Power Line Carrier Permissive as a Simple and Safe Method of Enabling Inverter Ride-Through Operation of Distributed Grid-Tied Photovoltaic Systems

R. Reedy[*], K. Davis[*], D. Click[*], M. Ropp[†] , and A. Shaffer[‡]
[*]Florida Solar Energy Center, Cocoa, FL, U.S.
[†]Northern Plains Power Technologies, Brookings, SD, U.S.
[‡]Lakeland Electric, Lakeland, FL, U.S.

Abstract— **Conventional anti-islanding techniques used in grid-tied photovoltaic (PV) systems pose many disadvantages at high levels of PV deployment. One such issue is the inability of these systems to ride-through grid disturbances. In this paper, the use of a Power Line Carrier Communications (PLCC) Permissive anti-islanding scheme is investigated as a means of safely enabling ride-through operation of grid-tied photovoltaic systems. Here potential fault scenarios are considered, along with performance, cost, and design considerations for the PLCC Permissive components, as well as potential system configurations and methods of implementation. While PV systems are the largest (and growing) form of distributed generation (DG) generating in parallel with utility feeders, it is important to note that this technique is effective for any DG technology, whether inverter-based or rotating, including wind, hydro and fossil fueled bio-gas machines.**

Keywords-photovoltaic; distributed generation; grid-tied; anti-islanding; ride-through

I. INTRODUCTION

Photovoltaic (PV) systems directly convert incident sunlight into usable electric power. The basic energy flow of a grid-tied PV system begins with the generation of DC electricity by an array of PV modules. This array is coupled with an inverter that performs many important functions including (a) providing maximum power point tracking of the array to ensure the most energy possible is harvested by the system, (b) converting DC electricity to AC, and (c) acting as the interface between the utility grid and the system, which includes synchronizing the power output and shutting off production during a potential islanding situation.

Islanding of a PV system, or other form of distributed generation (DG), refers to a situation in which a grid-tied inverter (or inverters) continues to energize a region of the utility grid that is isolated from the rest of the network. While islanding is intended in some circumstances, such as implementation of a micro-grid during peak load periods, or to preserve service to a critical load during fault conditions, it is the unintended island we address in this paper. Island conditions for grid-tied PV may result from: opening of utility disconnect devices due to faults; utility switching; intentional service disconnection; or accidental disconnection due to equipment failure, human error, or an act of nature. Islanding has severe consequences involving safety, potential damage to equipment, liability, and power quality of the electric network to which the island is connected.

The safety issues that arise from unintended islanding of distributed generation sources are driven by concern for the extremely dangerous "down-wire" scenario created when a high voltage overhead line falls on the ground, within reach of the public. Utilities go to great lengths to detect and de-energize these fallen conductors at the source of the radial feed, such as the substation, or the first upstream protection device, such as a fuse or line recloser. Given their public trust as operators of the distribution system, utilities simply cannot allow any dangerous backfeed from DG systems downstream from the downed wire.

Another safety problem with DG backfeed impacts the utility lineworkers who perform line maintenance. Though line work practices require the workers to always "consider it hot" by procedures which protect them even if there is backfeed, no utility can allow the potential for DG backfeed during switching and line maintenance work.

This demonstrates the utility need for a special form of control, namely the strong preference (or absolute requirement in many cases) for an effective means to instruct all DG on a given feeder to disconnect and remain offline during live-line switching procedures, such as paralleling and reconfiguring feeds, which can sometimes take 15 to 30 minutes. While large DG systems typically have control and metering infrastructure that the utility could access, given proper contractual and regulatory accommodation, the ever-growing number of small rooftop PV systems without any telcomm capabilities will become problematic in this regard. The Power Line Carrier Communications (PLCC) system proposed here for anti-island protection can provide this important functionality at no incremental cost or complexity.

Beyond the safety priority, DG presents a major operational problem for utilities when the distribution feeder is disconnected by a circuit breaker and then "reclosed" in a few seconds as part of the fault-clearing coordination scheme involving downstream fuses and other devices. When the fault protection systems initiate a reclosing cycle, all DG (even single phase PV units connected to a non-faulted phase of the feeder) should disconnect as quickly as possible (less than a second) and remain offline without attempting re-synchronization until the fault-clearing process is completed and the feeder has stabilized in its non-faulted final configuration. At no additional cost or complexity, this proposed PLCC-based anti-island system also provides a mechanism for the required hold-off during reclosing events.

