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Islanding Procedures and Associated Impacts for Transmission Connected Inverter Resources

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SUMMARY

With the ever increasing penetration of power electronics interfaced generation in transmission systems, challenges are associated with this shift to inverter-based resources (IBR) due to the well documented characteristics of high IBR systems such as low short circuit strength and inertia. Islanding of IBR with load is becoming an issue in N-1-1 contingencies in several jurisdictions, where the system operator is unsure of whether the island can be detected and safely de-energized.

This paper outlines the standards set by various governing bodies around how unintentional islands should be handled, either by safely de-energizing them or allowing them to be sustained. Case studies will also be carried out in PSCAD® to investigate how a 100% IBR-fed island performs under different load and generation conditions. Finally, anti-islanding protection will be benchmarked to assess their viability in protecting transmission-connected IBR from sustained unintentional islanding.

KEYWORDS

Anti-islanding, protection, inverter-based resources, transmission planning

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Introduction

With the ever-increasing penetration of IBR in transmission systems, challenges are created due to the well documented characteristics of high IBR systems such as low short circuit strength and inertia. A further challenge arises in islanding conditions, where the behavior of an island fed 100% by IBR is uncertain.

However, with more and more IBR being connected into transmission systems, particularly in radial layouts with IBRs tapped onto transmission lines, this is becoming an issue in several jurisdictions, where the system operator is unsure of whether the island can be detected and safely de-energized, and what technologies to use in order to ensure this.

This paper is structured as follows. Section II provides and overview of existing standards to prevent and protect against sustained unintentional islanding, and common islanding detection methods. Section III presents some simulation results from PSCAD® investigating how a 100% IBR fed island behaves under different load and generation conditions. Section IV benchmarks the performance of relays and active anti-islanding schemes against each other.

Standards

IEEE 1547 (2018) specifies for unintentional islanding that distributed energy resources (DERs) “shall detect the island, cease to energize the Area EPS, and trip within 2 seconds of the formation of an island”, however there is a clause in the standard that states that, with an agreement between the system operator and the DER operator, the operating time of the relay can be as much as 5 seconds [1].

IEEE 2800 (2020) specifies that “unintentional islanding protection system schemes used by the IBR units or the IBR plant shall not limit the IBR plant’s ride-through capabilities specified in this standard. If islanding of the IBR plant with any portion of the TS is not allowed by the TS owner, unintentional islanding protection shall be implemented, in accordance with the TS owner requirements” [2].

IEEE 2800 also specifies specific voltage and frequency ride-through requirements for IBRs. The voltage and frequency ride-through requirements are illustrated in Figure 1. These requirements are only applicable when the frequency is within the continuous operation or mandatory operation regions specified for frequency ride-through. Outside of these operation regions for voltage, it may be assumed that the IBR’s frequency protection will trip. Note that IEEE 2800 also provides for transient over-voltage limits, which protects against excessively high instantaneous voltage magnitudes, are not accounted for in this study.

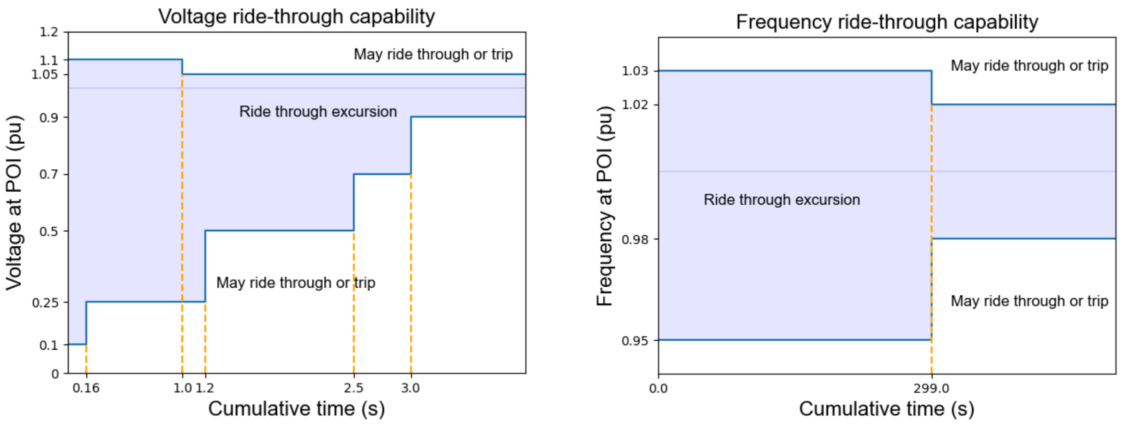

Figure 1
Voltage ride-through (left) and frequency ride through (right) capability specified for an IBR plant (without auxiliary equipment that can cause ride-through limitations) by IEEE 2800 [2]

