WHITE PAPER

Interactions of Plug-In PV with Protection of Existing Power Systems

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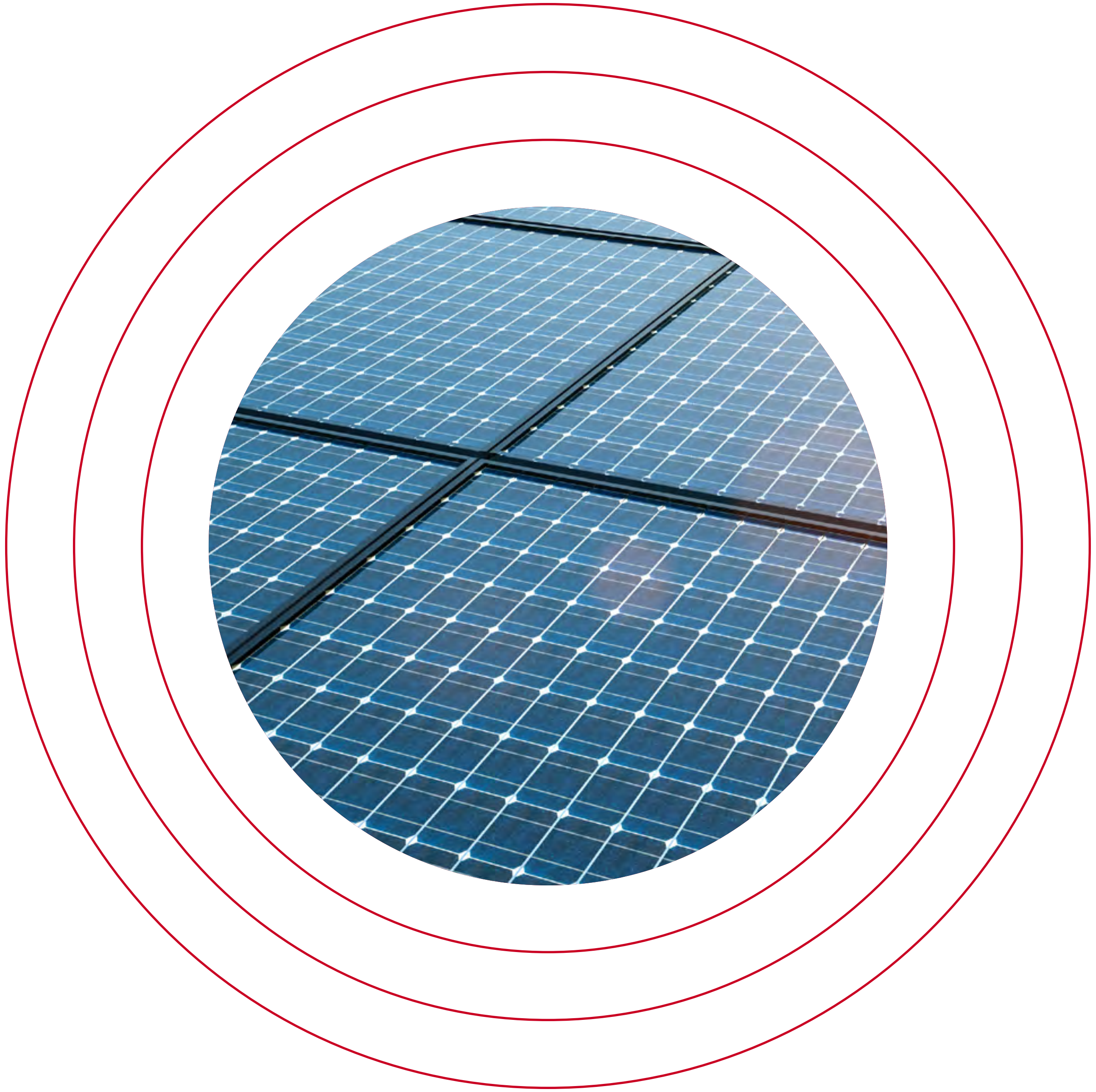
Introduction

There is growing interest in plug-in photovoltaic (PIPV) technology in the United States, particularly for residential consumer use. Traditional photovoltaic (PV) systems such as rooftop solar arrays have long been the standard in residential applications, but a better understanding of the unique hazards presented by PIPV is necessary to support safe use.

This white paper examines:

- **The differences between traditional PV systems and PIPV,** including installation methods and electrical integration with premises wiring.
- **The need for special attention to overcurrent protection** of the circuit to which PIPV connects, due to its unique configuration and interaction with existing wiring.
- **The unique risks associated with PIPV,** primarily because the output circuits of utility-interactive inverters are not evaluated for user contact or touch safety, which may pose electric shock hazards.
- **Consideration of Ground-Fault Circuit Interrupter (GFCI) requirements** and the interaction of PIPV with existing overcurrent and ground fault protection devices.

It is worth noting that additional hazards associated with PIPV are addressed in UL 3700, Outline of Investigation for Interactive Plug-In PV (PIPV) Equipment and Systems. This Outline of Investigation, led by UL Solutions engineers and experts, defines requirements for safety and compliance in PIPV as technology evolves.



Understanding PIPV and how it compares to traditional

Traditional PV systems typically include PV modules, their mounting system and an inverter to convert the generated direct current (DC) electricity into alternating current (AC). This AC power is then used by standard electrical equipment, distributed within the premises or fed into the utility grid. These PV systems may also be integrated into a broader distributed energy resource (DER) system, which includes other sources and elements, such as battery energy storage. In residential settings, PV systems are commonly installed on rooftops.