II. ANTI-ISLANDING METHODS

Previous studies have investigated the various islanding detection schemes [1-3]. These techniques are commonly classified as either passive or active techniques, both local to the inverter, or alternatively, techniques using communications between the utility and the inverter. Passive anti-islanding

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involves monitoring grid parameters locally (e.g. voltage, frequency) and then shutting off the inverter when those parameters exceed a predefined safe window of operation. Active techniques interact directly with the utility grid by introducing a small perturbation and observing the response. If the response falls outside of the appropriate threshold, then the inverter will cease to produce power. PLCC Permissive anti-islanding falls into the third category, which relies on communications between the utility and the inverter. Other examples of island detection requiring utility-to-inverter communications include: transfer-trip, direct SCADA communications, and synchrophasors.

The non-detection zone (NDZ) criteria is a commonly used method of evaluating the effectiveness of an anti-islanding technique. The NDZ refers to the range of local loads that the island detection method cannot detect. It is typical practice to model the on-site load as a parallel *RLC* circuit, as many of the local island detection methods have the most problems detecting this type of load, particularly high Q-factor circuits [1]. Island detection can especially be a problem when load matches generation.

It has been suggested that as long as the PLCC signal has the properties described in Section IV of this paper, then PLCC Permissive-based islanding detection should not have an NDZ. Fig. 1 shows a basic setup of a grid-tied PV system employing a PLCC Permissive based anti-islanding scheme. The Power Line Carrier (PLC) signal provides a direct continuity check of each phase from the transmitter, presumably located at a substation, to receivers located on that section of grid in which that substation feeds. In the preferred configuration, the PLC frequency is unique for each phase, mitigating most of the cross-talk potential along a long feeder. When everything is operating properly, the receiver continues to receive the carrier signal and in turn reports this to the inverter. If continuity is lost between the transmitter and receiver, the receiver will detect this potential island situation and alert the inverter to take the necessary steps (i.e. shut down, or switch to micro-grid operation).

In Figure 1, the receivers (PLC detectors) are shown as a separate device, but could be economically and reliably integrated into the inverter.

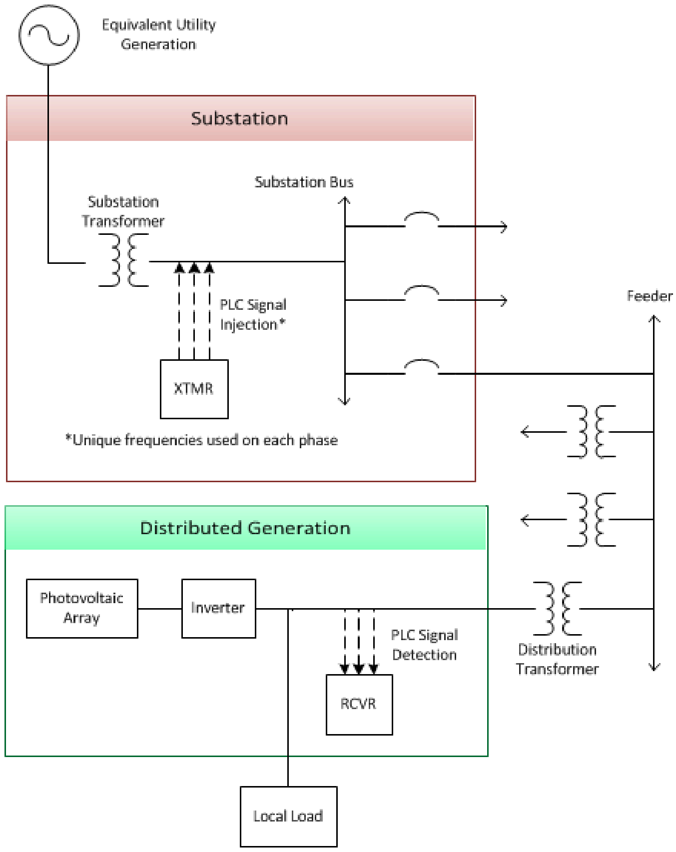

Figure 1. One-line diagram of a grid-tied PV system using PLCC Permissive anti-islanding in a radial electric power network

III. ADVANTAGES OF PLCC PERMISSIVE ANTI-ISLANDING

For many of the local island detection techniques (passive and active), successful implementation is often strongly dependent on the local load conditions, as well the number of inverters installed within the island, the mix of DG on the feeder, and the power output of those resources as compared to the load in the potential island.

Another disadvantage of many local island prevention techniques is that they require the inverter to shut down and stop production during even minor voltage and frequency disturbances. This means that the grid loses point-of-load generation resources during low voltage or deficit generation situations when those resources are needed the most. As penetration levels of PV climb towards 20%, such a sensitive trip level is untenable. PLCC Permissive anti-islanding provides a fail-safe means of enabling ride-through for grid-tied inverters.

