THE FUTURE ROLE OF PASSIVE METHODS FOR DETECTING UNINTENTIONAL ISLAND FORMATION

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ABSTRACT

AS increasing numbers of distributed generators (DGs) are deployed, utilities are becoming more concerned that these DGs may be able to support unintentional islands. Unintentional islands can be formed when any utility switching device isolates a portion of the area electric power system (EPS) that contains roughly equal amounts of sources and loads, and they potentially pose safety risks to personnel and integrity risks to customer equipment.
Methods to detect the formation of unintentional islands can be subdivided into passive, active, and communications-based categories. Most DGs today rely on active methods, but unfortunately the time is soon coming when this approach will no longer work. The reason is because of the need for DGs to supply grid support functions as DGs, and these grid support functions interfere with the operation of active island detection. This means that in the future there will be a much larger role for passive and communications-based island detection methods.

This paper will briefly explain the fundamentals of the island formation problem; discuss why grid support may spell the end for active anti-islanding; lay out the options for passive and communications-based island detection, with a brief strengths-and-weaknesses comparison for both categories; and delve into the challenges, strengths, and opportunities in passive island detection. A new, promising passive method will also be presented and used to highlight the challenges of passive island detection.

The work being reported in this paper was supported by an RDF grant from Xcel Energy.

I. NOMENCLATURE

DER	Distributed Energy Resource
DTT	Direct Transfer Trip
NDZ	Non-Detection Zone
PCC	Point of Common Coupling
PLCC	Power Line Carrier Communications
PLCP	Power Line Carrier Permissive
PLL	Phase-Locked Loop
RoCoF	Rate of Change of Frequency (df/dt)
SCADA	Supervisory Control And Data Acquisition

II. INTRODUCTION

ISLANDING occurs when a section of the power system including generation and loads (and potentially storage) becomes electrically isolated from the main grid and enters a “stand alone”, or microgrid, mode of operation. Generally, unintentional islanding supported by distributed energy resources (DERs) outside of utility control is undesirable for several reasons, including its potential to cause damage to customer, system or DER equipment, and the potential for safety hazards.

Applicable codes and standards, such as IEEE 1547™, require that DERs include means to prevent unintentional islanding [1]. Over the years, industry has responded to this requirement with a wide variety of methods to achieve this [2-4]. Broadly, the methods are subdivided into three categories: passive methods, which rely on changes in DER terminal measurements to detect island formation; active methods, in which the DER perturbs its output current in some way that creates a visible change upon island formation; and communications-based methods, in which system status information is communicated to the DER and used to detect an island. Passive methods are attractive because of their lack of impact on the system and ease of implementation, but they generally encounter difficulty in eliminating nondetection zones (NDZs) without false trips—in other words, they struggle to achieve both *sensitivity* and *selectivity* within the IEEE 1547-mandated trip times. Today’s active methods are cost-effective and have extremely small NDZs in low-penetration cases, but they are increasingly seen as unsuited for high-penetration situations. Reasons include that there is mounting evidence, including some from the field, that they may fail in certain cases with multiple DERs [5,6], and they can also cause power quality problems, but the key problems with active island detection today are that a) they tend to conflict with the grid-support functions that are becoming critically important as DER penetration levels rise; and b) they may degrade system transient response at high penetration levels.

Communications-based methods are likely the best future candidates to be the first line of defense in unintentional island prevention. These include synchrophasor-based methods [5-7], power line carrier communications (PLCC) or power line carrier permissive (PLCP) [8-10], SCADA integration [3,11], and direct transfer trip (DTT). In general, it is well accepted that the NDZs of these methods can be extremely small, although their island detection and cost effectiveness are still under investigation. One aspect of communications-based methods that must be dealt with is communications reliability—specifically, that DER functionality should be compromised as little as possible if communications are lost, and thus there needs to be a “fallback” island detection method in the case of loss of communications. This paper discusses the reasons why passive island detection is likely to be the ultimate selection as the fallback method, and describes some candidate passive methods that have high promise for this application.