The North American Electric Reliability Corporation (NERC) specify voltage ride through and off-nominal frequency capabilities in [3]. For frequency protection, the extremes of frequency operation occur in Quebec, where the frequency can vary up to 66 Hz (1.1pu) and as low as 55.5 Hz (0.925pu). Other zones in North America can handle much less variability in the frequency such as the Eastern Interconnection, which will trip frequency protection outside the range of approximately (0.96, 1.03) pu. For voltage protection, NERC imposes a time stepped threshold for under/over voltage ride through limits where the maximum overvoltage possible is 1.2pu, with instantaneous tripping occurring for any voltage sensed above this, and instantaneous tripping for any voltage less than ~0.45pu.

Unintentional Islanding Protection

Direct Transfer Trip

The most robust way of ensuring that an IBR-fed island is not allowed to sustain itself is direct transfer trip (DTT) by monitoring breaker/switch statuses. The breakers at the substations at either end of the transmission line that the IBR is connected into would be monitored by the IBR and the circuit breaker (CB) connecting the IBR to the transmission system would be opened if both breakers at each substation would also be opened. This would require fiber optic communication cables between the IBR and nearby substations, which is costly. Furthermore, with multiple generation units being tapped onto transmission lines between substations, DTT becomes increasingly complex in the communication between the IBRs and the substations. DTT in this form would guarantee islanding of IBR with load would not occur, aside from logistical problems i.e., fiber optic cables being cut, component failure.

Passive Islanding Detection Methods (P-IDMs)

P-IDMs (relays) monitor phasor values of currents and voltages at the IBR point of interconnect (POI) and trip if these phasors stray outside set thresholds. These methods of island detection are typically low cost relative to DTT, and do not have any impact on the power quality of the system. However, an island may not be detected if the generation and load are closely matched, as it would not cause a significant change in the voltage or frequency. Relays such as under/over frequency, under/over voltage, and rate of change of frequency (RoCoF) relays, among others have been used as P-IDMs in distribution systems [4].

Frequency and voltage relays are a relatively low-cost solution to anti-islanding protection, but, like all P-IDMs, they have a larger non detection zone (NDZ) compared to A-IDMs and DTT, and so run the risk of not de-energizing the generation unit safely in an islanding scenario.

In anti-islanding schemes implemented in DER in distribution systems, RoCoF relays with a 100ms sliding window measurement is often used as a form of P-IDM. The primary downside of the RoCoF relay is that it is challenging to calculate the frequency and RoCoF during transients. Further, making a tripping decision based on just 2 measurements could make it prone to misoperation, which could cause wider problems such as cascading tripping. A real world example of this is the event in the UK power system in August 2019, in which it is estimated that approximately 350 MW of DER generation was lost due to RoCoF tripping, which exacerbated the situation [5].

Active Islanding Detection Methods (A-IDMs)

A-IDMs implemented onboard the inverter inject perturbations into the power system specifically for the purpose of island detection. These methods are designed to have minimal impact during the normal grid-connected operation and produce large disturbances in voltage and/or frequency when islanded. Using an A-IDM in combination with passive methods such as over/under frequency, over/under voltage, and RoCoF results in a significantly reduced

NDZ and faster detection. However, with the increasing penetration of IBRs using different A-IDMs, there are concerns regarding negative interactions and power quality impacts. Relevant EPRI publications on A-IDMs can be found here [4], [6], [7].

Simulations

System Setup

To investigate islanding events involving IBR, several scenarios of islanding events were simulated in the EMT domain in PSCAD®. An example system is shown in Figure 2. This system comprises of:

- System equivalents at Bus 1 and Bus 2 modelled as synchronous generators
- Load model
- IBR model/s

An island fed 100% by IBR is created from this system by an N-1-1 contingency, by opening the CBs indicated. Simulation results of this scenario will be presented, with the islanding occurring at t=6.0s in the simulations presented.

