21, rue d'Artois, F-75008 PARIS
http://www.cigre.org

CIGRE US National Committee
2022 Grid of the Future Symposium

Voltage-Based Method for Low-Cost, Reliable Fault Isolation in Inverter-Based Microgrids (IBR)

C.T. KONSAVAGE, S.C. BILLAUT
Commonwealth Associates, Inc.
USA

SUMMARY

One substantial design challenge for the successful implementation of inverter-based (i.e., solar, battery, wind), grid-forming AC power systems is the ability to reliably detect and clear system faults to ensure safe and reliable power flow. These faults are particularly challenging to accurately locate in inverter-based resource (IBR) microgrids in islanded mode because the low fault current (and often unstable negative sequence current provided by these non-reactive, inverter systems) invalidates the usefulness of existing fault isolation technology. In these situations, abnormal, reduced voltage on faulted phases may allow for conventional protection systems to identify that a fault has occurred, but do not consistently allow for reliable, timely identification of the specific fault location, and subsequent isolation of the fault in an easily scalable, cost-effective manner.

There are no widespread, commercial products available to reliably detect and isolate faults in islanded IBR microgrids. When existing AC distribution systems are used as a microgrid in islanded mode, standard practice relies on contributions from synchronous-based generation sources to achieve sufficiently high fault current for tripping and isolation. In the absence of synchronous sources, as would be the case in a fully PV & battery-based system, modern overcurrent fuses and reclosers would not reliably trip for faults in the system. This is because inverter generation sources often do not see inertia to carry fault current based on electromagnetic characteristics, resulting in a quickly decaying time envelope due to the lack of inductive characteristics. Additionally, negative sequence analysis is unreliable for these applications.

Traditionally, protection methods applied to distribution systems have relied heavily on overcurrent technology- especially fuses. Unfortunately, overcurrent protection methods applied to IBR systems (which see fault current values hovering so closely to typical load current values or quickly decaying) may result in an anticipated tripping time of minutes or hours for traditional reclosers, breakers, or fuses. In some cases where traditional overcurrent settings philosophies of set value and timing are applied, the system may not trip at all. Other state-of-the-art protection methods for these applications currently rely on complex studies or

Sebastien.billaut@cai-engr.com

costly investment in communications equipment that may be misaligned with typical utility distribution company budgets and infrastructure. Consequently, methods other than overcurrent protection and costly/complex protection must be explored for devices to reliably and quickly isolate faults for IBR microgrids in islanded mode.

This paper presents the need for new distribution protection techniques for microgrid applications sourced by inverter-based resources. It identifies the effectiveness and cost of several existing protection techniques for these applications, and proposes a new, low-cost patent-pending method of reliably isolating these faults using a voltage-triggered, decentralized, time domain method of locating faults

KEYWORDS

Microgrid, Protection, Inverter-Based Microgrid, Islanded IBR, Fault Isolation, Voltage trigger

INTRODUCTION

As microgrid deployments increase worldwide, the penetration of inverter-based resources (IBRs) also continues to rise. Due in part to IEEE 1547, a standard providing the criteria and requirements for the interconnection of microgrids to utility scale grids, ride-through requirements demand that microgrid designs demonstrate exceptional resiliency in transient and fault conditions. Here we present the importance of fault protection in IBR microgrids, their unique controlled response characteristics, how these responses challenge current state-of-the-art distribution protection systems, and a patent-pending solution for cost-effective, scalable fault isolation solution in microgrids with high penetration of IBRs.

WHY ARE MICROGRIDS RELEVANT?

Microgrids are power systems with the ability to both operate as part of a larger, traditional power grid, or disconnect and operate as an autonomous subunit. Microgrids are especially useful in allowing local-based generation to serve critical loads during outages from the primary grid, as in the case of natural disasters or where load is isolated from large-scale generation. This reduces the impact of grid disturbances on customers and aids in overall system recovery during major transients. In this way, microgrids increase reliability and resiliency of the nation’s overall power delivery. Microgrids may also serve as a proving ground for technologies that may later scale up to widespread implementation across the bulk electric system.

According to the US Energy Information Administration’s website, “Electricity Explained: Electricity Generation, Capacity, and Sales in the United States,” there were 1.2 million MW of generation in the US in 2020, 13% of which was from non-hydroelectric renewables. [1] According to the Office of Energy Efficiency and Renewable Energy’s website “Department of Energy Releases New Tool Tracking Microgrid Installations in the United States,” of all US generation, only 3,100 MW (0.25%) was via microgrids.[2] However, in the coming years, microgrid deployment, and IBR microgrids, is expected to increase.

The DOE Solar Energy Technologies office projects that more than 1 in 7 US homes will have rooftop solar photovoltaic (PV) systems “by 2030 via “Solar Energy in the United

States”. [3] At least 16 U.S. states have set ambitious 2050 targets to reduce carbon emissions- some as much as by 90% in the case of Washington and Colorado, compared to 1990 and 2005 levels respectively. In addition, 30 U.S. states have set clean electricity standards requiring a certain percentage of electricity sold by utilities to be renewably sourced, per Laura Shields’s article, “Greenhouse Gas Emissions Reduction Targets and Market-Based Policies” at the National Conference of State Legislatures.[4] Although traditional generation sources may remain in some parts of the country, utilities could anticipate pockets in the traditional grid that are 80-100% renewably sourced.