It is instructive to note that for some communications-based methods, the meaning of “fallback technique” is different. For example, for PLCP, a fallback technique upon loss of signal cannot be used, because loss of signal is the indication that an island has been formed. Instead, “fallback” in this case means that there must be an island detection method available in cases in which there is no PLCP transmitter installed.

III. PASSIVE ANTI-ISLANDING AS THE SOLUTION

The selection of fallback method involves a tradeoff between island detection effectiveness and compatibility with high penetration. There will need to be considerable discussion among the power systems community to decide how this tradeoff is best handled, especially bearing in mind that what is being discussed is the *second* line of defense, not the primary.

In the near term, it is likely that most manufacturers would use their current anti-islanding scheme as the fallback, meaning that most inverters would revert to active anti-islanding. However, as previously noted, in the long term this strategy is probably unacceptable because of the lack of compatibility with grid support functions—grid support relies on DERs working to mitigate abnormal voltages, while active anti-islanding relies on exacerbating abnormal voltages. Using active anti-islanding as the fallback would cause DER grid support to become intermittent, which is likely not acceptable to system operators.

Passive island detection is the only remaining candidate. It does not adversely impact power quality or system transient response, and it can be made to be compatible with most grid support functions by appropriately modifying the run/trip decision criteria. However, even the best passive island detection methods are less effective in detecting islands than active methods. The following two issues are of particular concern:

1. It seems unlikely that any passive anti-islanding method could reliably pass an IEEE 1547-style RLC load anti-islanding test in which a 2-sec maximum time to trip is mandated. In a highly controlled laboratory environment and with an RLC load with a quality factor of 1, it is possible to match the generation and load real and reactive power so precisely that when the island is formed there simply is no detectable change in the PCC or inverter terminal voltage, and no passive criterion would see the island formation for a considerable period of time—in other words, there is a problem with detection *speed*.
2. It is difficult to ensure that a passive island detection method can reliably detect islands while maintaining a high degree of false trip immunity. Essentially, for any parameter that a passive island detection method may detect, if one visualizes a Venn diagram, there will be overlap between the set of values during which it is desired that the DER stay on-line, and the set of values indicating island formation. Using terms from the sensors field, this can be thought of as an issue of *sensitivity* vs. *selectivity*.

In summary, the passive island detection problems deal with *speed*, *sensitivity*, and *selectivity*. Concern #1 can be more readily understood using a schematic of the IEEE 1547 anti-islanding test setup, which is shown in Figure 1. The utility voltage source and its source impedance are at the left, and the Device Under Test (DUT), which may be any type of DER, is at the far right. In between is an R-L-C load and an interrupter of some type, shown here as a switch. To perform the test, the load resistance R_{load} is varied until the load's real power consumption precisely matches the output of the DUT, and then L_{load} and C_{load} are adjusted until the load quality factor is 1.0, and the load's reactive power consumption is equal to and opposite of that of the DUT. When this condition is reached, the current i_{grid} is essentially zero, and when the switch is opened to form the island, the switch is not interrupting anything. It is not difficult to see how this condition, if sufficiently well matched, could create a situation in which the voltage V_{load} does not change enough that any passive method would see the difference between grid-tied and islanded conditions.

Concern #2 was highlighted in a recent paper by Joós et. al. [12] that involved study of a composite passive island detection method utilizing a mixture of sixteen different parameters and a decision tree to determine when the system was islanded or grid-tied. The idea was to choose parameters such that the NDZ of any one parameter was covered by another, such that the composite method would have no NDZ. Although these investigators had an impressive success rate, it was not 100%; even with such a large set of parameters and a sophisticated set of decision criteria, they were not able to detect all islands without false trips—they achieved very good selectivity, but insufficient sensitivity. This paper also points out the important fact that in most *practical* cases, a passive island detection method like the one in [12] that uses a combination of techniques is likely to be able to detect the overwhelming majority of cases that would appear in the real world. Whether this is sufficient revolves around the question of the level of risk utilities are comfortable with, given that this is the *second* line of defense against unintentional islands.