There are 4 different MW loads simulated relative to the IBR power output: matched MW load, quarter MW load, half MW load, and double MW load. In these scenarios, unless stated otherwise, the reactive power output of the IBR is set to maintain the POI voltage at around 1 p.u. prior to islanding, rather than match the Mvar draw of the load. The load is modelled as either a static load model or a composite load model (50% static load, 50% motor load). In both cases, the loads draw a constant power. A high level diagram of the composite load model is also shown in Figure 2.

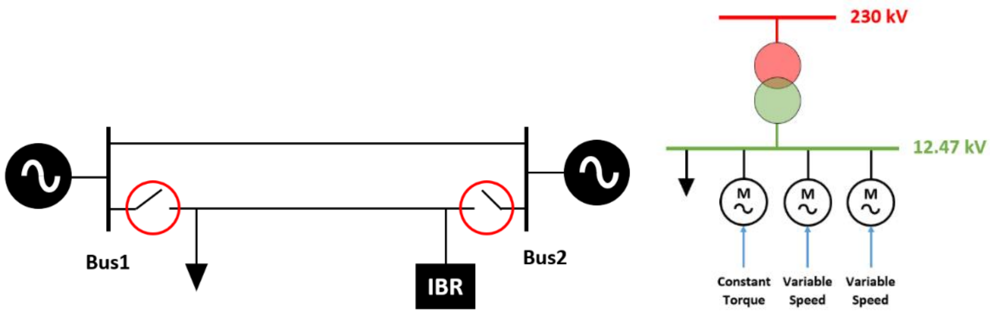

Figure 2
Islanding with single IBR infeed (left), composite load model (right)

A further scenario will be examined later in the paper in which the load power drawn is matched to the IBR power i.e., the power exchange between the wider power system is negligible. This scenario is the most likely scenario in which the island may survive (voltage and frequency remaining within typical boundaries) but is also simultaneously the least likely scenario to occur (when the island MW and Mvar generation is exactly matching the load MW and Mvar draw).

Single IBR Model

Initially, a system was set up with a single IBR model. The IBR model used in this example is a generic model that has been developed by EPRI through the DOE-funded PVMOD project [8].

Shown in Figure 3 is a simulation of the system setup shown in Figure 2 with a single IBR model when the MW draw of the load model is matched with the MW output of the IBR model for a static load model and a composite load model. In this simulation, the first CB opens at t=5.5s, and the second CB opens (forming the island) at t=6.0s.

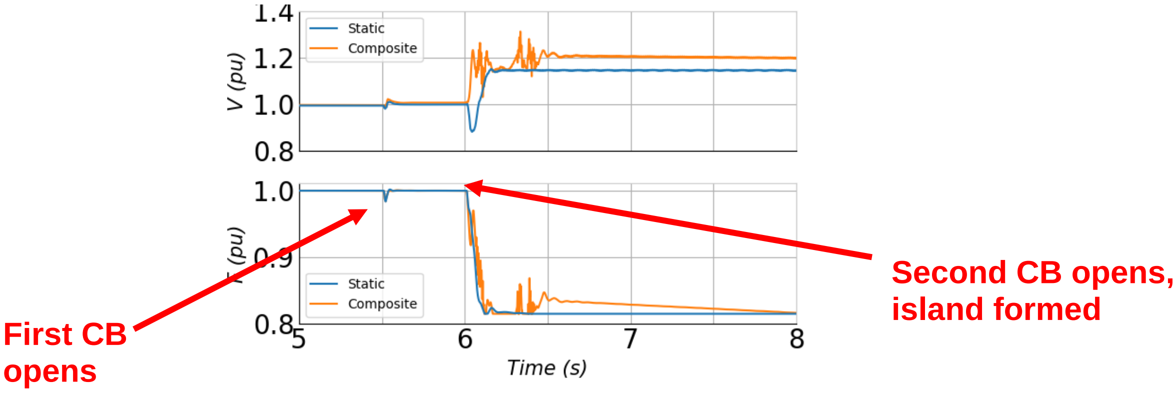

Figure 3
Matched MW load – single IBR infeed

In both load cases, the island frequency at the IBR model's POI collapses to the lower limit of the phase-locked loop of the IBR of around 0.82pu, which would likely cause instantaneous frequency relay tripping. The island voltage rises to and settles between 1.15pu and 1.25pu for the static and composite load cases.

