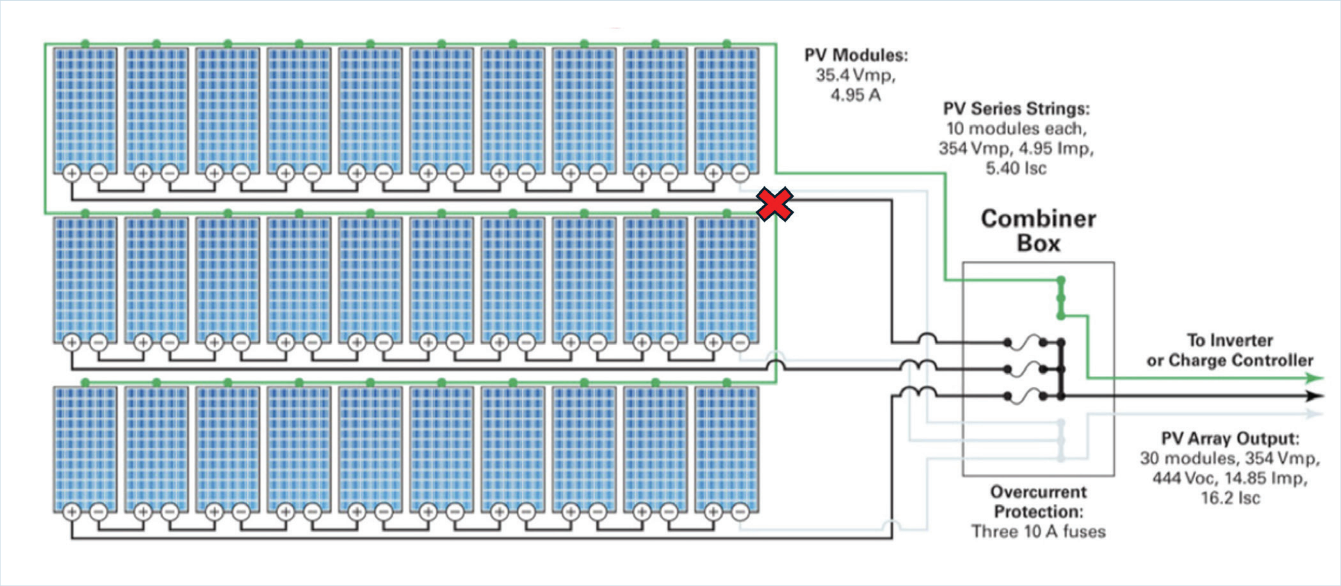
Any time that fuel, an ignition source, and oxygen are combined at optimal conditions, a fire can result. As is the case with all installations governed by the NEC, Overcurrent Protection Devices (OCPD) afford protection to equipment and conductors by limiting the current resulting from overloads, short circuits, or ground faults.[9]

In the configuration above and as shown in **Figure 1** where the first OCPD is located within the DC combiner "downstream" of the DC string conductors, any fault occurring on the load side of the OCPD would result in a tripping action. However, a fault in the DC string conductors, as shown in **Figure 2**, are present "upstream" of the OCPD and would therefore be unprotected, posing a significant safety hazard.

The scenario in **Figure 2** below represents inception of a ground fault formed between the DC string positive (black) and the chassis ground (green) at the location of the red "X". Ground faults can occur due to various causes, but common factors include the thermal degradation of a DC string connector from high resistance (initial inception as a series arcing fault) or conductor insulation damage resulting in an exposed "live" conductor contacting the metal surfaces of the solar PV module or racking system.

It is common practice for the array's DC string negative (–) and chassis ground to be inter-connected

Figure 2: Figure 1 (modified by Halliwell to show inception of fault)



within the DC combiner or inverter. This electrical connection allows for a pathway of fault current to flow between the monopolar positive (+) and negative (–) portions of the DC string. Per design, the two monopolar voltages formed at the solar PV module (i.e., positive and negative) are electrically isolated from each other and ground, forming a bipolar set referenced against the ground potential. When a fault current pathway is introduced, fault current will flow in the DC string circuit supplied by the series-connected solar PV modules.

As can be seen from **Figure 2** above, the outputs of the individual solar PV modules are series-connected so that only one positive and one negative conductor is routed to the DC combiner for each DC string. As a result of this configuration, the string voltages are high (i.e., ranging between 500 VDC and 1000 VDC) and pose a danger of serious injury or death if contact is made with an energized component ahead of the first OCPD at the DC combiner.