In considering what level of tradeoff is acceptable, it should be remembered that grid support functions will be needed much more frequently than island detection. Thus, a tradeoff that improves DER grid support capability while mildly compromising island detection effectiveness is likely to be logical from operational and risk standpoints, as long as the compromise in island detection effectiveness is not too great.

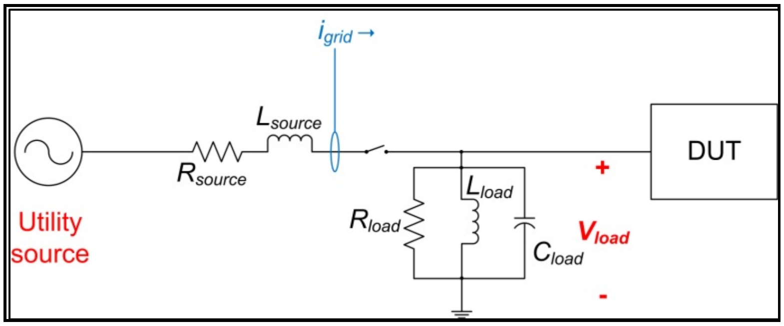

Figure 1. Schematic showing the configuration of the IEEE 1547 anti-islanding test.

However, the tradeoff between *selectivity* and *sensitivity* can be more favorably modified if *speed* is also considered. If one could allow a longer period of time to detect an island, then some passive anti-islanding methods may be able to achieve the needed selectivity and sensitivity. Currently IEEE 1547 mandates that no run-on of longer than 2 sec be permitted, but this may not be necessary if the standard were to allow decoupling of island detection, fault detection, and overvoltage detection. The IEEE 1547 anti-islanding test is designed to mimic a case in which a circuit interrupter opens *without a fault* while the DER output and local loads are closely matched. This case is difficult to detect because the change in the PCC or inverter terminal voltage can be undetectably small, as noted above. However, in a faulted case, there is no generation-load balance, and there are a number of means other than anti-islanding by which the fault may be detected. Because the detection criteria are so different, it is logical to separate fault detection from islanding detection. Fault detection must be quite fast (ideally, faster than the shortest reclosing interval), but there is no need to detect a balanced, unfaulted island so quickly. Thus, the island detection scheme could be given longer than 2 sec to detect a balanced, unfaulted island, so long as there was also fault detection that was reliable and acted much more quickly. Similar logic applies to transient overvoltage detection and prevention. Relaxation of the speed with which an island must be detected would provide a pathway for passive methods to improve sensitivity and selectivity simultaneously.

Also, a similar argument can be made for faults as was made for grid support functions in that faults are an unfortunately frequent occurrence, but balanced DER-load unintentional islands are relatively rare. Thus, a compromise that improves fault detection at the expense of island detection would likely be acceptable from operational and risk standpoints, as long as island detection is not compromised excessively.

One other critical issue with DERs is the problem of asynchronous reclosure, which can lead to severe damage to rotating machines (generators or loads) inside the island. However, asynchronous reclosure is associated with recloser action in the clearing of faults. The risk of asynchronous reclosure can be effectively mitigated by fault detection (if fault and island detection were decoupled) or "hot line blocking" or "dead bus detection" in which the voltage on the downstream side of the recloser is measured and reclosure is blocked if that voltage is too high. Fault detection mitigates asynchronous reclosure because of its speed (often the DER will trip offline before the recloser opens) and hot line blocking could be used if the reclosing interval is extremely short such that fault detection may not be quick enough. Hot line blocking is not prohibitively expensive in most cases; the largest expense is in the required PTs. Again the ramification is that the DERs could be allowed longer than 2 sec to detect a balanced, unfaulted unintentional island, without a risk of asynchronous reclosure, at the cost of a slight decrease in quality of service because of the longer effective recloser interval.

When all of these factors are taken together, it seems clear that a) passive anti-islanding is the preferred backup method to communications-based techniques; b) the performance compromise involved in passive methods may be tolerable, and that there are avenues for improving it; and c) decoupling island detection, fault detection and overvoltage detection would be highly beneficial.