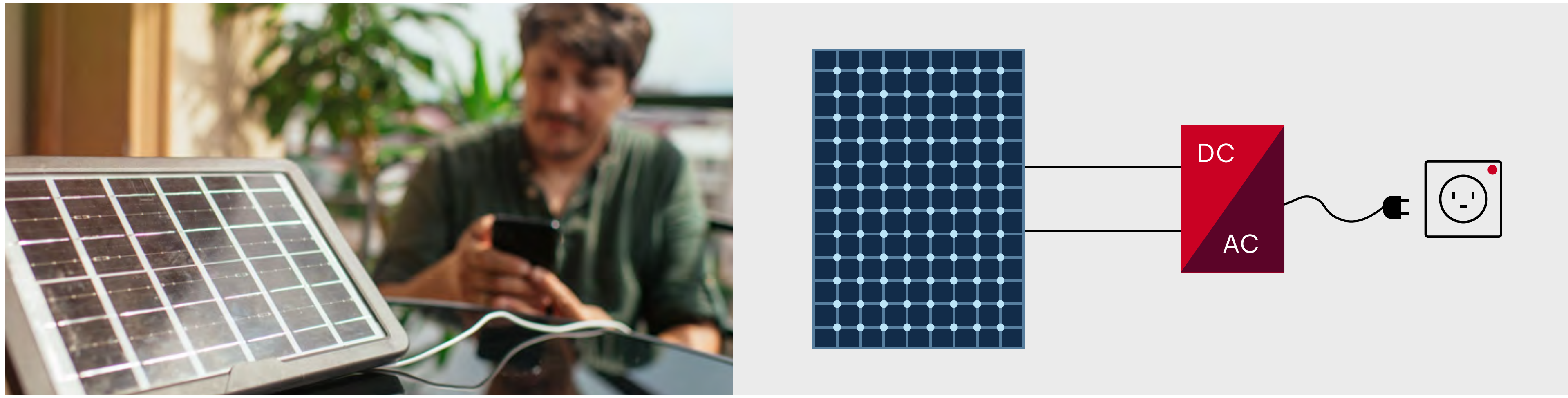
The first PV system was installed in the 1800s[1] and the technology has evolved significantly since then. Over the past four decades, widespread deployment of PV systems has led to valuable insights into module performance, potential hazards and practical approaches to risk mitigation. As a result, product safety standards and installation codes have continually evolved to provide consistent and appropriate requirements and risk mitigation. Safety standards for PV systems and their subsystems strive to promote safety through protection against electric shock, fire and mechanical hazards.

Today, in the United States and many other countries, PV systems are permanently installed and wired by qualified professionals using certified equipment that meets applicable safety standards. These installations are inspected and approved by code authorities for compliance with applicable codes. Electric utility engineers also review grid-interactive PV systems to verify adherence to local grid interconnection requirements.

1. A Brief History of Solar Panels, Elizabeth Chu and D. Lawrence Tarazano, U.S. Patent and Trademark Office.

The emergence of PIPV systems for residential use

PIPV systems are PV systems connected to building wiring through a cord-and-plug connection to a standard receptacle. These systems export power into a common residential receptacle using a power supply cord and attachment plug. Marketed for residential applications as a plug-and-play solution, PIPV products are designed for consumer installation and offer a more affordable way to adopt solar energy at home. Some PIPV products are referred to as “balcony solar” because consumers can choose to install them on residential balconies.



(a) (b)

Figure 1. (a) Balcony-type PIPV module installation; (b) PIPV electrical schematic.

An example of an installed PIPV system and an electrical schematic are shown in Figures 1(a) and 1(b).

Unlike traditional PV systems, PIPV systems have electrical wiring — specifically, the power supply cord — that is not permanently installed. These systems typically bypass review and authorization by code authorities, and utilities perform little to no oversight after the products are in use.

These unique factors necessitate a comprehensive review of the application of PIPV systems in relation to current standards, codes and existing infrastructure. These systems also require a thorough safety science assessment of the products and their installations.

Overcurrent protection

NFPA 70, the National Electrical Code® (NEC), is issued by the National Fire Protection Association (NFPA) and serves as the applicable model code for electrical safety in the United States. This includes the safety of premises, wiring systems and residential PV installations. The NEC is adopted, with or without amendments, by thousands of local jurisdictions across the United States and enforced by authorized regulatory officials.

Branch circuits and branch circuit conductors require overcurrent protection in accordance with Articles 210 and 240 of the NEC. The sizing requirement of the overcurrent protective device is specified in Sections 210.20 and 240.4. These requirements are based on several factors, including the size of the load, conductor size, conductor type, equipment and outlet receptacle rating. These NEC installation requirements, along with the use of listed overcurrent protective devices, protect branch-circuit conductors and loads from the full range of overcurrent.

For overcurrent protection of circuits that include multiple sources operating concurrently, Article 705 applies, although it does not explicitly cover a PIPV source connected to a branch circuit. Requirements in Article 690 address rules for the installation of PV systems; however, the existing requirements address the installation of permanently installed PV systems connected through dedicated wiring connections to the premises wiring system and do not specifically address PIPV systems connected through an existing receptacle.

The NEC requirements in Articles 210 and 240 are based upon a single source supplying power from the panelboard to the load circuit. A PIPV source back-feeding a receptacle introduces additional current that is not protected by the upstream panelboard branch circuit overcurrent protective device. Back-feeding branch circuits with two sources of power can overload conductors and provide current to loads on that circuit beyond their evaluated, tested and certified limits, which could result in a risk of electric shock and fire.