A fault upstream of the DC combiner would be unprotected and would release energy over an extended period, potentially igniting any fuel packages in the vicinity, such as roofing materials, and leading to a fire event. The lethal string voltage of several hundred DC volts would still be present when first responders arrived onsite to extinguish the fire to protect life and property. This scenario is what led to the NEC requirements regarding shut-off devices, known as RSDs.

NEC DEVELOPMENT OF RAPID SHUTDOWN REQUIREMENTS

Article 690 of the NEC was first added in 1984 to capture all requirements for installation of Solar PV systems. While typical modifications were made during subsequent code cycles, a major requirement was added in 2014 regarding RSDs. Rapid Shutdown refers to the rapid, safe reduction of voltage on conductors of solar PV systems installed on or in buildings.

According to Paragraph 690.12 of the 2014 NEC, Rapid Shutdown functionality was added to “reduce the shock hazard for firefighters” due to the lethal voltages that are present within solar PV strings and arrays.[10] In practicality though, Rapid Shutdown functionality applies not only to first responders, but also to site personnel tasked with performing maintenance on the Solar PV installation.

To mitigate these hazards in incorporating new requirements via Paragraph 690.12 of the 2014 NEC, the National Fire Protection Association (NFPA) began requiring specific Rapid Shutdown functionality on all conductors located within ten feet of the boundary encapsulating the rooftop installation. All conductors within this boundary are termed by the NEC as “Controlled Conductors”. Paragraph 690.12 of the 2014 NEC included five specific requirements relative to Rapid Shutdown: 1) the function must apply to