Shown in Figure 4 is the voltage and frequency traces of the island with a static load when the load power draw (MW and Mvar) is matched absolutely with the IBR output power, meaning there is negligible power being imported/exported to the wider power system. This results in the island surviving the islanding event, with the island frequency and voltage remaining inside typical frequency and voltage thresholds set in protective relays. voltage staying in the range [0.98, 1.0] and frequency staying within the range of [0.997, 1.003]. The voltage and frequency are kept within these limits by the voltage and frequency droop controllers in the IBR model. The frequency droop controller has a deadband of $\pm$0.0006pu and a droop gain of 10 for over frequency events, and the voltage controller has a deadband of [-0.1, 0.01] and a purely integral gain of 10. The ripple in the frequency is caused by the droop controller, which activates outside the deadband of and reacts to over-frequency by reducing the power output of the IBR. In this situation, in order to de-energize the island, it may be necessary to include an A-IDM to provoke the frequency and voltage outside of the typical operating ranges of the IBR and trip passive protection, otherwise the island would continue to operate indefinitely.

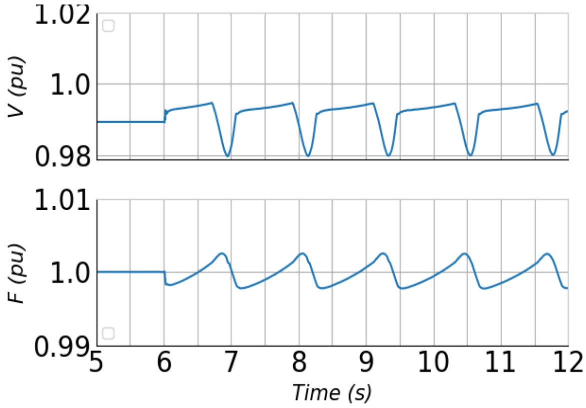

Figure 4
Matched load (MW and Mvar) – single IBR infeed – static load

Two IBR Models

To further test out the behavior of a 100% IBR-fed island, it was decided that multiple IBR models should be included to reflect real world scenarios, in which IBR from different vendors would be connected near to each other, and there would be uncertainty about the impact of these different control system designs on an island.

The system setup is identical to the system shown in Figure 2, with the addition of a second generic IBR model tapped onto the same transmission line as the existing IBR model and the load model. The second IBR is another generic IBR model. Henceforth, the PVMOD inverter model will be denoted IBR1, and the second generic inverter model will be denoted IBR2.

Shown in Figure 5 is the voltage and frequency traces at the POIs of both IBR models when the MW draw of the load model is matched with the combined MW output of the IBR models (reactive power not matched) for a static load model and a composite load model. As before, the first CB opens at t=5.5s, and the second CB opens (forming the island) at t=6.0s. In comparison to the case where there was a single IBR model, there is some more voltage and frequency instability in the composite load model case due to the motor load dynamic response.

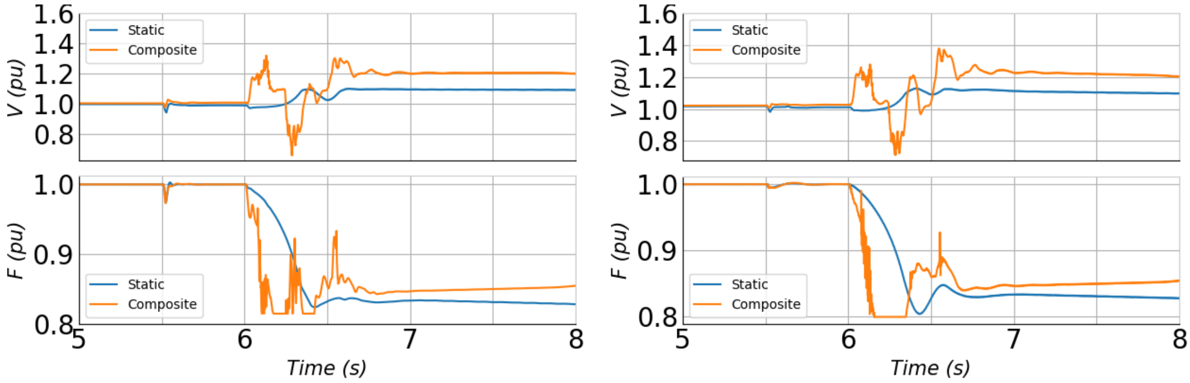

Figure 5
Matched MW load – two IBR infeed – IBR1 (left), IBR2 (right)