For example, an outdoor 14 AWG copper branch circuit protected by a 15 A circuit breaker is permitted to have multiple NEMA 5-15 receptacles for connecting loads on that branch circuit. If there is an overload condition on the circuit, the 15 A circuit breaker would sense the overload above 15 A and trip, safely de-energizing the circuit, as shown in Figure 2.

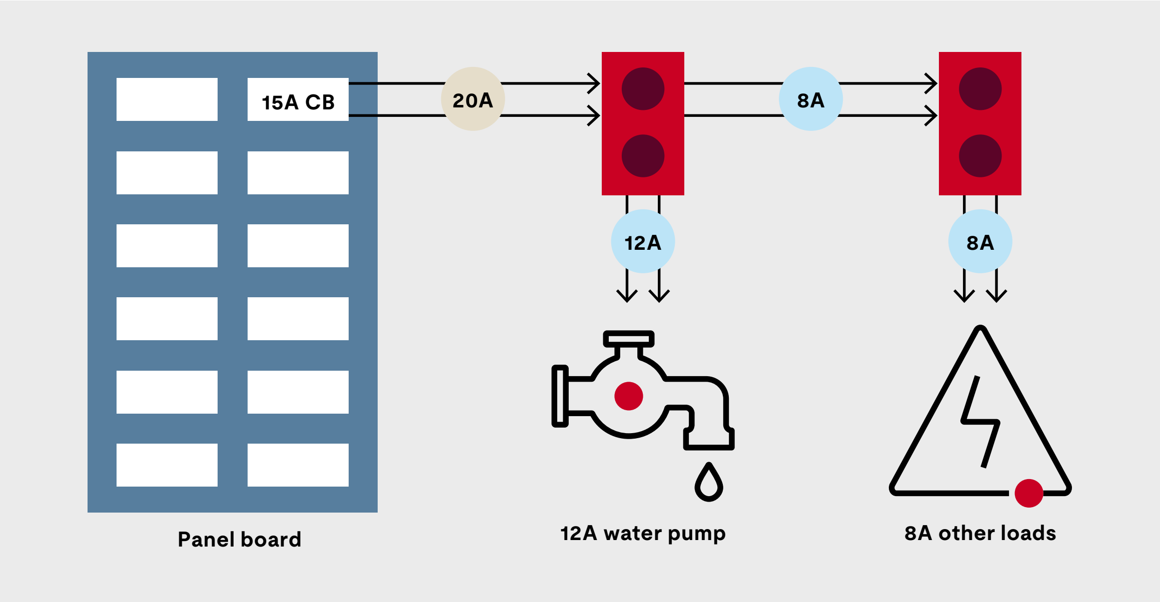


Figure 2. Branch circuit in an overload scenario without PIPV

However, if that same circuit has a Plug-in PV product back-feeding through one of the receptacles, and a similar overload condition occurs on that circuit, the PV inverter will contribute to the overload current. If the current from the utility (grid) source supply in the branch circuit is at or below 15 A, the circuit breaker at the panel will not sense the current within the branch circuit as an overload and will not trip the circuit breaker. The combined current from the utility source and the PIPV source can result in the circuit being continuously overloaded, posing a risk of fire or shock through damaged conductors, insulation and/or equipment connected to that circuit.

An example of the combined utility and 600 VA PIPV source current exceeding the 15 A branch circuit rating is shown on Figure 3, although situations may also exist where the PIPV source is larger than 600 VA or multiple PIPV sources are connected. The larger the PIPV source, the higher the likelihood of an undetected overload occurring. However, even small PV sources can introduce an undetected overload on the branch circuit conductors.

While NEC Section 705.12(B) does permit an installation where the sum of 125% of the power source output circuit current (i.e. PV source) and rating of the overcurrent protective device does not exceed 120% of the busbar ampere rating (e.g. in a panelboard), the permission is limited only to equipment where a busbar is connected to loads and where the primary power source (utility) and PV source are located at opposite ends of a busbar containing loads. Such a configuration limits the likelihood of an overload on the busbars as the loads draw the current between the two sources. However, the busbar location requirements and 120% limit are not applicable for branch-circuit wiring, and a PIPV configuration intended for use by consumers cannot be reliably maintained.

Additionally, in the panelboard application with the additional 20% current from a PV source permitted by NEC Section 705.12(B), each branch circuit will have properly sized overcurrent protection for the branch circuit conductors and connected loads. In the PIPV real circuit application, the conductors and loads are not sized or protected for the additional PIPV output current that is added to the branch circuit.