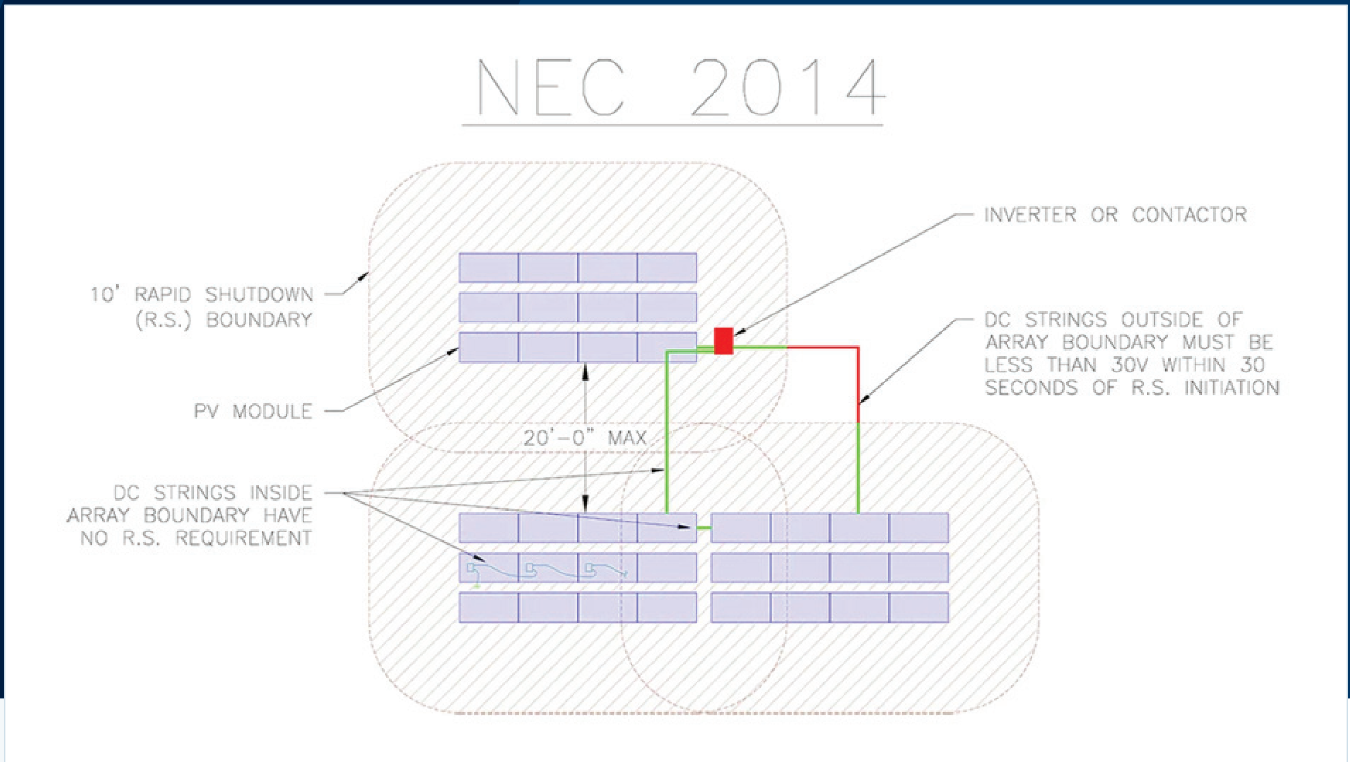


Figure 3: 2014 NEC Rapid Shutdown Boundary[10]

conductors longer than 1.5 m (5 ft) inside a building or more than 3 m (10 ft) from a PV array, 2) upon shutdown initiation, voltage and power must be reduced to 30 volts and 240 volt-amperes within 10 seconds, 3) voltage and power shall be measured between any two conductors and between any conductor and ground, 4) the shutdown methods must be clearly labeled per 690.56(C), and 5) the equipment performing the shutdown must be listed and identified for safety.

A graphical representation of the requirements of 2014 NEC Paragraph 690.12 is depicted in **Figure 3**. Within this Figure, a representative sample of three DC strings is shown. All conductors which are contained within the ten-foot shaded boundary are highlighted in green. According to this edition of the NEC, all conductors associated with the DC string, DC combiner, or inverter located within ten feet of the boundary were not required to contain Rapid Shutdown functionality.

By closer inspection of **Figure 3**, conductors associated with the top and bottom-left strings would not require Rapid Shutdown. However, the conductors associated with the bottom-right string in routing to the "inverter or contactor" (see area of the figure with wiring highlighted in red) would require Rapid Shutdown. As is easily recognized, this 10 foot boundary limitation inadvertently created a scenario where only portions of the system could be secured with Rapid Shutdown functionality while others would remain energized at nominal voltage were allowed by the 2014 NEC.

In this configuration, only the conductors associated with the bottom-right strings which extend beyond the 10-foot shaded boundary require limitation to not more than 30 VDC within 30 seconds, but the conductors associated with the top and bottom-left sub-arrays could remain at nominal voltage (i.e., several hundred volts). This condition still poses a safety hazard within the 10-foot boundary from the array.

Therefore, to address the deficiencies introduced within the 2014 NEC in mitigating the risk, the 2017 Edition of the NEC tightened the requirements regarding the boundary. Paragraph 690.12 of the 2017 NEC was expanded to include more stringent requirements. In general terms, per paragraph 690.12B(2)(2), all conductors located within one foot of the boundary shall be limited to not more than 80 VDC within 30 seconds of Rapid Shutdown initiation. Additionally, by 690.12B(1), all conductors outside of the boundary or more than three feet from the entry into a building shall be limited to not more than 30 VDC within 30 seconds of Rapid Shutdown initiation.

A graphical representation of the revised requirements of the 2017 NEC Paragraph 690.12 is provided in **Figure 4**. The changes enacted in the 2017 Edition