Active Islanding Detection Methods

To see the impact of A-IDMs, the system was set up as shown in Figure 2, with a GE frequency shift A-IDM incorporated into the PVMOD inverter model control system.

The results for this example system with a static load with a matched load (MW and Mvar) is shown in Figure 6. Clearly, the addition of GEFS is de-stabilizing the network versus the stable island without GEFS, causing the frequency to plummet quite quickly to below 0.95pu, certainly tripping frequency protection. This exhibits the ability of A-IDMs to de-energize islands that may sustain themselves otherwise.

Note that this study does not clearly show a need to de-energize all islands containing IBR and load, as the simulation shown in Figure 4 is possible that an island consisting of IBR and load can be safely sustained with a stable voltage and frequency. However, if a utility wishes to de-energize all islands consisting of IBR and load, and an instance of an exactly matched generation and demand scenario is likely, A-IDM methods can help in these instances.

It must be noted that the gain of the GEFS scheme must be chosen carefully such that it de-stabilizes the network in the event of an islanding and reduce the time taken to safely de-energize the network, but also such that it does not de-stabilize the network when an islanding event has not occurred.

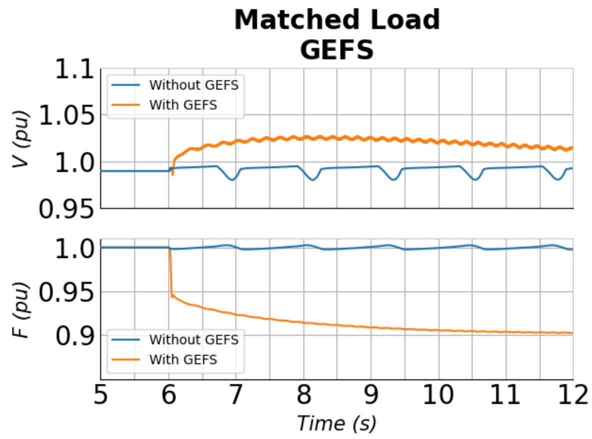

Figure 6
Matched load – single IBR – GEFS

Unintentional Islanding Protection Benchmarking

In response to islanding events such as the scenarios presented in the previous section, it was important to investigate several protection schemes that can protect against islanding and safely de-energize an island shortly after forming.

Voltage and frequency relays are commonly installed on IBRs in both distribution and transmission systems, with generic thresholds given in Table 1 and Table 2. Further, RoCoF relays are commonly installed with a 5 Hz/s threshold over a 100ms sliding window in DERs, and so they will also be assessed along with voltage and frequency relays.

Table 1 – Frequency Thresholds

Frequency (p.u.)	Time Delay (s)
0.95	0.16
0.97	2
1.05	0.16
1.03	2

Table 2– Voltage Thresholds

Voltage (p.u.)	Time Delay (s)
0.5	0.16
0.65	0.32
0.75	2
1.2	0.002
1.15	0.48
1.1	1

Single IBR Model

The performance of the relays (with and without an A-IDM) for an island with a single IBR model is shown in Figure 7. The performance of the voltage and frequency relays are remarkably similar, both tripping in 13 of the 16 islanding scenarios individually, but most importantly, the combination of a voltage and frequency relay provided full protection against an islanding scenario in these test cases.

The RoCoF relays performed very poorly, tripping early in 14 of the 16 scenarios. The relays consistently tripped upon the opening of the first CB, when the IBR was not yet islanded. Further, the addition of the GEFS scheme exacerbated this, causing the RoCoF relay to trip early in 100% of the scenarios with GEFS versus 75% of the scenarios without GEFS.

