A Proposed Passive Islanding Detection Approach for Improving Protection Systems

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Abstract— Nowadays, distributed generation (DG) is commonly used in networks. In spite of the numerous benefits of DG units in these networks, several challenges are introduced such as unintentional islanding, reverse power flow, protection concerns, etc. In this paper, a new passive islanding detection approach is proposed depends on the production of voltage sequence components at every relay location not only at the DG point of common coupling. The proposed approach uses only one threshold value for all relays in the distribution network. The performance of the proposed approach is not influenced by changes in type, capacity or location of DG. The proposed approach is evaluated under different transient conditions such as capacitor switching, load switching and DG switching. Also, the performance of the suggested islanding approach has been compared with most prevalent islanding detection techniques. The performance of the proposed algorithm is stable during balanced and unbalanced conditions. Moreover, detecting the islanding case at all relays provides the ability to improve the protective relays performance by updating the protection setting for all relays based on local measurement only without the need for fault current limiters (FCLs) or a communication network. The proposed approach is evaluated using the Canadian distribution system embedded with DG units in MATLAB/Simulink simulation. The achieved results demonstrate that the proposed approach is robust during all non-islanding events. Also, it succeeds to detect islanding condition with high confidence without non detection zone (NDZ).

Keywords: Distributed generator, local measurements, microgrid, non detection zone, passive islanding detection, protection system, and voltage sequence components.

1. Introduction

Distributed generation (DG) would offer reliable, quality and efficient supply to consumers. However, great challenges arise to the existing conventional protection schemes as a result of integrating DG units into the distribution network [1]. To maintain the continuity of service in case of main utility outage, the critical loads are fed by the DG units, and the islanded mode is formed [2]. Islanding cases can be divided into intentional or unintentional. The scheduled maintenance to the main grid is considered intentional islanding, while the occurrence of faults or other uncertainties at any time in the power system is described by unintentional islanding. In fact, islanding detection is considered an important mission for integrated power distribution networks, so standards of UL 1741 and IEEE 1547 explain both planned and unplanned power islanding, DG interconnection and other considerations for correct operation [3].

Unintentional islanding is considered a hazard to power system security that may possibly injury the maintenance workers and damage utility operations, and equipment. During islanding case, the DG units may not be able to contribute sufficient fault current to activate the traditional protection relays and consequently islanding operation may destroy the system equipment, affect power system reliability and threaten the maintenance worker's life. Therefore, islanding in power distribution networks is considered an actual challenge for protection engineers. Furthermore, in the event of unintentional islanding, overload conditions may occur because of the suspended utility operation, which significantly affects the frequency and voltage levels of DG units. Moreover, as DG incorporation rises, the necessity for unintentional islanding detection will be more substantial and challenging [4].

Different techniques are discussed in the literature for detecting the islanding case. These techniques are generally classified into local and remote techniques [5]. Generally, local techniques depend on the measurement of some variables or parameters at the DG terminal, including passive and active techniques [5].

The under/over frequency protection (OFP/UFP) and under/over voltage protection (OVP/UVP) are the most commonly used conventional methods of passive islanding detection methods [6]. Implementation of these conventional techniques is cost effective and simple. However, these techniques have inadequate performance during small power mismatch islanding. For overcoming these limitations, several enhanced techniques are also proposed. A hybrid algorithm is suggested to detect the islanding scenario depending on the rate of change of reactive power (**ROCORP**) and voltage (**ROCOV**) at the point of common coupling (PCC) of DG [7]. Further in [8], the total harmonic distortion (THD) of current and **ROCORP** are utilized simultaneously to detect the islanding case. The phase shift between the current and voltage is also implemented as a measure for islanding detection in [9]. The techniques relying on proportional power spectral density [10], the rate of change of frequency dependent impedance [11], harmonic grid impedance [12] are some of the advanced passive islanding methods declared in the literature to achieve quick islanding detection. Further research studies are also conducted based on sequence components [13-15]. In [13], the THD of current and voltage unbalance are implemented together for islanding detection. A universal islanding detection technique depending on the sequence current components has been discussed in [14]. However, the universal islanding detection technique cannot detect the islanding scenario in the event of the perfect matching between generation and load demand. Also, the scheme is not designed for updating the protection relays setting. Moreover, the scheme is based on the current signal at DG terminal only which is usually varied depending on the loading condition. Another hybrid passive technique depending on the rate of change of positive sequence of voltage and current signals is introduced in [15]. For more enhancement in the accuracy and speed of the islanding detection methods, S-transform based method and adaptive-network-based fuzzy inference system (ANFIS) [16], wavelet singular entropy-based technique, data mining-based intelligence technique and probabilistic neural network-based technique are also suggested and discussed in the literature [17].