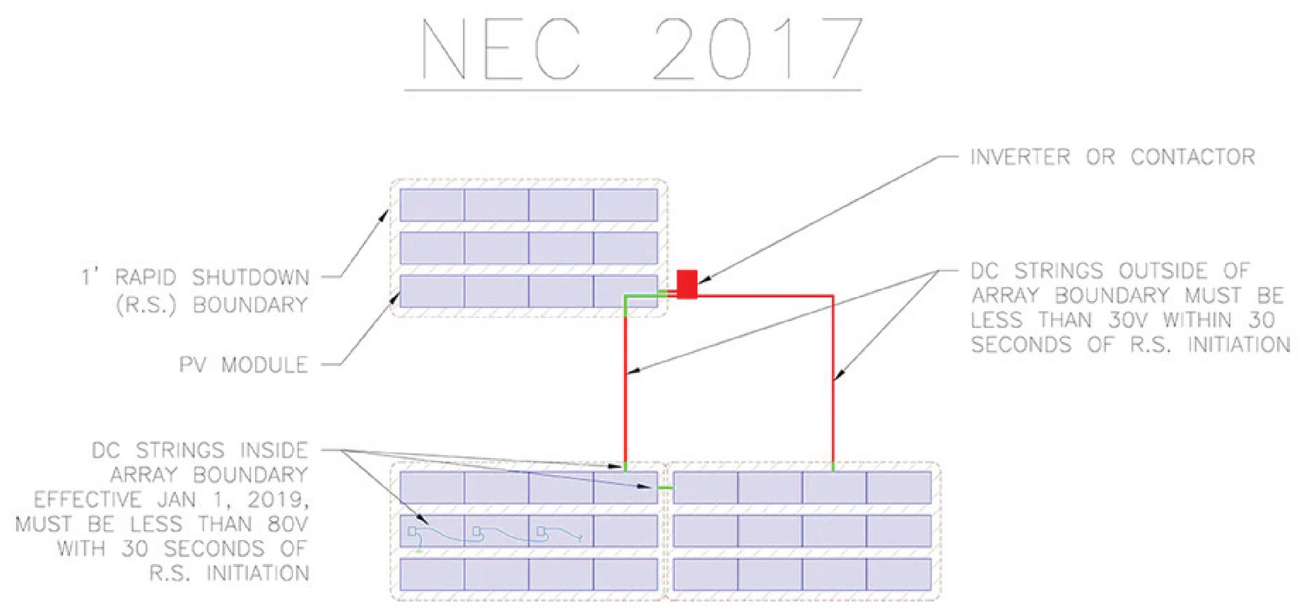


Figure 4: 2017 NEC Rapid Shutdown Boundary[10]

of the NEC effectively eliminated the boundary variations in the installed environment by simply reducing the boundary from 10 feet to one foot. Since 2017, Paragraph 690.12 of the NEC has remained consistent with respect to the one-foot boundary.

INCEPTION OF RAPID SHUTDOWN FUNCTIONALITY

To comply with the requirements for Rapid Shutdown beginning with the 2014 code revision cycle, system designers and manufacturers developed RSS solutions utilizing RSD. RSDs are commonly referred to as Module Level Power Electronics (MLPE) and fall under the same MLPE umbrella as module optimizers and monitors. For clarity, module-level simply refers to components at or near the solar PV modules.

Other variations of Rapid Shutdown functionality were also developed for incorporation into DC combiners and inverter designs, but the most encountered configurations employ MLPE RSDs. For this reason, RSDs will be specifically introduced and discussed as a solution for compliance with NEC Paragraph 690.12.

RSDs are typically attached to the underside of the solar PV module frame (as shown in **Figure 5**) or alternately affixed to the racking structure upon which the solar PV modules are mounted in rooftop installations. **Figure 5** is a graphical representation of integration utilizing a widely encountered MLPE RSD product.

Figure 5 depicts a series of individual MLPE RSD devices (one of which is highlighted in red) installed under each of four solar PV modules in a sample DC string. The integration of the MLPE RSD effectively replaces the direct daisy-chain of solar PV modules depicted in **Figure 1** by connecting each solar PV module's positive (+) and negative (-) conductors (highlighted in orange) to the respective inputs of the MLPE RSD. Connectors are provided at the ends of the cables to facilitate the configuration. As is shown in **Figure 5**, the outputs of each MLPE RSD are then connected in series. The combined outputs of the MLPE RSDs form a DC string which is routed to the DC combiner – in other terms, the MLPE RSDs are connected between the solar PV modules and the DC combiner.[12]

The "on" or "off" status of the DC string's MLPE RSDs is controlled by a RSS transmitter (highlighted in green). Within **Figure 5**, the RSS transmitter is shown floating between the inverter and DC string. In practice however, the RSS transmitter is either installed within its own enclosure or integrated into the DC combiner/inverter. The RSS transmitter is outfitted with a Current Transformer (CT) core through which one conductor of the DC string wiring is routed. Through the CT core, the RSS transmitter injects a high frequency AC carrier signal ("keep-alive") onto the DC string conductor, which is sensed by the internal circuitry inside each MLPE RSD. This functionality is known as Power Line Communication (PLC) and facilitates transmission of directives regarding the "on/off" action to accomplish Rapid Shutdown of the