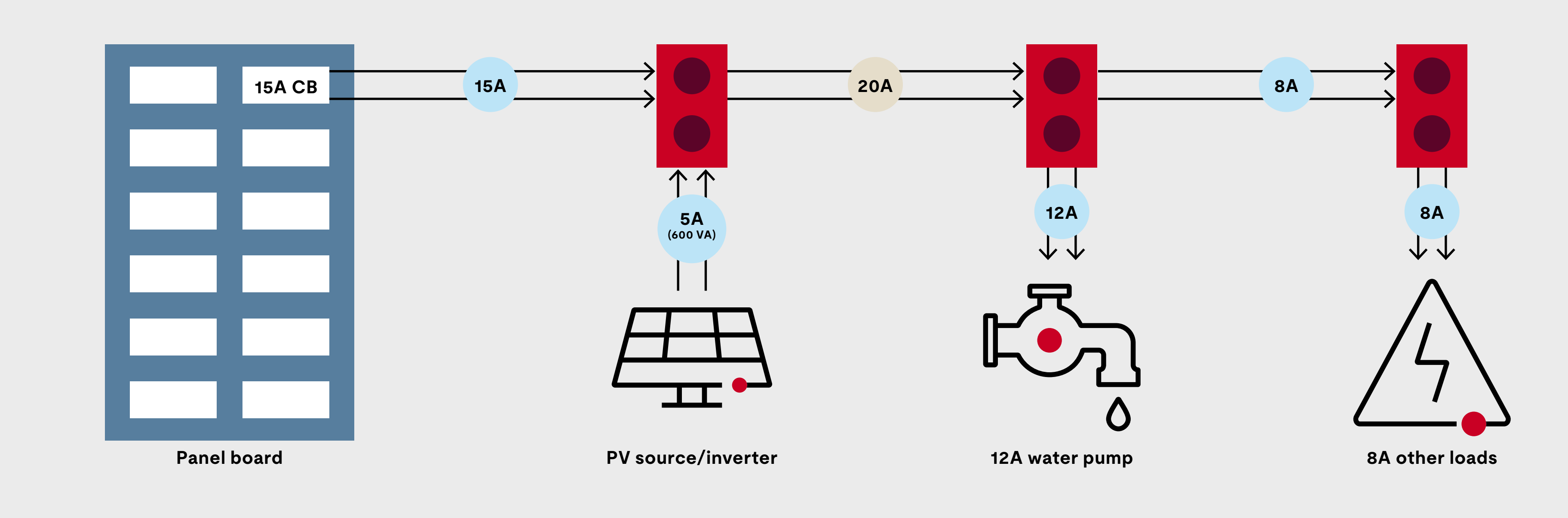


Figure 3. Branch circuit in an overload scenario with PIPV

When multiple PIPV units are connected to a single branch circuit, users may inadvertently increase the risk of conductor overloads that go undetected by the circuit's existing overcurrent protection. Although the use of multiple PIPVs on one circuit is generally discouraged, the potential for this scenario remains high due to consumer unawareness of the associated safety risks. This risk is further compounded when PIPV products utilize standard NEMA 5-15 plugs and are installed by individuals without electrical training. To address these concerns, several mitigation strategies are proposed below, though additional solutions may also be viable depending on system design and regulatory developments.

Dedicated circuit with unique plug-in PV receptacle

To mitigate the risk of undetected overloads, one effective strategy is to require that Plug-In PV (PIPV) systems be installed exclusively on dedicated branch circuits. This ensures that no additional loads share the circuit, thereby preventing cumulative current from the utility and PIPV sources from exceeding conductor ratings. Implementing this approach necessitates the use of a uniquely configured plug and receptacle system, designed to connect only to the designated circuit and incompatible with standard NEMA 5-15 receptacles. This prevents users from relocating the PIPV unit to other circuits, which could undermine the safety strategy. In this configuration, the PIPV source backfeeds power solely through the dedicated circuit to a properly rated overcurrent protective device at the panel. When appropriately sized for both the PIPV output and conductor capacity, this device can reliably detect and interrupt overcurrent conditions, safeguarding the wiring and terminations.

Unique PIPV receptacle with integrated overcurrent protection

In branch circuits that include multiple receptacles, a practical mitigation strategy involves replacing the first receptacle with a uniquely configured PIPV receptacle that incorporates an integral overcurrent protective device. This configuration ensures that the PIPV system can only be connected at a designated point in the circuit, preventing users from inadvertently plugging the unit into other receptacles that lack appropriate protection. By limiting the PIPV connection to a single, purpose-built receptacle, the risk of overloading conductors due to cumulative current from both the utility and PIPV sources is significantly reduced. The integrated overcurrent protective device must be properly rated to match the PIPV output and the branch circuit conductor size, ensuring reliable detection and interruption of overcurrent conditions. This approach enhances safety by maintaining control over the installation location and electrical characteristics of the PIPV system.

Unique PIPV receptacle with oversized conductors

Another mitigation strategy involves replacing the first receptacle in a branch circuit with a uniquely configured PIPV receptacle, combined with the use of oversized conductors. By installing larger-gauge branch circuit wiring, the system can accommodate the combined current from both the utility and PIPV sources without exceeding conductor ampacity limits. This approach reduces the risk of overload under scenarios like those illustrated in Figure 3. To ensure safe operation, the PIPV output should be limited to a defined maximum rating, and the number of PIPV units connected to the circuit should be restricted. This can be achieved through the use of proprietary receptacle configurations that prevent unauthorized or unintended connections. All loads and receptacles on the circuit must be appropriately rated for the total expected current. For example, a 12 AWG copper conductor rated for 20 A can safely carry up to 16 A of continuous current (based on an 80% derating factor).

Power control systems with unique plug-in PIPV receptacle

A further mitigation approach involves integrating power control systems (PCS) into branch circuits that support PIPV installations. PCS technology, evaluated under UL 3141, Outline of Investigation for Power Control Systems, and addressed in NEC Article 120 and Section 705.13, actively monitors and regulates the output of multiple power sources to help the total current remain within safe operating limits. When installed by qualified personnel, a properly designed PCS can detect and respond to combined current from both the utility and PIPV sources, preventing overload conditions on branch circuit conductors. To maintain compatibility and safety, the PIPV system must connect through a uniquely configured receptacle that restricts installation to circuits equipped with PCS protection. This configuration prevents users from inadvertently plugging PIPV units into unprotected receptacles, thereby maintaining the integrity of the overload mitigation strategy.