Methods to adequately protect the utility system from electric faults are an important part of the viability of power grid evolution. Without fault isolation, the ultimate consequence of a fault would be a complete Microgrid outage. As the nation pivots to increasing reliance on inverter technologies through renewable generation sources or battery energy storage sources, utilities cannot rely on the same large generation, long distance transmission protection technologies to address this new composition of power generation and delivery.

The Problem: Manufacturer-specific inverters define fault current characteristics in islanded inverter-based microgrids

One substantial design challenge for the successful implementation of inverter-based (i.e., solar, battery, wind), grid-forming AC power systems is the ability to reliably detect and clear system faults to ensure safe and reliable power flow. These faults are particularly challenging to accurately locate in IBR microgrids in islanded mode because the low fault current and often unstable negative sequence current provided by these non-reactive, inverter systems invalidate the usefulness of existing fault isolation technology. In these situations, abnormal, reduced voltage on faulted phases may allow for conventional protection systems to identify that a fault has occurred, but do not consistently allow for reliable, timely identification of the specific fault location, and subsequent isolation of the fault in an easily scalable, cost-effective manner.

There are no scalable, low-cost commercial products to reliably detect and isolate faults in islanded IBR microgrids. When existing AC distribution systems are used as a microgrid in islanded mode, the standard practice relies on contributions from synchronous-based generation sources (4-10 times greater than continuous rated current) to achieve sufficiently high fault current for tripping and isolation. In the absence of synchronous sources, as would be the case in a fully PV & battery-based system, modern overcurrent fuses, and reclosers would not reliably trip for faults in the system. This is because inverter generation sources often do not see inertia to carry fault current based on electromagnetic characteristics, resulting in a quickly decaying time envelope due to the lack of inductive characteristics (Figure 1). Studies by the National Renewable Energy Laboratory have demonstrated low penetration of IBR DERs to contribute ~1-2 times rated continuous current for <1 cycle; high penetration contributes ~2-4 times rated continuous current for 0.06-0.25 cycles. [5]

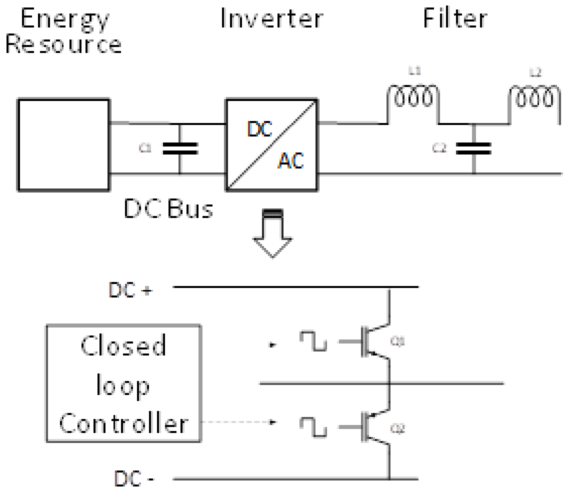

Figure 1: Controlled Current output

In theory, inverters could be programmed and fabricated with response times or fault output comparable to inverter-based sources. However, in practice inverter response characteristics vary by manufacturer and are designed to optimize cost, reducing the withstand capabilities of the inverter gates and therefore reducing the overall overcurrent capabilities and functions of the inverter. Functionally, this results in inverters generally limiting the amount of fault current produced. As an example, consider a power system simulation with inverter-based resources and a line-to-ground persistent ("bolted") fault as shown in Figure 2, modeled in PSCAD power system software. After a fault is initiated, the simulation shows an initial current peaking at 2.5pu or less within 0.15 cycles, then resolving to 1.1-1.2 times load current as a steady-state bolted fault.

The essence is that both current magnitude and phasing remain relatively constant before and after a line-to-ground fault happen on an inverter-based system. Overcurrent protection methods applied to systems like these, which see fault current values hovering so closely to typical load current values or quickly decaying, may result in an anticipated tripping time of minutes or hours for traditional reclosers, breakers, or fuses. In some cases where traditional overcurrent settings philosophies of set value and timing are applied, the system may not trip at all. Consequently, methods other than overcurrent protection must be explored for devices to reliably and quickly isolate faults for IBR microgrids in islanded mode.