IV. CANDIDATE PASSIVE METHODS

A. Total harmonic distortion-based methods

These methods were pioneered in Japan in the early 1990s [13] and new developments continue to appear periodically [14]. They in essence involve an interaction between harmonic-producing loads and system elements in the island, and the harmonic impedance of the feeder. The idea is that a sudden jump in total harmonic distortion, or in certain harmonics known to be related to certain loads or the inverter, could be used to detect the isolation of the island. Under certain circumstances, this method works reasonably well, but it has two drawbacks. One is intuitive: the level of nonlinear load in the system today has led to a condition in which voltage distortion, while grid-tied, occasionally becomes quite high, making it nearly impossible to select a THD threshold that achieves both selectivity and sensitivity. The other can be understood by considering the generic feeder shown in Figure 2. In this generic feeder, a utility source is shown at the left, along with its source impedance and the substation transformer. Loads are shown as generic load blocks, and two PV systems are shown in green, along with their distribution transformers (shown as Δ-Y in the figure because that is the most common configuration).

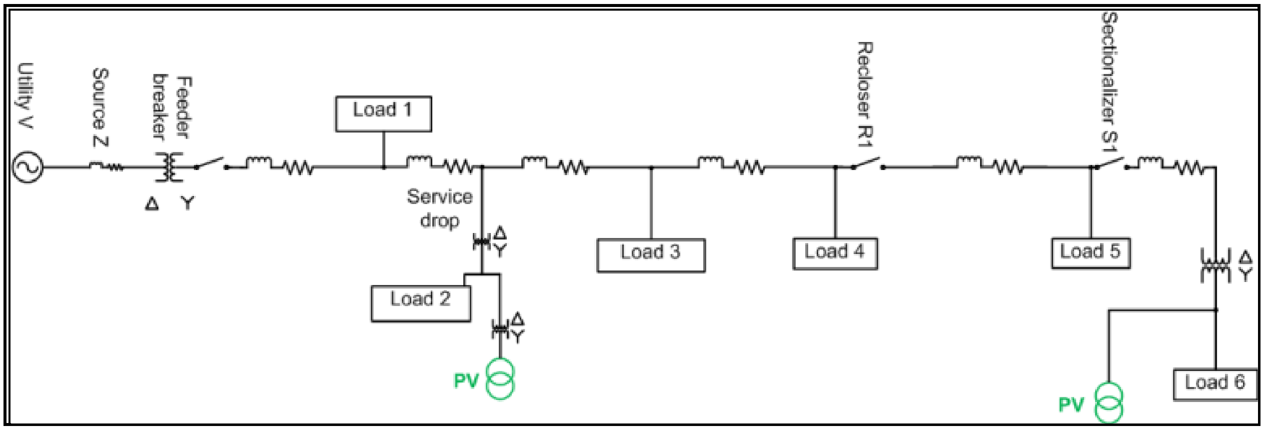

Figure 2. Generalized model of a distribution feeder.

This generic feeder also includes a downstream recloser R1, and a sectionalizing switch S1. It is clear that if the recloser R1 or sectionalizer S1 is opened to isolate the PV system at the far right of the figure, one would expect a dramatic change in the harmonic impedance of the system as seen from the PV. However, if the feeder breaker (at the far left) were the switch that opened to form the island, the harmonic impedance of the substation transformer is already quite high, and one cannot reliably say that opening that breaker would significantly change the harmonic impedances as seen from the PV systems. THD-based methods may become unreliable in a system like this.

B. Deliberate injection of a current harmonic and detection of the corresponding voltage harmonic

Technically, this is an active method because it involves changing the inverter output, but it is included here because it is an obvious extension of the THD-based methods. Note that this method has also been applied to a specific harmonic deliberately injected by the inverter, as a measurement of the harmonic impedance of the feeder at that specific frequency. However, this method has largely fallen into disuse because of its impact on power quality and its reduction in effectiveness in the multiple inverter case. Also, while the deliberately-injected harmonic method can generally achieve good sensitivity in single-inverter cases, it struggles to obtain selectivity on weak grids.