Touch safety risks in grid-interactive inverters

Grid-interactive inverter output circuits are not evaluated for user contact and touch safety

PV inverters take DC energy from the PV modules and convert it into AC output power that can be used to power loads. One specific type of PV inverter is the utility grid-interactive inverter that synchronously exports power in parallel with the electric utility grid. Grid-interactive inverters are evaluated in accordance with IEEE 1547 and IEEE 1547.1 for grid connectivity and UL1741, the Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources, addressing product safety and grid connection functionality. The IEEE 1547 and IEEE 1547.1 electric utility grid performance requirements and tests focus on the inverters performing specific actions and functions intended to support stable operation of the electric utility grid. Some of those grid performance functions include cessation of output current during extreme abnormal grid events such as high overvoltage, low undervoltage and loss of utility grid voltage. In certain locations, such as California, PV inverters are also required to have specific advanced grid support functionality for some applications.

The utility grid interconnection performance requirements are designed to align the functionality of PV inverters with that of electric utility generation and system protection equipment. Under the grid-interactive performance requirements, the AC output terminals and wiring of grid-interactive inverters and generators are only evaluated to limit and sometimes cease output current flow under specific abnormal operating conditions of the electric utility. Utility interactive inverter output circuits are considered hazardous circuits. Hence, they are required to be protected from general access, enclosed appropriately and insulated from human contact.

There may appear to be a similarity between the required function to cease current flow from a grid-interactive inverter output circuit and the concept of preventing human exposure to the inverter output. However, there is a significant difference in the hardware requirements, software requirements and evaluation between ceasing output current for grid performance requirements and providing protection from electric shock and other hazards for the public from those outputs.

Further, grid-interactive inverters also make use of software for most control functions. Software that controls safety circuits needs an extra level of evaluation and control to prevent misoperation and shock hazards reliably. Utility grid interconnection performance requirements and tests focus exclusively on the suitability of connections to the grid and do not address electric shock, energy, and fire hazards that could pose a risk to the general public from accessing the inverter outputs. This presents a critical safety concern for PIPV products due to the unconventional use of the attachment plug as a power output interface.

Addressing electric shock safety for the general public

Product safety standards and electrical codes are designed to protect the public from exposure to circuits and components that may present hazards, such as electric shock. Typically, parts classified as electrically hazardous are enclosed to prevent contact, while any components that remain accessible are subject to rigorous evaluation to ensure they meet safety criteria. These components must demonstrate that they do not pose a risk under normal or foreseeable abnormal conditions, a concept commonly referred to as “touch safe.”

Touch-safe circuits must incorporate robust and reliable protective measures to prevent hazardous voltage or current from becoming accessible. These protections are evaluated under both normal and abnormal operating conditions, including scenarios involving overloads, hardware failures, insulation breakdowns and software malfunctions. Consumer products intended for general public use are specifically designed and tested to help ensure that, in the event of a failure, the product defaults to a safe state, minimizing risks of electric shock, high energy exposure or fire. This principle of “fail-safe” design is foundational to modern safety engineering.

For example, USB circuits and Class 2 low-voltage, limited-energy power supplies used to power many consumer electronic products are designed, tested and certified with the expectation that consumers may come into contact with the outputs. These outputs are rigorously evaluated to maintain low voltage and limited electrical energy output, thereby reducing hazards under both normal and foreseeable abnormal conditions.

Even after a touch-safe circuit is evaluated for protection from electric shock, its conductors and components must be spaced appropriately, isolated and insulated from all other hazardous circuits and uninsulated live parts, such as higher-voltage PV DC and battery source circuits. This prevents the touch safe circuit from potentially becoming energized and losing its protection from an adjacent hazardous circuit.

Although PIPV and AC modules share many physical similarities, there are significant differences in their installations, installation locations and accessibility to users. AC modules and their wiring are not typically exposed to the general public’s contact. In support of this concept, NEC Section 690.33(C) requires that any user-accessible connectors be of a locking type to prevent access to hazardous live parts. AC modules and their wiring are typically installed on roofs and are not exposed to physical interactions or damage associated with regular user contact.

Conversely, ground-fault circuit interrupter (GFCI) electric shock protection is required for appliances in wet locations where user interaction and potential damage to the products and wiring are expected. PV module construction includes glass and thin, flexible plastic to insulate cells and internal wiring that operate at hazardous voltages. PV modules could be more susceptible to damage that exposes live parts to the user in an environment that is not typical of rooftop applications. The PIPV product type, installation location, proximity to users and likelihood of regular user contact necessitate GFCI protection.

It is important to understand that GFCI protection applies only to the AC portions of PIPV systems. The DC circuits in PIPVs present different shock hazards and are typically isolated from the AC side, meaning GFCI devices will not protect against shock hazards in the DC circuit. Since PV modules remain energized whenever exposed to light, DC circuits require alternative protective measures. These can include physical barriers, electronic safeguards or a combination of both. UL 3700 addresses the appropriate protection strategies for these DC circuits.

Risks associated with PIPV output cord and attachment plug

Most commercially available PIPV products have common 15A power cords with accessible plug pins. Common 15A NEMA 5-15P attachment plug blade terminals, which terminate a power supply cord, were designed to connect a piece of utilization equipment, such as an appliance, to a receptacle connected to a source of power. Plug blade terminals become de-energized when they are removed from a receptacle and do not pose a shock hazard when used to connect a load to an outlet. However, those plugs are not intended, evaluated, tested or rated as the output conductor for a power generation source. If a PIPV product is exposed to sunlight, it will generate electricity, which can cause the plug blades to be energized at hazardous levels on the accessible plug blades, unless special mitigation measures are successfully implemented.