All of the aforementioned passive techniques are depending on measurements at DG terminal only to detect islanding condition. Also, the selection of a suitable threshold in these techniques is difficult since it is affected by loading conditions. Several simulation studies for islanding and non-islanding cases are required to determine the suitable threshold value at each DG terminal. If the threshold value is selected to be very low, there are probabilities of false tripping during non-islanding events (switching on/off of capacitor banks and large loads, etc.). On the other hand, if the predetermined threshold value is selected at a high value, there will be large non detection zone (NDZ), where the scheme shows incapability in islanding event detection. Besides, these techniques are not designed for updating the settings of the other relays if major changes occurred in the network [18].

In conclusion, islanding detection is accomplished in passive techniques by witnessing significant deviations into the system's output parameters. Passive methods have fast detection, inexpensive as well as uncomplicated to be implemented [19]. Passive techniques also do not produce disturbance in the system. These techniques are accurate when there is a great mismatch in demand and generation in the islanded part [20]. However, the passive schemes may fail to sense the islanding situation when the load and DG power are balanced. Therefore, passive methods suffer from large NDZ and it is challenging to decide the threshold value.

Active techniques are generally based on the principle of the external signal being injected into the system, which disturbs the DG output parameters up to a substantial level upon islanding situation occurrence. In case of grid-connected mode, the injected signal is not significantly distorted, but an effective variation is detected in the system under the islanding situation. Active methods provide faster response and high reliability [21]. Using active methods, islanding case can be sensed even under the DG power and local load are closely matched [21]. However, the active methods reduce the output power quality, degrade the system stability and require long time for detection [22]. On the other hand, active methods, such as the thyristor-based scheme proposed in [18], allow calculating the system equivalent impedance, which varies for islanded and grid-connected conditions. Then, the appropriate setting is selected without any communications. However, this thyristor-based scheme is based on active islanding detection technique which produces harmonics that may degrade the system stability. Also, several simulation studies are needed to determine the suitable impedance threshold value between islanded and grid-connected conditions and hence it will not be easy to be set in the field. Moreover, the scheme is not tested under other non-islanding events which may affect its performance. Also, such scheme may not be effective for weak grids because the equivalent impedances for the grid-connected and islanded modes of operation become close to each other [18].

The remote method uses the advanced signal processing methods and communication infrastructure that are utilized for islanding detection. Remote methods have no NDZ and have high reliability in comparison with local islanding detection techniques [23]. Their performance is independent of the type of DG units involved. The operation is also correct in case of multiple DG units and no nuisance trips. Moreover, their power quality impact is not perceptible [23]. These schemes are not preferred due to the high cost, complexity, and implementation problems.

In this paper, a passive approach is proposed for islanding detection based on a new suggested sensitive islanding detector. The detector represents the product of voltage sequence components at every relay location based on its corresponding local measurements. The proposed approach succeeds in detecting islanding operation with high confidence with no NDZ. It is very simple and does not produce any harmonics or affect the system stability such as active methods.

The organization of this paper is presented as follows:

description of the suggested islanding detection approach is introduced in Section 2. Modeling and simulation results for evaluating the proposed islanding detector on Canadian distribution system are discussed in Section 3. Finally, the conclusion is summarized in Section 4.

2. Proposed Islanding Detection Approach

Generally, the grid is a strong source of voltage magnitude and frequency. In grid-connected operational mode when the circuit breaker (CB) in Fig. 1 is closed, the frequency and voltage at the PCC are mainly governed by the grid. Accordingly, the voltage measured at the PCC is expressed as,

$$V_{PCC} = V_G \times [\frac{(Z_{load} // Z_{DG})}{Z_{line}+Z_G+(Z_{load} // Z_{DG})}] + V_{DG} \times [\frac{(Z_{load} // (Z_{line}+Z_G))}{Z_{DG} + (Z_{load} // (Z_{line}+Z_G))}] \quad (1)$$

Where Z_G , Z_{load} , Z_{DG} and Z_{line} characterize the impedance seen by main grid, load, DG and transmission line, respectively. V_{PCC} , V_{DG} and V_G represent the measured voltage at PCC, DG and grid respectively.