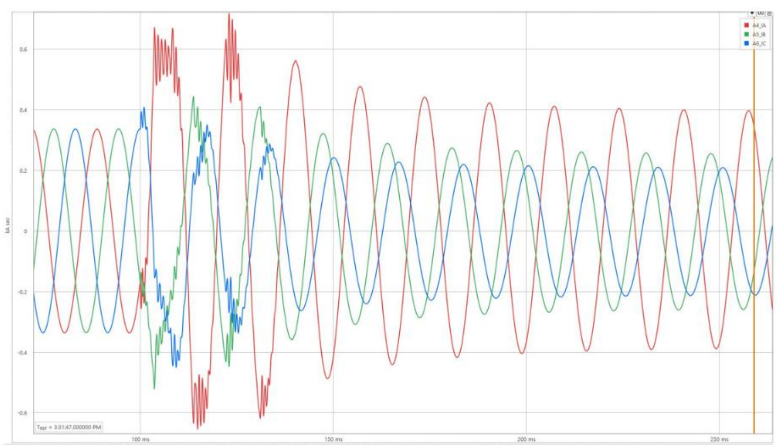

Figure 2: Power System Modeling- Line to Ground Fault Imposed on Inverter-Based System

Beyond current based relaying, other commonly used protection techniques include impedance or distance relaying and directional relaying. However, these may also be affected by other control behaviors as it relates to negative sequence current. Due to the impedance response of rotating machinery, the appearance of negative sequence voltage at the terminal of a synchronous generator proportionally implies the existence of a negative sequence current. The relationship between the negative sequence voltage V2 in reference to the negative sequence current is a reliable machine response used in fault location algorisms in relays. The negative sequence I2 is a reactive response to the appearance of the negative sequence voltage V2. From sequence network analysis, this means that I2 leads V2 by 90 degrees reliably in faults fed by synchronous machines. This is not necessarily true for inverter-based energy sources, wherein the relationship between the terminal voltage and fault current contribution can be nonlinear. As a result, impedance-based or distance elements may not operate reliably for IBR microgrid protection in islanded mode.

To date, the IBR controls performance has not matched that of rotating machinery when it comes to asymmetrical fault response. The negative sequence produced is low in comparison to the positive sequence currents. Also, the angle relationship between the negative sequence voltage and the negative sequence output is not purely reactive. In fact, the response can oscillate over time between reactive and capacitive, as illustrated in Figure 3, per the Office of Scientific and Technical Information (OSTI) technical report, “Impact of Inverter Based Resource Negative Sequence Current Injection on Transmission System Protection.” Considering these unique fault characteristics, traditional protection techniques must be thoroughly reviewed for applicability to IBR microgrid fault isolation. Therefore, directional protection elements reliant on phase angle may not operate reliably for IBR microgrid protection in islanded mode.

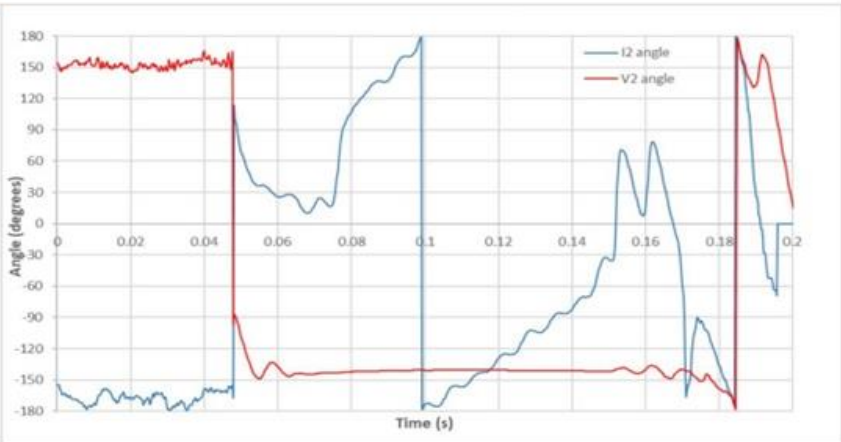

Figure 3: Angles of Filtered Negative Sequence Current (blue) and Voltage (red) during AB Fault

Other promising state-of-the-art distribution protection methods for distribution applications encompass current differentials, traveling wave, machine learning, and voltage-based detection. However, current differential, traveling wave, and machine learning techniques all have limitations of reliability, cost, or scalability when applied to microgrid environments. Current differential protection schemes can be sensitive and possibly set at sufficient values immune to IBR control response oddities. However, current differential applications require communication infrastructure for effective deployment, which is not typically seen on existing distribution grids. Current differential applications also require aggregating current information from sources and load contributions at each protection isolation point, which very quickly increases implementation cost.

Traveling wave relay protection is fast, it requires very high sampling rates as it relies detection of wavefronts and the timing of their reflections on the network. This type of protection is newer and successfully implemented on the transmission network. In theory, performance of traveling wave technology could be largely unaffected by the differing IBR microgrid fault characteristics described previously. However, there are key differences between the distribution network and the transmission network that could affect its performance. In transmission networks, there are few or no tapped loads and the line lengths are large allowing for clear differentiations of the wavefronts leading to adequate timing and fault locations. In distribution networks conversely the distances are short and the tapped loads numerous, making the high-frequency recording of reflecting wave look more like white noise rather than a wavefront that can be timed (Figure 4). This means that the technology in its current state cannot perform adequately without additional components or extensive system modeling, which could result in a high cost of deployment.