IEEE 1547 utility export limits are not designed to protect people from electric shock hazards. Under islanded or open phase conditions, the inverter is allowed up to two seconds to cease output current. The two-second performance allowance and lack of a single-fault shock safety reliability evaluation can create a risk of electric shock on the exposed attachment plug blades used in a PIPV product. Therefore, relying solely on the inverter grid connection function to limit exposure to human shock hazards at PIPV plug blades is not an appropriate solution.

New PIPV product safety requirements must supplement the utility grid-interactive performance requirements with touch safety requirements to protect the public from electric shock hazards for the PIPV output circuits. Touch safety limits will need to include additional hardware protection measures, different protection components, additional evaluations and testing, including software safety assessments. The safety evaluation must account for single-point failures in critical components of the protection hardware circuit, as well as software failures.

Potential solutions for PIPV output circuit shock safety protection

Utility grid-interactive performance functionality by itself is insufficient to protect the public from electric shock hazards on the PIPV plug blades and other accessible parts in the output circuit. Multiple methods might prove suitable to provide electric shock protection on PIPV output circuits for the public, including:

- **PIPV unique configuration plug and receptacle –** A uniquely configured, mating pair that does not have exposed live parts that can be contacted by the user.
- **Accessible grid-interactive/touch safe output circuit –** A grid-interactive inverter that includes additional protection for its PIPV output circuit to provide necessary, reliable electric shock protection for the public. This would require additional functional safety assessments of the software and hardware to demonstrate that the hazards have been mitigated under normal and abnormal (fault) conditions.

Ground fault circuit protection for user safety in PIPV systems

A GFCI is a life-safety device designed to protect people from electrical shock hazards caused by damaged equipment or wiring. The NEC requires GFCI protection in environments where water increases the risk of electrical shock. Common examples include outdoor areas, wet or damp locations, and spaces near sinks, bathtubs or pools, such as bathrooms, kitchens and pool pump circuits. According to NEC Section 210.8(A), all outdoor circuits serving dwelling units must be equipped with Class A GFCI protection, implemented through at least one of the following approved installation methods:

GFCI circuit breaker – installed on the branch circuit panel board supplying one or more outdoor receptacles

GFCI receptacle – installed on the branch circuit at the first outlet in a string feeding multiple other outdoor receptacles

It should be noted that NEC Section 210.8(A) requires outdoor receptacles to be on a branch circuit that is separate from other building loads, including indoor circuits.

Safety risks when PIPV interaction compromises GFCI protection

Damage of GFCIs

There is a significant compatibility concern with PIPVs back-feeding existing branch circuits that were only intended and evaluated for traditional source-to-load power flow.

UL 943, the Standard for Ground-Fault Circuit-Interrupters, evaluates GFCI protection for unidirectional current flow (e.g., from the panelboard to the load). This one-directional current flow is signified by required markings for “line” and “load” connections on the GFCI. GFCI protection of these circuits must be maintained throughout their use and installation to mitigate the risk of electric shock to the public.

Significant concerns have been noted related to the misuse of GFCIs when backfed. This damage has resulted in GFCI circuitry failure, allowing power to continue while leaving the branch circuit unprotected from electric shock hazards that GFCI functionality is designed to address.

It is foreseeable and expected that the use of a PIPV with a NEMA 5-15 attachment plug allows for uncontrolled installations and connections to non-bidirectional breakers and receptacle-type GFCI-protected circuits.

PIPV products are generally designed for consumer use, allowing connection to existing residential electrical circuits. However, the back-feeding of power into a GFCI-protected circuit — an inherent function of PIPVs — is currently outside the scope of GFCI certification and performance standards. To accommodate this bidirectional power flow, updates to UL 943 Standard requirements are necessary to support continued GFCI protection of the branch circuit when a PIPV system is present. These updates should include provisions for appropriate identification markings specific to bidirectional use. Ultimately, this will require the installation of a properly evaluated and certified bidirectional GFCI device on circuits connected to PIPV systems.

The risk of electric shock increases with grid voltage and requires a corresponding shorter trip time to limit electric shock energy. If the local load current drawn on the protected circuit is lower than the inverter generation output current, the circuit voltage will increase until the inverter ceases output current. The UL 943 disconnect duration limit is voltage dependent, and a higher circuit voltage after the GFCI trip increases the electric shock energy and would correspond to a shorter duration GFCI response via a shorter trip time. The voltage following the GFCI trip is a function of the inverter output current and the load on that circuit. The GFCI has no means to interrupt the PV inverter output current to protect against the increased electric shock hazard.

During a ground fault, circuit breaker type GFCIs only open the ungrounded current carrying conductor to isolate and interrupt panelboard power to the protected load circuit. For circuit breaker protected GFCI circuits, the grounded conductor (neutral) remains solidly connected through the panelboard’s neutral to ground bond reference. That neutral to ground reference provides a ground referenced return current path for the PV inverter output current, such that tripping the circuit breaker type GFCI does not also interrupt a ground-fault current path from the PV inverter output.

Even if a circuit was provided with appropriate bidirectional GFCI protection, the PIPV with a NEMA 5-15 attachment plug could mistakenly or intentionally be connected to a branch circuit without appropriate bidirectional GFCI protection that interrupts both line and neutral current carrying conductors, posing a significant likelihood of creating electric shock hazards on the unprotected circuit.