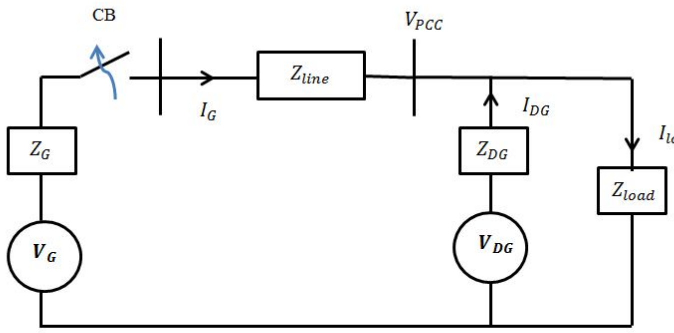


Fig. 1. Analyzing a network under islanding condition.

On the other hand, when the CB is open (islanding mode), the measured voltage at the PCC is expressed as:

$$V'_{PCC} = V_{DG} \times [\frac{Z_{load}}{Z_{DG} + Z_{load}}] \quad (2)$$

For grid-connected mode, there is no substantial change in the PCC voltage. Thus, the transient events such as load, capacitor and DG switching will result in small changes and the network remains almost balanced.

In contrast, during islanded mode, the voltage will be concurrently changed and determined by the DG as expressed in Equation (2). It is observed from Equation (2) that the grid impedance does not exist in the PCC voltage. The system during the transition to the islanding mode loses its stable reference power supply and the presence of unbalance is considerably expected in PCC voltage [8], [24].

The main idea of the proposed approach is to benefit from the fact that the major change in the network topology (when the grid is disconnected) results in significant unbalance between the phases and hence significant increase in the calculated symmetrical components of the measured voltage at PCC as indicated in Equation (3). Consequently, these components are considered in this proposed technique as an effective parameter for islanding detection.

$$\text{The islanding detector } (\Psi) = V_{pos} \times V_{neg} \times V_{zero}$$
$$= \frac{(V'_a+\alpha V'_b+\alpha^2 V'_c)}{3} \times \frac{(V'_a+\alpha^2 V'_b+\alpha V'_c)}{3} \times \frac{(V'_a+V'_b+V'_c)}{3} \quad (3)$$
$$= \frac{1}{27}(V'_a+\alpha V'_b+\alpha^2 V'_c) \times (V'_a+\alpha^2 V'_b+\alpha V'_c) \times (V'_a+V'_b+V'_c)$$

The islanding case is confirmed if the proposed islanding detector exceeds a predetermined threshold value during one cycle and at the same time it was not having a fixed value during this period.

Choosing a proper threshold value is a critical concern. If the threshold magnitude is chosen to be very low, there are probabilities of mal-operation of the technique during non-islanding events. On the other hand, if the threshold value is set at a high value, there will be large NDZ. In this paper, one threshold value is used for all relays in the network since it depends only on the voltage signal which is almost constant at all buses and independent of loading condition. The threshold is chosen in this paper for all relays based on the islanding event with zero power mismatches. It is considered the worst islanding case. The threshold values of $V_{pos} \times V_{neg} \times V_{zero}$ are adjusted to be 10 pu of the base value (which is typically equal zero at normal operation) for all relays.

Since the proposed detector depends only on the voltage signal, it is possible to detect the islanding scenario at all protection relays with only one threshold value.

3. Modeling and simulation results

In this section, the proposed approach is verified on the Canadian distribution system embedded with synchronous-based DG units and operated in grid-connected and islanded modes using MATLAB/Simulink simulations. Canadian urban benchmark, 60 Hz distribution system, with 4 added synchronous-based DG units is presented in Fig. 2 [25]. It is used in this paper as a test system for the purpose of comparison with the conventional DOCRs protection scheme in [25], which applies FCL on the same test system, as will be described in Section 3.3. There are 21 directional overcurrent relays (DOCRs) that have the standard inverse time current characteristic (A and B are chosen 0.14 and 0.02, respectively). Other network parameters are presented in [25]. The DG units are rated at 2 MVA and 0.9 power factor, which are located at buses 4, 5, 6 and 9.