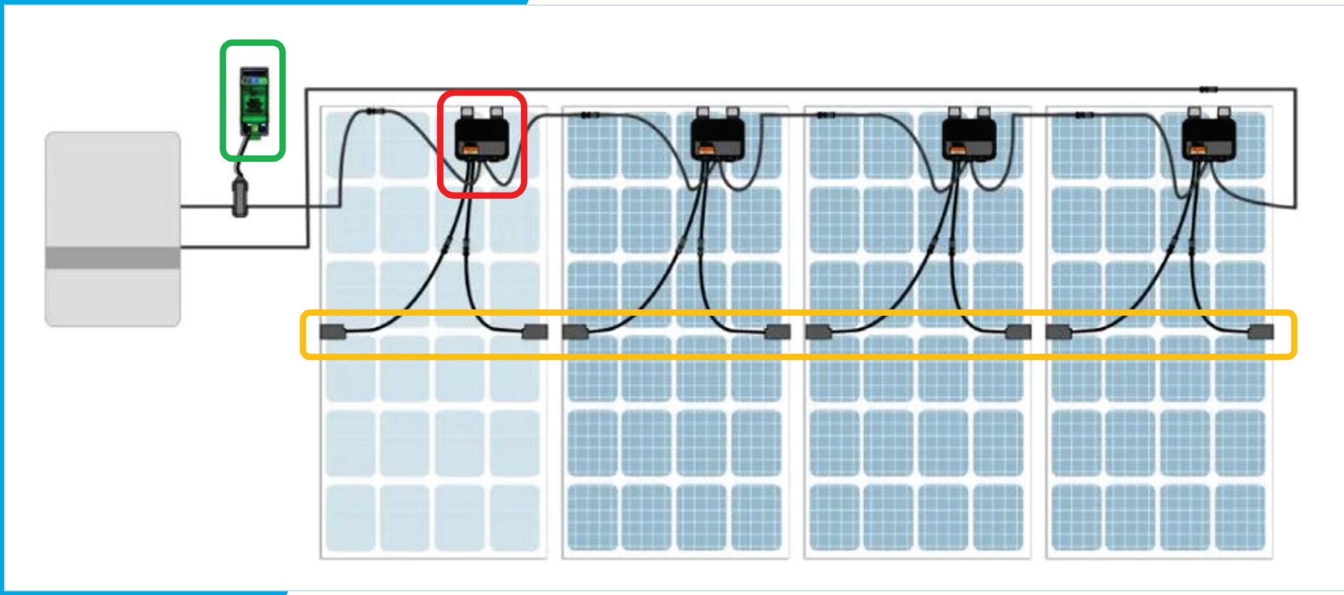


Figure 5: RSD Integration with Solar PV Modules[11]

MLPE RSDs when ordered.[13] In practice, multiple DC conductors associated with one inverter are routed through one RSS Transmitter CT. The number of conductors which can be routed through the CT core is set by the manufacturer.

By inserting the MLPE RSD's internal contacts in series with the solar PV module, the capability to control the output power of each solar PV module is incorporated. During normal operation, the RSS transmitter delivers the "keep-alive" signal to each MLPE RSD in the DC string. This facilitates an "on" status within the MLPE RSD and results in solar PV power contributions to the DC string.

Upon receiving a Rapid Shutdown order, the RSS transmitter ceases its "keep alive" signal and the MLPE RSDs in the respective DC string respond by opening in an "off" status. In this state, the MLPE RSDs effectively serve as solid state switches capable of reducing the individual solar PV module's output power to zero. In doing so, the MLPE RSD accomplishes Module Level Rapid Shutdown within the confines of the one-foot boundary prescribed by the 2017 and later editions of NEC Art. 690.12.[14]

CONCLUSION AND FUTURE ARTICLES

The present article regarding technologies associated with Rapid Shutdown was meant as an introduction to the basic concepts of integration within the DC string to comply with the requirements of Paragraph 690.12 since its incorporation in the 2014 NEC. However, the very technology that is required by the NEC to make the solar PV system safe for first responders is also suspected as a potential root cause in many rooftop solar PV fires. To investigate this, Halliwell has conducted laboratory research in the areas of RSD technology, functionality, and failure modes, as well as those associated with solar PV connectors. We are at the leading edge within the forensic industry regarding root cause analysis of solar PV system fires and failure modes. In future articles, we will dig deeper into the specifics of MLPE RSD technology, connectors, installation requirements, installation errors, and failure modes resulting in combustion.

Halliwell's commitment to scientific rigor and empirical research sets us apart in the forensic investigation of solar PV fires. While others may rely on intuition and generalized assumptions, our approach is rooted in data, laboratory testing, and a deep understanding of failure mechanisms. As the industry grapples with the unintended consequences of safety-driven technologies like rapid shutdown devices, our work provides critical insights into their true impact on system reliability. By continuing to push the boundaries of forensic engineering, we not only help resolve disputes with clarity and precision but also contribute to the advancement of safer, more resilient Solar PV systems.

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