The only method of fully eliminating any NDZ is to use non-local anti-islanding methods [1]. Some examples of island detection requiring utility-to-inverter communications include: signal produced by disconnect, direct transfer-trip by fail-safe SCADA communications, synchrophasors, and as proposed here, PLCC Permissive.

The minimum requirements for anti-island protection should be re-stated for clarity:

1] a system which operates with essentially no NDZ . This particularly includes the very challenging scenario of a single phase down-wire event (the most common down-wire event) being fed by three-phase PV inverters.

2] a system which “fails safe”, in that any component glitch will return the inverter to a safe operating mode (including transfer to a local micro-grid) or shut down.

Likewise, the preferred attributes of a system include the ability of the utility to force the DG offline in an emergency or urgent situation, and prevent DG from attempting to re-synchronize until a post-fault reclosing sequence is complete; and the ability to reliably detect islanding while still facilitating grid-support functions.

The proposed PLCC Permissive system addresses these requirements and preferences in a very simple and effective way. Past review papers [1,4] have suggested that the only real limitations of the PLCC anti-islanding method are cost-related. However, it has already been shown [5] that PLCC Permissive receivers can be made very inexpensive, and there exist many potential possibilities to address transmitter cost concerns through a better understanding of the performance requirements (which are less stringent than many other PLC-based technologies) and intelligently designing simplified components that are much cheaper, but still meet the minimum requirements needed for effective operation. Coincidentally, the economics of this approach improve significantly at higher levels of deployment (through amortization of transmitter cost), which is where ride-through and additional utility control is much more valuable. We note the detectors for each phase signal can be extremely low cost (in volume), since they face the simplest of all communication challenges—detection of presence or absence of a signal above some low threshold, which also means that PLCC bandwidth constraints are not a barrier in this application. The detectors could be built as stand-alone receivers, or included as on-board electronics by the inverter manufacturer.

IV. System Configurations for PLCC Permissive Anti-Islanding

Before considering potential system configurations, the following list includes some of the important requirements for an effective PLCC Permissive anti-islanding scheme, some of which can be found in further depth in [5]:

1. The carrier should operate continuously and have low energy consumption.
2. The carrier should propagate through the network with limited attenuation.
3. Three unique frequencies should be utilized for each phase of the three-phase power system, so that single phase events can be detected.
4. The carrier should be non-reproducible locally.
5. There should be an acceptable signal to noise ratio.
6. To ensure limited impact on energy yield, an appropriate anti-islanding fall-back scheme should be in place. This important area will be considered in the next section.
7. Both the transmitter and receivers must perform reliably for long periods of time with minimal maintenance.
8. While transmitter cost can be amortized over the many distributed resources installed on that local utility network, receiver cost must be very low to ensure there is limited increase in the levelized cost of energy (LCOE) for the PV system.

Two methods of implementing the PLCC Permissive anti-islanding scheme are considered. The first involves the use of a dedicated, low cost PLC transmitter, while the second involves piggybacking the PLC signal using commercially available automated meter reading equipment, an idea investigated in previous studies [5]. While both of these configurations rely on proven technology and no significant technological advances are required, proper design and optimization of all of the potential system configurations is still necessary to ensure economic competitiveness and high performance.

While there are obvious advantages to the latter approach (further amortization of transmitter cost), there are also reasons for considering a separate, dedicated PLC transmitter installed on each phase of the substation bus with dedicated detector/receivers installed at each inverter operating within that region. The “effective” bandwidth requirement for detection of the PLC Permissive is the lowest possible. Signal presence detection will accommodate very poor signal-to-noise ratios, allowing for effective deployment on very long feeders and reliably communicating feeder line continuity status where data communications and control cannot pass reliably by PLCC systems. This raises the observation that an effective low cost system may best be designed around dedicated transmitters and detectors that are simple yet robust and reliable.

V. Anti-Islanding Transition Sequence

When considering implementation of a PLCC anti-islanding scheme, some potential concerns arise from the perspective of the PV system owner. For instance, consider when the PLC receiver doesn’t detect the Permissive for a reason not related to a feeder fault. This could occur when a PLCC transmitter is down for maintenance or if the PV system is installed on a feeder lacking the PLCC Permissive infrastructure. Additionally, at the extremes of long feeders, even a simple carrier signal may be attenuated below the detection threshold.