The traveling wave complementary component is most probably machine learning, specifically neural deep network engines. Generating a significant amount of waveform training material from electromagnetic transient simulations may enable a neural engine to recognize the picture of the fault location from a specific fault isolation location, successfully locating faults. However, electromagnetic transient program simulations require a significant amount of computing resources, and by extension, is also true for training deep neural networks. Traveling wave combined with machine learning is likely a costly method that would encounter significant scalability challenges.

Adaptive relaying is an additional technique that could be successfully applied in islanded IBR microgrids, based on the grid connection status, where more restrictive settings could be applied to the microgrid in islanded vs grid-connected mode. However, studies might be required to analyze the systems states to determine the adaptive settings ranges. It may also be necessary to use communications to inform of the network state to all fault isolation locations. Both of these requirements have significant hardware and study needs, implying cost and scalability challenges.

In conclusion, overcurrent, impedance, and distance elements are unreliable in performance, given the fault characteristics of islanded IBR microgrids. Although current differential, traveling wave, adaptive relaying, machine learning, or some combination of these may be capable of reliably isolating islanded IBR faults, all require costly and complex implementation. Current differential requires advanced relays at multiple points and communications. The traveling wave relays associated with neural networks and machine learning require extensive network location-specific deep training. Adaptive settings require state estimation studies and communications. Consequently, adoption of these techniques demands a significant cost investment and introduces scalability issues.

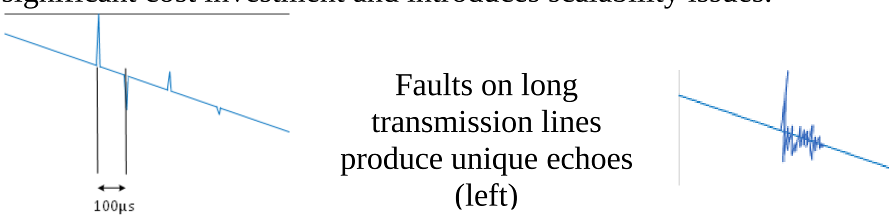

Figure 4: Traveling Wave Noise Increases with Shorter Line Distances

The Solution: Voltage-based detection with decentralized timers for IBR fault isolation

One solution is a systematic approach to fault isolation in islanded IBR microgrids that relies on undervoltage detection and local timers for operation, in collaboration with existing overcurrent devices on the distribution grid. This patent-pending methodology is under development by Commonwealth Associates, Inc. via a decentralized, time-domain, voltage-triggered distribution line isolation technique that does not rely on communications or costly modeling.

Effective deployment of this technology would require a system of several isolation devices across a distribution power system. Each instance of device implementation combines a voltage sensor and timer to locally trip an isolation device (Figure 5).

When sensing a voltage drop, the controller initiates a time delay to allow any existing overcurrent (i.e., fuse) elements to trip first, for the case of sufficiently large fault magnitudes. If the fuse does not trip, the controller on the device with the shorter timer setting trips first. If the source voltage does not recover, the device closes back. Timers continue to trip and close devices until the voltage stabilizes. When this happens, the latest device tripped stays disconnected. The fault is isolated. This method enables the protection system to overcome the overcurrent technology limitations because the voltage drops reliably in inverter-based systems, even when fault current does not rise appreciably. Therefore, voltage-based protection systems can operate reliably where traditional current-based methods cannot.

Undervoltage Detection with Time-Based Isolation: Details of operation

In AC power systems for residential and industrial loads, distribution planners typically use a set of 4 to 6 fuse curves to plan the protection on a distribution feeder. This protection scheme is a robust and straightforward process that allows for quick distribution coordination. Similarly, the patent-pending device can be planned simply and robustly as follows.

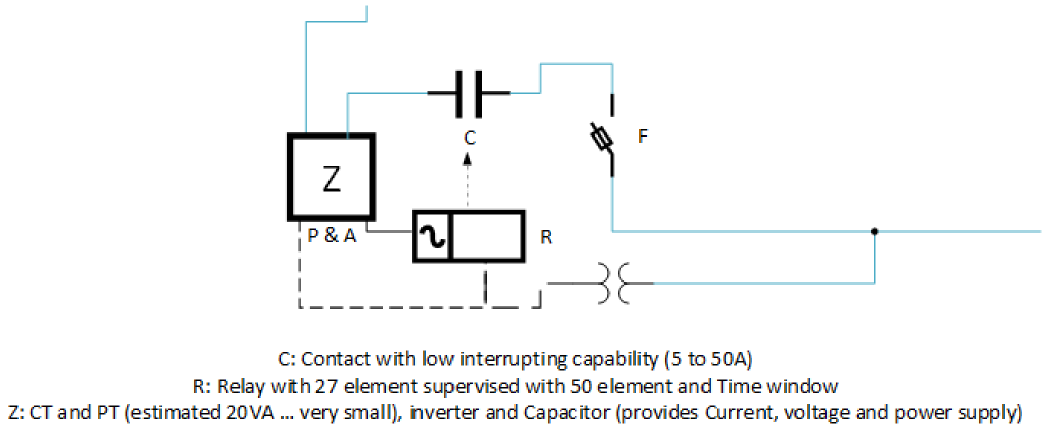

Figure 5: Schematic of Undervoltage Timer Device

The planning engineer starts by assigning a unique integer to each device on each of the phases. Each integer matches a unique assigned time window. Ideally, the lowest integers are closer to the load, starting with the least critical load and finishing with the most critical load. Then greater integers are assigned to the upstream location where larger loads will need to be disconnected. The duration between each device trip allows the inverters of the system to restore steady-state conditions if the most recent trip successfully isolates the fault.