C. Methods based on frequency spectra

Recent activity in the area of passive island detection has largely focused on the use of advanced frequency transforms to attempt to discern when an island forms. Several investigators have published impressive results in this area [15-18]. Wavelet transforms have received special attention because of their potential ability to resolve transient phenomena without excessive window lengths. Methods based on frequency spectra appear to have high promise to improve both selectivity and sensitivity. However, one must still make a tradeoff and either favor selectivity or sensitivity, and many of these methods are highly computationally burdensome and thus difficult or expensive to implement.

D. Methods based on statistical analysis of frequency, and a new proposed method

These methods have been explored primarily in conjunction with deliberately-injected perturbations [19,20]. These methods appear to work reasonably well, although they technically are actually active methods because of the output perturbation required. However, for the past three years as part of an Xcel Energy RDF-supported project, the present authors have been experimenting with harmonic and statistically-based methods without a deliberate output disturbance. One method in particular has shown good promise, a method utilizing the histogram of the rate of change of frequency that has been dubbed RoCoF-H. RoCoF-H relies on the same physical mechanism described above, namely that the frequency controls of the islanded system are significantly different than those of the grid, and thus there should be patterns in the rate of change of frequency (*df/dt*, or RoCoF) that can be detected if given sufficient time. The histogram is the means selected for detecting these changes.

Consider the plots in Figure 3, which show the histogram of the absolute value of the absolute value of *df/dt* during a grid connected situation (left) and for islanded DERs (right). The grid's frequency controls tend to produce a bimodal distribution. Most of the abs(*df/dt*) values are bunched against the left side of the plot because frequency changes on the main grid tend to be governed by the electromechanical properties of many large rotating machines, and are thus very slow. The smaller group appearing at higher abs(*df/dt*) values in the grid-tied plot arises from switching events, which actually cause perturbations in phase that are registered by instrumentation as momentary fast frequency changes. To use this as an island detection method, the approach adopted here has been to use a simple bimodality index *B* defined according to Equation (1):

$$B = \frac{\sum_{Bin2} X_i}{\sum_{Bin1} X_j + \sum_{Bin3} X_k} \tag{1}$$

where *Bin1*, *Bin2*, and *Bin3* are histogram bins with boundaries chosen to correspond to the low, middle and high groupings shown in Figure 3 and X_j, X_i, and X_k are the elements of those bins respectively. When the DERs are grid tied, nearly all of the abs(*df/dt*) values should fall into *Bin1* and *Bin3*, and $B \approx 0$. After the island forms, there is more frequency "jitter" in the island because of the DER frequency controls, some, but not all, of the abs(*df/dt*) values move into *Bin2*, and $B > 0$. For systemwide frequency events, many values will move into *Bin2*, and $B >> 0$. For this work, simulations were used to set the boundaries of the bins.

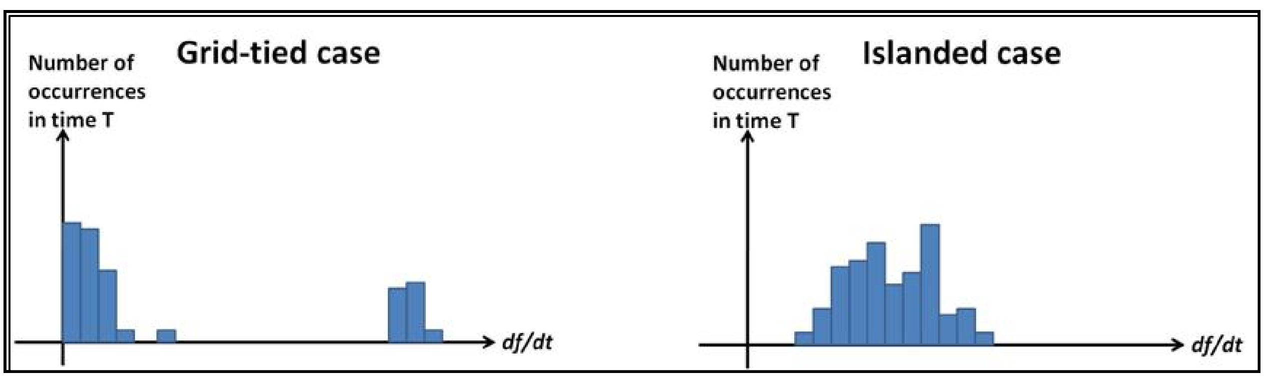

Figure 3. Histograms of frequency during grid-tied (left) and islanded (right) conditions.