Safety risks when PIPV interaction compromises GFCI protection

Blinding of GFCIs

A second significant concern related to GFCI protection is the potential of blinding GFCIs when using PIPV. A PIPV is a parallel coupled supply source connected to the branch circuit, where two or more sources share the same centrally located neutral-ground bond reference at the main panel board. During a ground fault event, branch circuit GFCI protection interrupts the utility grid power source from the load. However, a PIPV parallel supply present on the isolated load circuit continues to supply current to the ground fault for up to two seconds following the loss of utility power. UL Solutions conducted testing to observe the behavior of GFCI protected branch circuits backfed by PIPV isolated PV grid-interactive microinverter. See Annex A.

The possibility of PIPV blinding the required ground fault circuit protection is a significant safety concern. Engineered solutions are required to minimize the risk of this occurring in practice.

GFCI Hazard Mitigation in PIPV Systems

Potential solutions to mitigate hazards with GFCI interactions are outlined below. It should be noted that other means may be found suitable.

Unique plug-in attachment means – Requiring a unique (non-NEMA) connector configuration for PIPVs, where intermatibility is achieved by the same manufacturer mating halves so the PIPV cannot be plugged into an existing non-PIPV circuit, could mitigate the risk of a shock hazard as described above. A unique configuration is an effective means to mitigate unintended use, thereby not compromising GFCI protection for both existing legacy GFCI protection and preventing back-feeding of non-bidirectional GFCIs. A PIPV with a proprietary mating plug and receptacle, connected in the appropriate circuit location on a branch circuit with a certified, marked and evaluated GFCI protective device, will maintain necessary GFCI electric shock protection and mitigate risk conditions.

Dedicated circuit – Requiring that PIPV can only be installed on a dedicated circuit (i.e., with no other outlets and loads) helps ensure that compatible GFCI protection is provided for that circuit.

Summary

PIPV products can offer innovative methods for harnessing renewable energy to generate clean power for the public. However, they can present significant hazards when connected with traditional wiring systems used in the United States and other locations.

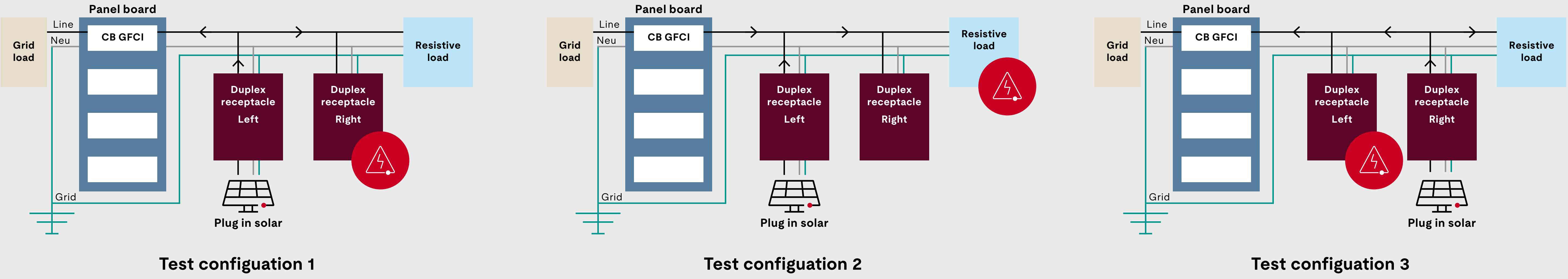
Based on the concerns outlined, special risk mitigation requirements are necessary to allow the safe use of PIPV products. In the absence of these special measures, PIPV can present electric shock hazards and fire hazards to consumers, potentially defeating protective technologies required for public protection without any awareness that the previous protection has been compromised. Allowing PIPV to be plugged into any existing branch circuit with no mitigation for the above concerns is not supported by UL Solutions. There are potential engineered solutions that can be applied and will be necessary to promote safe use of PIPV products. These can include both inherent product features and special installation practices that allow the public to choose electricity sources while also remaining safe.

Annex A

GFCI research testing with PIPVs

UL Solutions conducted testing to observe the behavior of GFCI-protected multiple receptacle branch circuits backfed by an isolated PV grid-interactive microinverter that included bidirectional current flow. This laboratory testing included three potential GFCI installation configurations on single-phase branch circuits rated 120Vac.

The following three test configurations were conducted, differing in the current flow direction(s). The test configurations varied based on the location of the isolated PV inverter, ground fault, GFCI location and GFCI type.



GFCI circuit breaker testing

All test configurations were initially conducted using a GFCI circuit breaker in the panelboard. The tests were conducted with a 500-ohm ground fault representing the human body impedance model as required by UL 943. A simulated ground fault was introduced by connecting the 500 Ohm resistance in the circuit at the location represented by the lightning bolt. UL 943 requires the GFCI to interrupt the circuit operating at 120 volt alternating current (VAC) within 28.6 milliseconds (ms). This response time is considered compliant if the average of 10 measurements meets the 28.6 ms. Baseline testing was conducted on the circuit protected by the GFCI circuit breaker without a PV inverter. The GFCI circuit breaker detected and interrupted the circuit and de-energized the load within 12.6 ms (the average of 10 measurements).

Test configurations 1, 2 and 3 were conducted with an isolated PV inverter exporting continuous power to the circuit, and then the 500 Ohm ground fault was introduced. Ten measurements were recorded and averaged for each of the three test configurations.

The results were as follows:

Configuration 1 – 36.3ms

Configuration 2 – 32.8ms

Configuration 3 – 36.7ms

All test results exceeded the maximum allowable interrupting time of 28.6ms (for the average of 10 measurements) according to UL943, which also requires that any single test iteration shall not exceed 125% of interruption time limit.