For example, consider Figure 6 where time interval T1 corresponds to the earliest action and a distribution planner employee has associated T1 with device A. T2 corresponds to device B, etc., through the longest time T6 corresponds to device F. If the trip of device A isolated the fault, the portion of the system that remains energized returns to stable voltage levels before time T2. All timers would reset to 0, ending the operation. However, if device A's trip did not clear the fault, device A would close back, and the timers would continue to run until time T2. At time T2, device B would trip so that only B is now tripped. If this clears the fault, the portion of the system that remains energized will return to stable voltage levels before T3. This series of trips/closes in the system continues until fault isolation and voltage restoration.

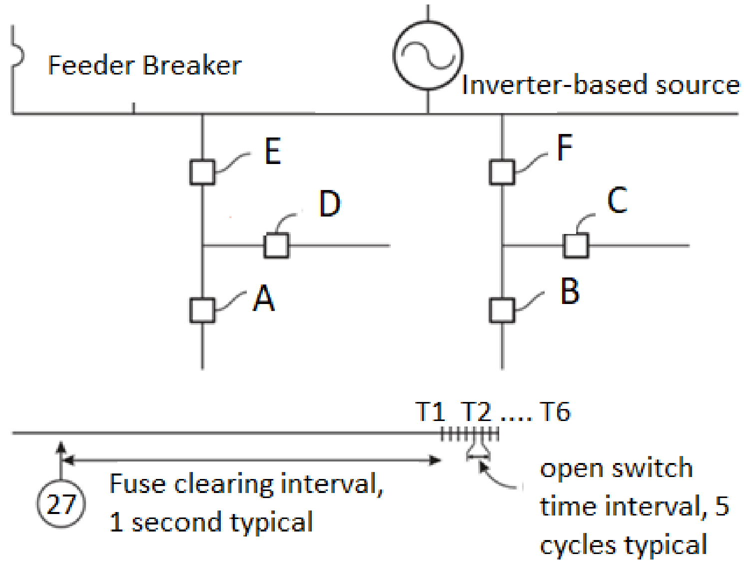

Figure 6: Example of Prototypes Deployed Throughout a Distribution System

Benefits of Technology: Undervoltage detection with time-based isolation is scalable, cost-effective, cross-compatible

The innovation of pairing under-voltage sensors with timers via a prescribed pattern simplifies the protection planning of the microgrid, aligning it with widespread planning techniques currently used for fuse and recloser deployments. This enhances the scalability of the protection system by leveraging existing Distribution Planning Engineer skill sets, avoiding a need for complex system studies, and eliminating a need for advanced computer hardware in each device.

Localized control of the system also represents an easily scalable microgrid protection design as the new solar, battery, or other sources or circuits are added to the grid. This is because advanced reevaluation of fault conditions and flow paths is not required for each device added to the grid. In addition, costly communication infrastructure and equipment are not required because there is no communication between devices or a master controller. As an added benefit, this localized design also improves resiliency against cyberattacks that may otherwise infiltrate a wireless communication or a master control system.

Integrating these undervoltage timer devices with existing distribution overcurrent protection technology further enhances its scalability, and allows for integration with existing off-the-shelf equipment, to avail the benefits of both technologies. The proposed undervoltage technology may be deployed on existing recloser relays or fabricated as stand-alone isolation devices that can optionally be paired with fuses for integration into existing distribution systems. In the latter case, the need to break current at significantly lower ampacity than in traditional grid scenarios also introduces an opportunity for fabrication cost reduction compared to reclosers or switches typically deployed on distribution systems.

SPECIALIZED APPLICATIONS

Deployment of a low-cost product that reliably isolates faults for inverter-based microgrids in islanded mode would benefit many different sets of end users. A device capable of reliably locating and isolating IBR grid faults would be well-suited for specialized applications where IBR microgrids are expected to grow significantly in the coming years- in residential communities impacted by natural phenomena hazards, military base energy installations, and remote lunar or Martian base installations.

Residential communities affected by natural phenomena hazards, like hurricanes, tornados, and extreme temperatures are often impacted by widespread loss of power, due to the hazard separating generating source from load. Moving generating sources closer to loads via microgrids and implementing smaller-scale IBRs could be a solution to restore power to these communities more quickly after an event. For these communities, a reliable method of IBR microgrid fault isolation is critical for grid reliability, which reduces the restoration time following hazards.