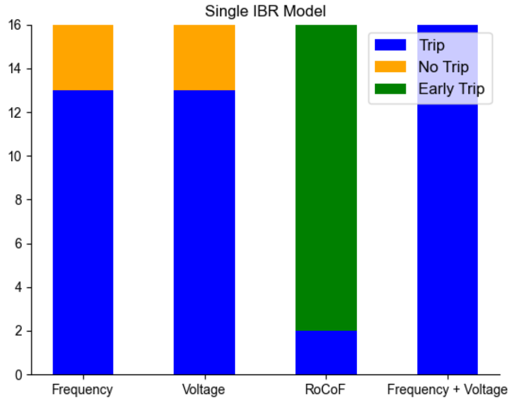

Figure 7
Protection performance – single IBR

In the scenario in which the MW and Mvar power drawn by the load is exactly equal to the IBR output power, without GEFS enabled on the IBR model, the frequency and voltage relays did not trip, as they stayed comfortably within typical operating limits, shown in Figure 4. However, with the addition of GEFS, the GEFS scheme sufficiently de-stabilizes the island such that the frequency relay de-energizes the island for both the static and composite load scenarios, and the voltage relay also operates on one of the two studies. This is summarized in Figure 8, where frequency protection tripped in both the static and composite match load cases, while voltage protection tripped in just 1 of the 2 scenarios.

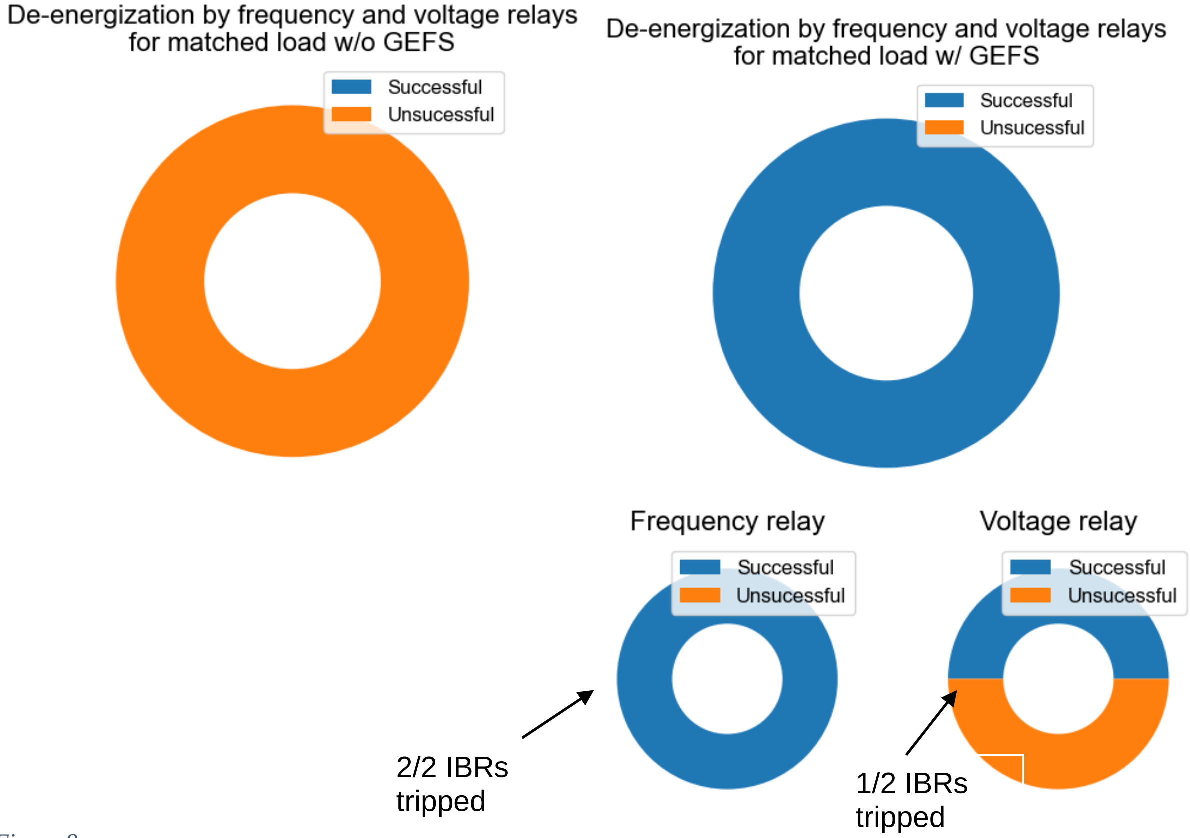

Figure 8
Protection performance – single IBR – matched load with and without GEFS