As the decision criterion, a "zero time" rule has been adopted, the reason for which will become clear when the simulation results are presented. The "zero time" rule says that an island is said to be detected when the value of *B* is in the range of $0 < B < 10$ over more than 75% of the window length.

V. SIMULATION PROCEDURE

The RoCoF-H and other statistical methods have been extensively tested in EMTP-RV. In this paper, representative results are reported on four feeders. The feeders were the IEEE 34-bus distribution feeder, which is unusually long, mostly overhead, and high-impedance; and three real-world feeders in Xcel Energy's northern territory, using detailed feeder data provided by Xcel. One of the three Xcel feeders is a very stiff (low impedance), short feeder supplying primarily industrial load; one is a very weak (high impedance), long feeder in a rural and agricultural area; and the third is in-between in stiffness (medium impedance) and serves a suburban region.

On each of the four feeders, four cases were simulated. The first two cases were chosen to represent difficult cases for island detection. Case 1 is a multiple-inverter case, in which many three-phase inverters were added to the feeder until a generation-load match could be achieved. As one example, the number of three-phase inverters added to the IEEE 34-bus system was 18. These inverters were spread along the feeder because the inductance between the inverters is believed to exacerbate the loss of anti-islanding effectiveness in the multi-inverter case [21]. Phase-phase balancing was achieved by adding single-phase inverters to the more heavily loaded phases.

Case 2 was a case involving a mixture of types of DER. From an anti-islanding perspective, the most difficult combination of DERs arises when inverter-based DERs are combined with synchronous generators, so that is the case that was selected here. Some of the inverters in the multiple-inverter case were removed to make room for a single 1 MVA synchronous generator.

The latter two cases do not involve islands, but instead are tests of false-trip immunity (i.e., cases in which ride through is desired). Case 3 was a ride-through case simulating a loss of mainline generation resulting in a systemwide frequency event. In this case, it is highly desirable that the island detection method be able to distinguish this case from an islanded case and stay online to support the system. For this work, the frequency trajectory used was the one measured during the major Italian blackout of 2003 [22], scaled to 60 Hz for this work. To implement this frequency trajectory, a programmable variable-frequency source was created in EMTP-RV and programmed to follow this trajectory based on a lookup table.

Case 4 is another ride-through case, this one involving a major local switching event. Again, the anti-islanding system must be able to distinguish such an event from an island to avoid excessive false tripping. To simulate this event, a heavily-loaded 200-hp three-phase induction motor was switched directly across the line at a distal point on the feeder.

In the simulations reported here, the upper edge of *Bin1* was set to 3 mHz/sec, and the upper edge of *Bin2* to 8 mHz/sec. The frequencies were measured by a phase-locked loop.

VI. RESULTS

Example simulation results from EMTP-RV are shown in Figures 4 and 5. Figure 4 shows the results in Cases 1 (left plot) and 2 (right plot) on the IEEE 34-bus feeder. The island forms at 40 sec with the real and reactive power almost perfectly matched. The bimodality index is exactly zero until the island forms, after which point it rises fairly quickly and then exhibits a "noisy" behavior. In Case 1 (left plot), the island is detected in less than 1 sec. In Case 2, the bimodality index again jumps from zero before island formation to a "noisy" nonzero value after island formation, but the bimodality index takes a bit longer to respond in this case relative to Case 1 (longer than 2 sec), but once it does respond, the values of bimodality index seen in Case 2 are higher than those in Case 1.