For example, Puerto Rico endured the largest electricity blackout in US history because of 2017's Hurricane Maria. With 1.5 million customers impacted, 11 months of repairs were needed to restore infrastructure sufficiently to power all neighborhoods.[6] Until ~18 months after the hurricane, the power grid on the island was fragile, with rolling brownouts and blackouts, some of which were caused by temporary faults due to animal contact.[7] As a result, the Puerto Rico Energy Bureau later mandated that development of renewable-based microgrids on the island increase to 3.5 GW of solar power and 1.3 GW of energy storage by 2025 to mitigate future incidents.[8] Furthermore, in 2019, Puerto Rico passed a law requiring that 40% of the island's energy must be supplied by renewables by 2025, and 100% of energy must be supplied by renewables by 2050.[9] Consequently, devices that reliably locate and isolate faults for IBR microgrids like these would improve the resiliency of these grids during future weather hazards, improving the quality of service, as well as reducing restoration time .

Military base energy installations are another use case for IBR microgrid fault isolation technology. In May 2022, the US Navy and Marine Corps announced a commitment to implementing cybersecure, zero carbon generation microgrids at military bases as a part of its Climate Action 2030 plan. This announcement follows an earlier briefing by the US Army, which committed to installing microgrids at each of its 130 bases. In addition to cybersecurity and carbon reduction goals, the military is concerned with self-reliance and grid resiliency to ensure power delivery to its bases during natural disasters. In 2020, the navy implemented a Resiliency Strategy requiring critical facilities to be capable of islanded operation for at least two weeks.[10] Similarly, the air force has also committed to transitioning the capability enhancing alternative energy technologies to its facilities.

Communications-free, IBR-fault locating technology that combines unprecedented levels of reliability with cost effectiveness supports the use of sustainable, renewable energy systems for military bases, maintenance depots, research laboratories, test centers, or other related AC distribution system users. While also eliminating the consideration of cyber threats, a fault isolation technology to integrate with existing, commonly used distribution protection systems and achieve its targets without a reliance on a primary controller or communication systems would represent a significant cost reduction in equipment and materials compared to other automatic circuit reconfiguration technologies.

A reliable, IBR microgrid fault isolation technology that does not rely on communications also has a use case for outer space applications. NASA's focus on deep-space (beyond low Earth orbit) exploration poses a set of practical challenges in autonomous power system management and control. One aspect of this problem is to use a fault protection scheme that ensures unprecedented levels of reliability. Both IBR AC and DC power systems require solutions to enable fast fault detection and isolation capabilities unique from traditionally sourced AC grids. NASA needs innovative technologies in the areas of lower mass, switchgear, and power management control that can withstand extreme temps, lunar dust/regolith, Mars dust storms, and space radiation levels.

NASA has traditionally implemented DC microgrids as power sources in its advanced aircraft and spacecraft. Given that lunar or mars surface power may rely on DC, AC, or hybrid AC-DC transmission and distribution, it is critical that solutions for fault management techniques in each of these arenas be developed for potential applications to prove feasibility and provide realistic performance metrics. Proven solutions for small scale power distribution space applications may not necessarily translate to the future diversity of loads, generation sources, and long distances required on lunar or planetary bases. Although there is no equivalent to a lunar or planetary base on earth, earth-based AC power transmission and distribution may be the source of protection engineering methodologies most directly applicable to NASA base deployment.

The development of reliable fault detection technology for inverter-based AC power systems has many advantages to NASA. First, such development would enable future space applications to leverage existing terrestrial products and AC system advantages for power transmission and delivery while accommodating NASA's current approach for power generation and energy storage. Additionally, development of the proposed product would improve upon the reliability and interoperability of mixed-generation source grids by being backwards-compatible with both mixed grids and inverter-based grids. This allows for improved protection reliability in cases where the generation portfolios are primarily comprised of synchronous generator sources, as well as cases where generation is primarily inverter-based, and a diverse combination of generation percentages in between. Hence, the protection system continues to function at a high level for a wide array of dynamic conditions, greatly improving the overall reliability and interoperability.

EXISTING RESEARCH

The primary problem being addressed in this paper is the need to reliably detect and isolate faults for cases of inverter-based generators in AC power grids. The reason this problem is unique and differs from the past 100+ year history of power grid protection is that the inclusion of inverter-based solar, battery, and wind systems results in an output of current during fault conditions that is substantially lower than what is seen in traditional generation portfolios. This is because inverter generation sources often do not see inertia to carry fault current based on electromagnetic characteristics resulting in a quickly decaying time envelope due to the lack of inductive characteristics.

Studies by the National Renewable Energy Laboratory have demonstrated low penetration of IBR DERs to contribute ~1-2 times rated continuous current for <1 cycle; high penetration contributes ~2-4 times rated continuous current for 0.06-0.25 cycles.**Error! Bookmark not defined.** This is significantly lower than the 4-10 times rated continuous current typically seen in traditional, synchronous generator systems.