While this further underlines the potential of the combination of a frequency relay and a voltage relay to sufficiently protect against islanding, particularly in cases where the island is sustaining itself, it also shows that A-IDMs can play a role in scenarios where the islanding event is not severe enough to trip with passive protection alone.

Two IBR Models

Now, it is also important to simulate the impact of tapping multiple IBRs into the island to investigate the impact of this on the stability of the island, and whether it will be more difficult to de-energize the island.

The performance of the relays is shown in Figure 9 for frequency, voltage, and RoCoF relays with and without GEFS enabled in IBR1. These results aggregate the tripping of the relays installed at IBR1 and IBR2.

As in the previous case, the performance of the frequency and voltage relays is quite positive, with frequency relays successfully operating in 14 of the 16 scenarios (with and without GEFS) and voltage relays operating 11 of the 16 scenarios with and without GEFS. The RoCoF relays again misoperate the vast majority of the time, and so should not be considered as effective anti-islanding protection in transmission systems.

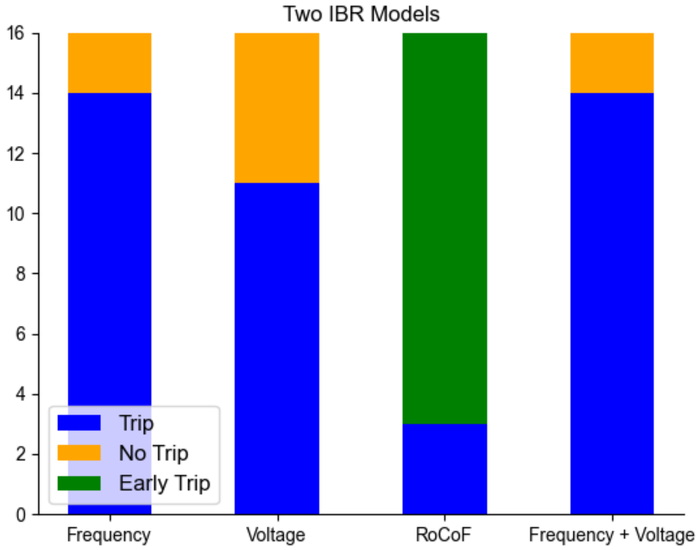

Figure 9
Protection performance – two IBRs

However, unlike in the single IBR cases, there was a case in which the combination of frequency and voltage relays did not successfully de-energize the island in the double MW load case, with and without GEFS. This underlines the need for case-by-case study for each power system where this may be an issue, and to consider implementing a special protection scheme in cases where the island may not be successfully de-energized.

Again, the GEFS scheme can play an important role in scenarios in which the island voltage and frequency stays within typical operating limits. In the static load case in which the MW and Mvar output of the IBRs is matched exactly with the load (there is no power exchange with the system equivalents prior to islanding), the island is not de-energized when GEFS is not enabled, but it is successfully de-energized by the frequency relays when GEFS is enabled. The voltage relays do not trip in this instance for either IBR, but the frequency protection trips for both IBRs in this case.