Figure 5 shows results from Cases 3 (left plot) and 4 (right plot) on the IEEE 34-bus feeder. These are the ride-through cases in which no island is formed. In these cases, the bimodality index is clearly not zero, but it is important to note the vertical axis values, which are much higher than in the islanded case. Figure 5 also shows that the ride-through case results are characterized by high spikes in *B* separated by periods of zero value, whereas under the islanded conditions in Figure 4 *B* does not return to zero for any appreciable time after the island forms. It was this result that led to the adoption of the "zero time" rule as a decision criterion: during systemwide events, as the frequency moves through its transient, the leftmost grouping of *df/dt* values in the grid-tied plot in Figure 3 occasionally slides into *Bin2*, resulting in a large spike in *B*, and then slides back to the left, resulting in *B* dropping back to zero. With the "zero time" criterion, RoCoF-H successfully distinguishes and rides through both of the events in Figure 5 but still catches the islands in Figure 4.

Unfortunately space restrictions prohibit showing all of the results on the three Xcel feeders, but they mirror the results obtained on the IEEE feeder; the plots appear virtually the same as those shown in Figures 4 and 5. In all cases, RoCoF-H detects all of the islands (although the engine-genset case sometimes takes longer than 2 sec) and correctly rides through all of the non-islanded cases, using the "zero time" criterion.

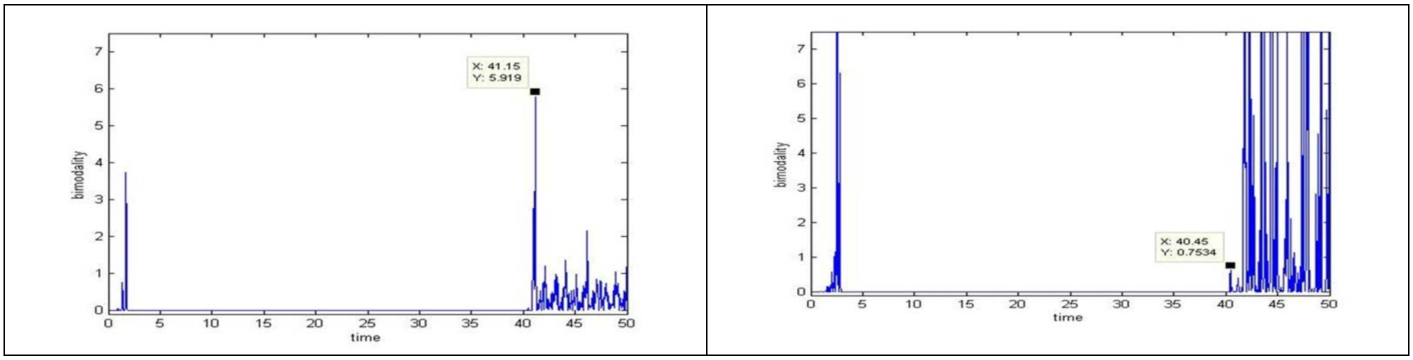

Figure 4. Value of bimodality index during a Case 1 (left) and Case 2 (right) test on the IEEE 34-bus distribution feeder. The island occurs at 40 sec and is detected in < 1 sec on the left and just over 2 sec on the right.