The predominant method of fault isolation is using overcurrent devices that rely on the mix of generation sources resulting in sufficiently high contribution from synchronous machines to overcome the limitations of inverter-based fault currents. According to NREL's 2010 report, "currently, inverter-based DER provides insignificant or minimal contribution to the power balance on most utility distribution systems. A significant increase in DER is expected to come online in the near future. As the penetration level of DER increases, the effect of DER may no longer be considered minimal. The electrical equipment ratings, capability, and coordination of the protection systems will merit a closer investigation…."**Error! Bookmark not defined.**

There are no commercially available products that can reliably detect faults in inverter-based power grids. This is confirmed in IEEE PES Power and Energy Magazine's May/June 2021 issue, which identified relevant research associated with microgrid protection for applications of inverter-based sources.[11] Proposed methods to solve the problem of unreliable fault detection for microgrids included increasing fault current, using direct overcurrent techniques and distance relays, implementing differential protection, using traveling wave techniques and goose or other advanced communication, implementing adaptive relaying, or using machine learning. Researchers included the following:

- Dimitris Lagos, Vasileios Papaspiliotopoulos, George Korres, and Nikos Hatziargyriou via the National Technical University of Athens (Athens, Greece), as reported in Digital Object ID 10.1109/MPE.2021.3057950
- Matthew J. Reno, Sukumar Brahma, Ali Bidram, and Michael E. Ropp via Sandia National Laboratories, Clemson University, and University of New Mexico, as reported in Digital Object ID 10.1109/MPE.2021.3057951
- Scott Manson and Ed McCullough via Schweitzer Engineering Laboratories and Tesla Energy, as reported in Digital Object ID 10.1109/MPE.2021.3057953

Three of the four research groups cited voltage-based detection as a potential solution with the technical challenge of specific fault location. The researchers agreed that voltage techniques could reliably detect faults, but not adequately identify the fault location for isolation. No researchers identified the inclusion of timers as part of the method.

Aside from voltage-based detection, all other methods or combination of methods identified by the researchers as potential, promising solutions require communications infrastructure to implement or highly complex evaluation of each configuration of sources and loads, which is not easily scalable as sources or loads change over time and represents high cost to electric utilities. For example, machine learning in combination with adaptive relay settings was identified as a potentially promising solution; however, the implementation of machine learning requires the simulation of faults at all possible points within a microgrid configuration, automating all different types of elements, observing fault current levels, and creating a statistical map of all different situations. Based on this map, researchers would identify the most frequent states of the system and analyze what relay settings were most likely to be the most practical in most or extreme conditions. When new feeders, loads, or generators are added to a system like this, the complex analysis must be performed anew, which is not a feasible implementation for most distribution companies with standard industry resources. The reliance on studies and expensive hardware therefore limit scalability. Additionally, whether these machine learning systems rely on overcurrent protection or undervoltage protection to initially detect the faults, they would require costly communication infrastructure to maximize reliability, as no local, communications-free systems have yet been identified as solutions.

FUTURE DEVELOPMENT

Engineering consulting company Commonwealth Associates, Inc. has filed for a patent to protect the undervoltage, decentralized timer-based method of IBR fault detection described in this paper on 09/15/2020 via application number 17/011,538 (Figure 7). The application is still under review, with finalization expected in 2022. The company is poised to begin hardware-in-the-loop testing on existing relay technology within the next 1-2 years, with custom-built prototype manufacturing and small-scale deployment to commence shortly thereafter. Discussions with established medium voltage power equipment manufacturer partners is in progress.

One technical question that must be answered in product development is the coordination of timers among a set of deployed devices for complex loads. Developing an accurate philosophy for setting product timers to accurately reflect a PV inverter's ability to ride through transients must be developed through inverter control system modeling, given the low penetration of inverter-based microgrids currently in the US. Although the theory behind local undervoltage detection is well known, specific parameters of timer interaction have not yet been determined for complex power configurations. The data resulting from testing various timing considerations would directly inform future prototype considerations for the minimum viable number of devices required per grid segment for timely fault isolation.