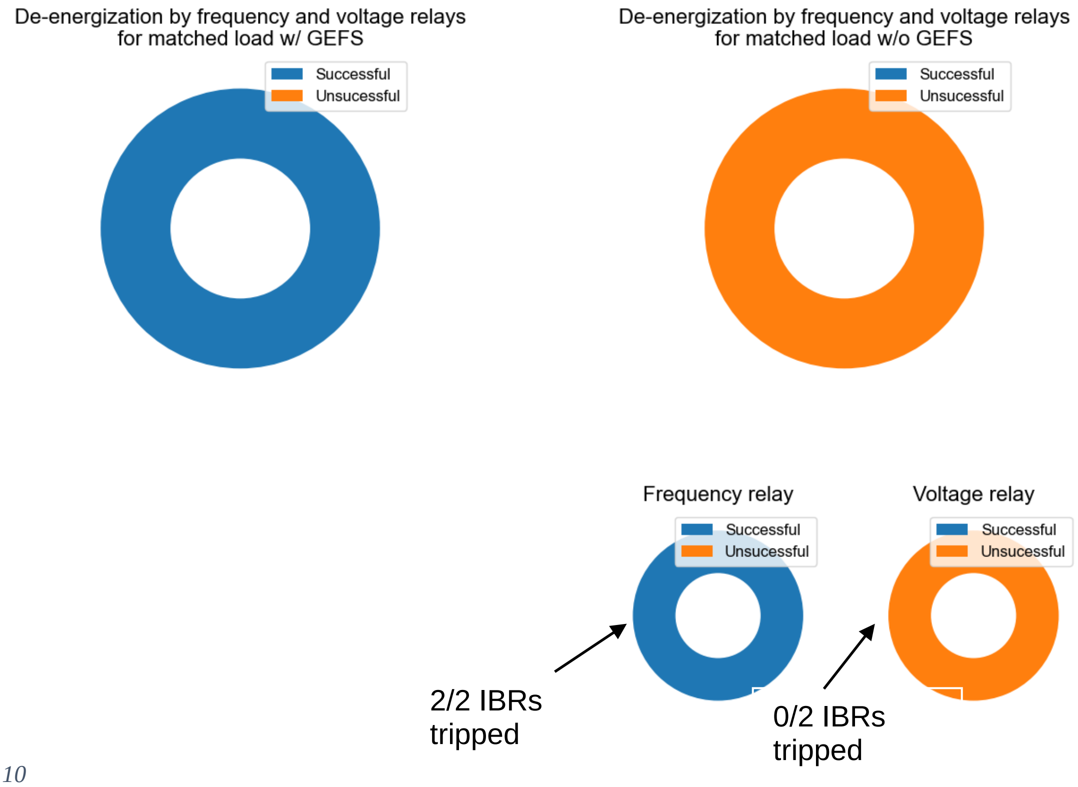

Figure 10
Protection performance – two IBRs – matched load with and without GEFS

The composite load case is not presented here because it was not possible to find a scenario in which the composite load case with 2 IBR models feeding into the island would maintain the island voltage and frequency within typical operating limits, underlining the low probability of a matched MW and Mvar generation and load event occurring in an island of IBR and load.

This may also mean that A-IDMs might not be necessary in cases where multiple IBRs feed into an island with a high amount of motor load in the area, although it likely depends on several factors such as the control schemes implemented in the IBRs, the controller interactions of the IBRs, and the dynamics of the motor loads.

Conclusion

Islanding of IBR with load is becoming more and more of a reality in transmission systems with the increasing penetration of radially connected IBRs. It is important to study islanding scenarios of IBR with load with varying types and magnitudes of load draws, with notable differences occurring with the inclusion of motor load and with low vs. high amounts of MW load relative to the IBR output. Further, it is important to consider the case in which the island does not exchange power with the rest of the power system prior to islanding (matched MW and Mvar), as this is the most likely scenario in which the island will survive and maintain the voltage and frequency within the typical operating limits.

DTT offers the gold standard in protecting against unintentional islanding, as it is not measurement dependent. However, it is by far the highest cost due to the construction costs associated with laying fiber optic cables between each substation and IBR plants.

A combination of frequency and voltage relays provides a high level of protection against islanding for a wide array of load scenarios, particularly when the island is importing/exporting a non-negligible amount of power with the rest of the power system. However, this does not guarantee full protection in all scenarios, and may require an SPS. RoCoF protection does not seem like a viable passive protection mechanism due to them being prone to misoperation during non-islanding events.

With regard to A-IDMs, in the instance where an island survives and keeps the voltage and frequency within the operating limits, A-IDMs such as GEFS can be an effective way of de-stabilizing the island and consequently tripping the passive protection. However, an A-IDM may not be always necessary, and should not be implemented if not necessary as it could risk falsely detecting an island, de-stabilizing the power system and tripping generation offline. Further, their impact on power quality should be studied before installing an A-IDM scheme.

Acknowledgements

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