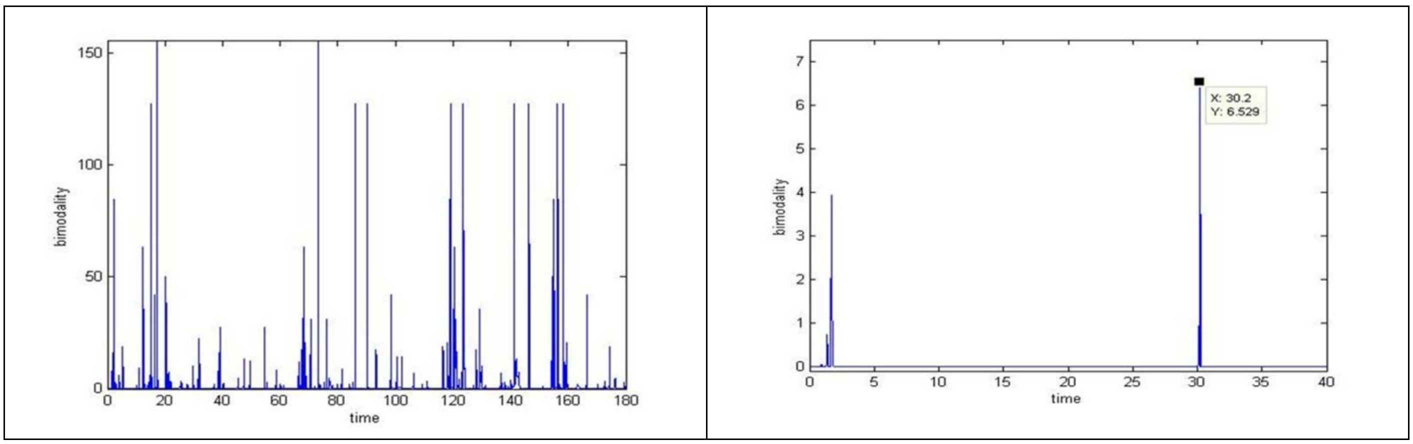

Figure 5. Value of the bimodality index during a Case 3 (left) and Case 4 (right) test on the IEEE 34-bus feeder (no island; ride-through test).

VII. Discussion

The results given here show that this passive method, like many others, has high promise for being effective in practical field situations, particularly if the method is allowed longer than 2 sec to distinguish between ride-through and island events. In the simulation testing thus far, with the "zero time" decision criterion, RoCoF-H has had excellent success in achieving selectivity and sensitivity simultaneously.

In addition to its promise of effectiveness, this method has some other notable advantages as well. One is that while it may seem complicated on the surface, because it does not require extensive signal processing, it is very easy to implement and can be executed on low-cost computational devices. It has shown good effectiveness on a wide variety of feeders with different characteristics, and for a broad range of DER combinations.

The RoCoF-H method does have some weaknesses. One is that while it does appear to give good selectivity and sensitivity, it obtains the improved selectivity at the expense of speed of detection. This is a trait that may be shared with other passive methods [12]: they *could* achieve good selectivity and sensitivity, but only if they are allowed longer than 2 sec to detect an island. Any method with this property would need to be coupled with fast fault detection, as described above. Another is that the values selected for the bin edges will depend on how the frequency is measured. For this work, a phase-locked loop was used, but if a different technique were used—say, a phasor measurement unit—the simulation results suggest that the frequency estimation and measurement characteristics of the measurement unit will need to be taken into account when the bin values are selected. Efforts are currently underway to develop a table of appropriate bin values for different frequency measurement devices and techniques. An additional disadvantage is that the robustness of this method would be adversely impacted if deployed on a weaker grid, such as that in Hawaii, although initial results suggest that the method can still be effective there if the bin values are appropriately adjusted. Finally, the bin values may also depend weakly on the mixture of DERs present on the feeder, particularly on the fraction of DERs that are based on rotating machines. RoCoF-H does work with rotating machines, but simulations and intuition suggest that the positions of the histogram groupings in Figure 3 will move slightly as the ratio of inverter-based to rotating machine-based DER varies. Fortunately, this effect is relatively small, and it does appear that bin values can be selected that work for all combinations of DERs**.**

VIII. Conclusions

Passive anti-islanding, which until recently has been largely dismissed as a first-line defense against unintentional islanding because of its inability to achieve both sensitivity and selectivity, may have a critical role in the future as a backup method to communications-based methods, a role for which active anti-islanding will be unsuited at higher DER penetration levels. This paper argues that passive anti-islanding may perform much better if it can be allowed longer than 2 sec to detect an unfaulted island with generation-load balance, and an argument has been presented that it should be permissible to allow more than 2 sec in this case *if* island detection and fault detection in DERs can be decoupled. Finally, this paper has introduced a new passive island detection method, RoCoF-H, and has shown that this and a number of other passive methods have the potential to achieve the needed sensitivity and selectivity, particularly if they are allowed longer than 2 sec to detect the island. RoCoF-H is relatively easy to implement in inexpensive hardware and requires no output perturbation. In all of the cases simulated, RoCoF-H successfully detected all islands, including multiple inverter islands and islands with rotating generators, while successfully riding through local switching and systemwide frequency transient events.

IX. Acknowledgments

The authors wish to thank Dr. A. Berizzi for providing the frequency trajectory data for the Italian blackout.

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