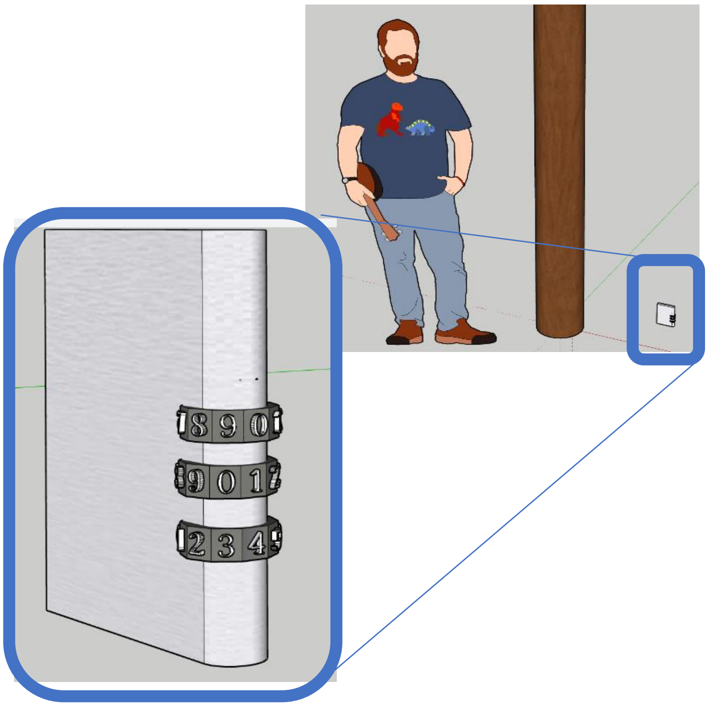

Figure 7: Artist's Rendering of Voltage Based Device with Timers

Another technical question is determining the optimal number of downstream fuses that could be paired with undervoltage, decentralized time domain isolation devices for effective and timely fault clearing. Although a "worst case" (most costly) scenario would likely involve a one-to-one pairing of lateral fuses with fault isolation devices or one-to-one pairing of reclosers with undervoltage, decentralized time domain algorithms, it may be possible to effectively isolate all islanded IBR microgrid faults with less frequent deployment across a given power system.

An additional question to answer is how much the aspect of relatively low fault current in islanded IBR grid faults would impact the future design of medium voltage switches, to aid in a reduction of fabrication costs compared to existing state-of-the-art protection systems for synchronous-machine-based microgrids. The undervoltage, decentralized time domain solution could be deployed by implementing this methodology across existing reclosers, or else deployed in their own power equipment housing as standalone devices accompanied by fusing. If used as standalone devices, there may be an opportunity for a reduction of fabrication cost and device power demand, if able to function with weaker dielectrics and weaker motors, compared to standard recloser technology. In theory, the lower fault current values could allow for less strong, cheaper dielectric materials. However, neither this nor the relative level of mechanical force required to extinguish arcs in these scenarios has yet been evaluated.

CONCLUSION

Microgrids are likely to be an important part of a more resilient power in the world. This future change will be mostly true if cost-effective methods of fault protection and isolation are available. While the likely high content of IBRs resource mix will challenge current protection philosophies, there are alternatives that while promising, are expected to come at a premium cost. The undervoltage, local timer protection method is there to offer a scalable cost-effective solution to enable a future where microgrids add to power system resiliency.

BIBLIOGRAPHY

[1] *Electricity Explained: Electricity Generation, Capacity, and Sales in the United States.* US Energy Information Administration, 18 Mar. 2021. Last Accessed Mar. 2022. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php

[2] *Department of Energy Releases New Tool Tracking Microgrid Installations in the United States.* Office of Energy Efficiency and Renewable Energy, US Department of Energy. Last Accessed Mar. 2022.

[3] *Solar Energy in the United States,* DOE Solar Energy Technologies Office, Last Accessed Jan 2022. *https://www.energy.gov/eere/solar/solar-energy-united-states*

[4] Shields, Laura. *Greenhouse Gas Emissions Reduction Targets and Market-Based Policies,* National Conference of State Legislatures, 11 Mar. 2021, www.ncsl.org/research/energy/greenhouse-gas-emissions-reduction-targets-and-market-based-policies.aspx.

[5] Keller, J. and B. Kroposki. *Understanding Fault Characteristics of Inverter-Based Distributed Energy Resources,* Technical Report NREL/TP-550-46698, January 2010. https://www.nrel.gov/docs/fy10osti/46698.pdf

[6] Fernandez Campbell, Alexia. “It Took 11 Months To Restore Power to Puerto Rico After Hurricane Maria. A Similar Crisis Could Happen Again.” Vox. 15 August 2018. https://www.vox.com/identities/2018/8/15/17692414/puerto-rico-power-electricity-restored-hurricane-maria

[7] “Puerto Rico Power Fully Restored 18 Months After Hurricane Maria Wiped Out the Grid,” The Weather Channel, 21 March 2019. https://weather.com/news/news/2019-03-21-puerto-rico-power-restored-hurricane-maria

[8] Proctor, Darrell. “Businesses Using Microgrids to Ensure Power in Puerto Rico.” Power Magazine, 1 December 2021. https://www.powermag.com/businesses-using-microgrids-to-ensure-power-in-puerto-rico/

[9] Bade, Gavin. “Puerto Rico Governor Signs 100% Renewable Energy Mandate.” Utility Dive. 12 April 2019. https://www.utilitydive.com/news/puerto-rico-governor-signs-100-renewable-energy-mandate/552614/

[10] Wood, Elisa. “Navy Becomes Latest Military Branch to Set a Microgrid Goal as Part of Climate Strategy,” Microgrid Knowledge. 27 May 2022. https://microgridknowledge.com/navy-microgrids-climate-strategy

[11] “Microgrid Protection: Reflexes of the Central Nervous System for Power,” *Power and Energy Magazine*, Volume 19, Number 3: May/June 2021. *https://magazine.ieee-pes.org/*