Taking a closer look at the test results oscilloscope data, the blue waveform is the ground fault current through the 500 Ohm body model. As depicted by the blue trace, the circuit breaker GFCI detected and opened the circuit in slightly more than a ½ power frequency cycle, followed by the GFCI interruption of the grid power. After the GFCI circuit breaker opens, the grid power (indicated by the red arrow) continues to flow through the PV inverter output current until its anti-islanding function detects the loss of grid power and ceases the AC output current flow. The blue and green traces to the right of the red arrow clearly show continued PV inverter current flow into the ground fault for roughly 1.5 cycles after the GFCI tripped. The Blue Trace shows the total net duration of ground fault current from the utility grid plus the continued current flow from the PV inverter until the anti-islanding protection ceases current export at 35.1ms, exceeding the UL 943 limit.

Blue Trace – Ground fault shock hazard current through the 500 Ohm body impedance model

Green Trace – Voltage across the ground fault. Grid voltage before GFCI trip (at red arrow) and voltage supported by inverter output current following the GFCI clearing.

Purple Trace – PV inverter output current

Note that in this case, the GFCI circuit breaker randomly selected for this testing performed significantly quicker than the response time required in UL 943. Other GFCI circuit breakers, which would still comply with the UL 943 requirements, could demonstrate longer response times of up to 28.6 ms.

A grid-interactive inverter is required to cease-to-energize its AC output within two seconds of loss of the utility grid source according to UL 1741 and IEEE 1547 anti-islanding performance requirements. Grid-interactive anti-islanding is a performance function that is inherently variable and dependent on the parallel loads and utility source feeding the circuit. The response time to anti-islanding conditions often varies between several cycles and can be up to two seconds. The GFCI safety and grid interconnection performance requirements are not compatible, and additional protection measures are necessary to maintain the GFCI timing and energy limits to prevent the risk of electric shock. It should be noted that, for the above-ground fault test conditions, the particular inverter responded much faster than the grid interconnection requirement, which allows up to two seconds. However, not all inverters will respond as quickly as the one tested above.

GFCI receptacle testing

This section covers testing of the same three configurations using a GFCI receptacle (instead of a GFCI circuit breaker). Test results were observed to comply with UL 943 interrupting time requirements. A GFCI receptacle type differs as it interrupts both the ungrounded line conductor and the grounded current-carrying neutral conductor. By opening the neutral-grounded conductor, the PV inverter output circuit is disconnected from the panelboard neutral-to-ground bond, which removes the inverter's current return path for a ground fault shock current. The phenomenon was observed in the previous test case, where the PV inverter output current continued to flow into the simulated human body, with a 500 Ohm load resistance, after the GFCI trip during the inverter anti-islanding current cessation. In this GFCI Receptacle test condition, the inverter no longer had a neutral-to-ground reference in the panelboard. Without a reference to ground, the inverter output did not feed current into a ground fault, simulated by a 500 Ohm load resistance representing a human body. These results clarify the need for bidirectional type GFCIs that must open and interrupt all current-carrying conductors to remove the ground fault return for the PV inverter output current during anti-islanding current cessation and to maintain the GFCI clearing time to limit ground fault energy.

Any electrical reference of the branch circuit to ground can provide a return current path for a grid-interactive inverter to supply electric shock ground fault current. Many products intentionally have filter circuits with components between current-carrying conductors and ground to reduce electrical noise. These filters, as well as common circuit leakage current and miswired circuits, as described in the next section, have the potential to similarly reference the inverter output circuit and cause extended current export beyond the UL 943 GFCI protection limits.

Additional testing

At a later date, we anticipate performing additional PIPV testing with other protection technologies in a single-phase, three-wire 120Vac/240Vac circuit configuration with a shared neutral (often called split phase). This configuration will also need to be reviewed for practical use with PIPVs.

Annex B

How the US is different from Europe

PIPV products have become popular in Europe. Residual current, such as residual current circuit breakers with overcurrent protection (RCBOs) and residual current circuit breakers (RCCBs), are equipment installed in European Union (EU) household circuit installations to provide integral personal protection against electrical shock hazards and overcurrent protection. These protective devices are required to open all current carrying conductors (2 pole, 4 pole), maintaining residual current shock protection. Receptacle type GFCIs, like residual current devices (RCDs) open all current carrying conductors and continue to maintain ground fault protection. However, Circuit Breaker GFCI types only open the ungrounded conductor. This maintains the neutral to ground bond, allowing the PIPV inverter to continue current export (up to two seconds), which defeats the GFCI electric shock protection.

RCCBs are not used in the US, but they do have some notable differences from the Ground Fault Circuit Interrupters (GFCI) protection required to be used in the U.S., as defined in codes like the NEC.

The high-level functionality of the RCCB and GFCI protection is intended to limit electric shock hazards for load products powered by the electric power system. These protective devices monitor, measure and limit ground fault current that can cause electrocution for adults and children who come into contact with electrically live parts from damaged appliances, wiring and other electric load products. Both of these protective products interrupt electric current flow into a ground fault within a very short period. At 120Vac, the GFCI products are required to stop the ground fault current within 0.0286 seconds to limit the electric shock energy that could enter a human body to avoid electrocution hazards. As the magnitude of the AC ground fault increases, the disconnection time becomes shorter to limit exposure time and total shock energy, as per the Class A equation.

The main difference is that GFCI interrupts the circuit at 5mA ± 1mA to provide let-go protection, which allows individuals to remove themselves from the hazard voluntarily. An RCD interrupts the circuit at 30mA, the threshold to protect against ventricular fibrillation, and exposure times are slightly extended compared to GFCIs. The lower threshold in the US standards provides more conservative protection for persons at higher risk, including children and the elderly, who are more susceptible to electric shock hazards.

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