These concerns create a need for automatic transition to a conventional anti-islanding mode of operation upon loss of carrier. This feature would allow the utility to have the value of ride-through for a vast majority of PV generation on their system, but still gives system owners full energy production value (though limited functionality from the utility perspective) in those cases where the PLC signal isn’t detected due to a non-fault related condition.

Fig. 2 shows a proposed transition sequence between a fully functional, ride-through enabled mode of operation that is made possible through PLCC Permissive anti-islanding, and a limited functionality mode of operation using traditional anti-islanding methods.

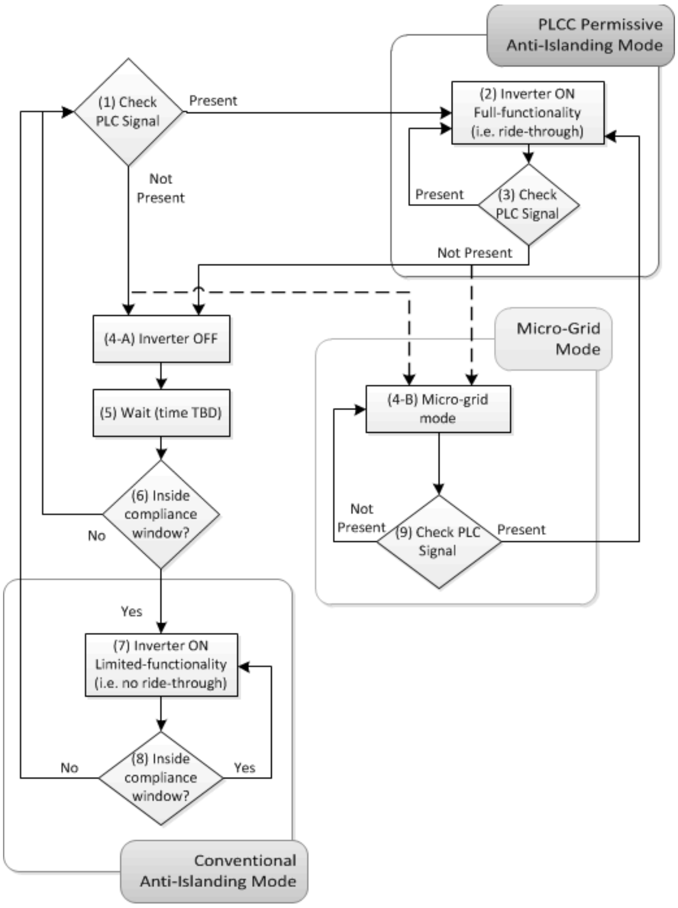

Figure 2. Anti-islanding transition sequence

Included here is a description of each of the numbered steps included in the flowchart (Fig. 2).

1. Check PLC signal
2. Inverter on with full-functionality (i.e. ride-through enabled)
3. Monitor PLC signal for acceptable threshold
4. (A) Inverter off ***OR*** (B) switch to micro-grid
5. Wait a time To Be Determined (but likely to be 15 minutes or so) for completion of fault clearing sequences, utility switching actions, etc.
6. After the prescribed wait time, check if grid is within the anti-islanding compliance window
7. Inverter on with limited functionality (i.e. no ride-through and conventional active anti-islanding)
8. Compare 3φ voltage and frequency to the anti-islanding compliance window
9. Periodically check (time TBD) for PLC signal above threshold to initiate return to fully functional mode

A slight modification of this sequence could provide the utility with the preferred control capability to force the DG to remain offline, such as might occur during a feeder overload or other emergency, or to reduce transients and inverter cycling during line switching procedures.

This can be accomplished simply by including a logic step during the Wait Time. This step would recognize a unique set of PLC "pulses" as a Hard Shut Down Command, and block the return of the PV Inverter to the grid until a valid and continued PLC Permissive is again received. The utility control system could begin this sequence by shutting off the PLC transmitters in the substation, waiting a short time, then "bumping" the transmitters with the unique sequence.

VI. Conclusions

PLCC technologies are proposed for safe, simple and effective solution of one of the most vexing problems presented to utility operators by high penetrations of DG: how to keep the ever-growing generation resource online during system disturbances, with concurrent absolute certainty that a dangerous unintentional island does not present a backfeed hazard, and do so for any penetration level or combination of DG.

Future Work

Future work will include a validation of the design concepts on the distribution system of Lakeland (Florida, USA) Electric, using off-the-shelf components from a supplier of PLCC metering and control equipment. Results from the validation should lead to improved design, in terms of cost, performance, and energy requirements for the PLCC receiver and continuous carrier transmitter, as well as detailed simulation of carrier propagation in a number of different environments and scenarios.

Acknowledgment

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