Moreover, the proposed approach is evaluated with inverter based DG units of photovoltaic systems (PV) and wind systems with double fed induction generators (DFIG) which have lower short circuit level compared to synchronous-based DG units as will be introduced in

Section 3.2. The achieved results indicate that the proposed technique is independent of DG type.

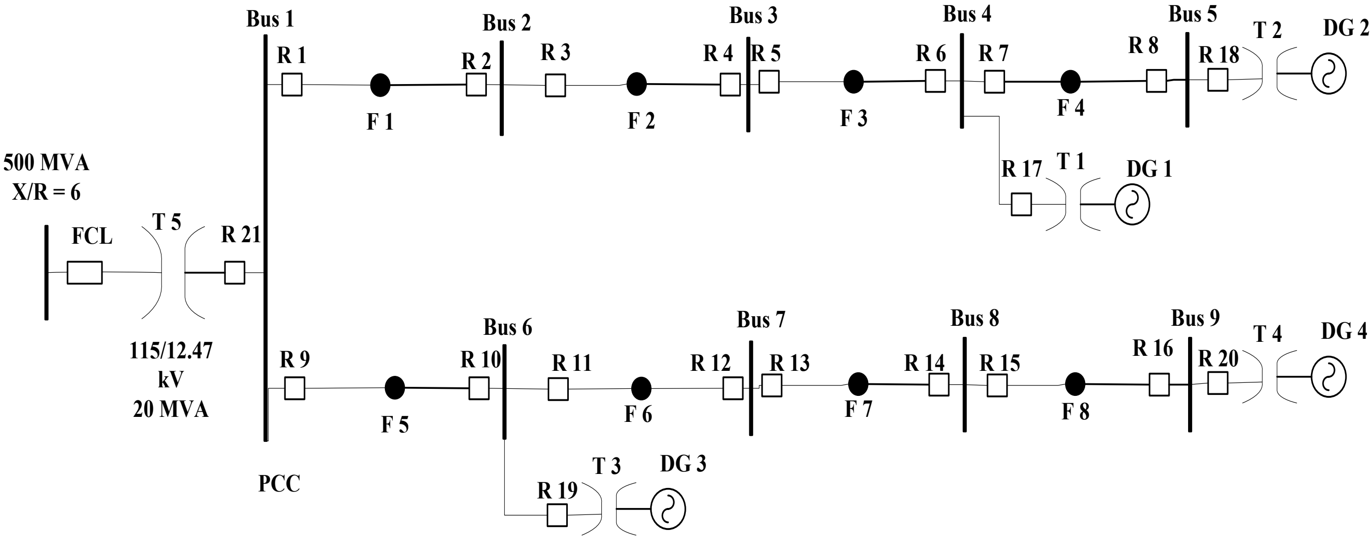


Fig. 2. Canadian distribution system embeded with DG unit.

3.1 Evaluating the proposed islanding detection approach

Some of disturbances, during which islanding detection techniques may suffer false operation, are the capacitor switching, load switching and DG switching. Consequently, in the next subsections, the proposed technique is evaluated under all these operational conditions. The results were recorded at three random locations chosen to represent different bus types: at feeder relay (R7), at DG relay (R20) and at load relay connected to bus 2. The islanded case is obtained for all cases by disconnecting PCC relay (R21).

3.1.1 Islanding scenario

The variation of the suggested islanding detector after islanding occurrence at all feeder and DG relays is illustrated in Fig. 3. The islanding detector values are approximately equal at all relays. From Fig. 3, it is clear that the calculated value of the proposed islanding detector exceeds the chosen threshold value (10 pu) at all relays.

In general, passive islanding detection methods may be seriously affected by the NDZ of active and reactive powers. If the load and DG power output are almost balanced, power mismatches ΔQ and ΔP are approximately equal to zero. In this case, the variation of voltage or frequency is not sufficient to discover islanding state [26]. Most of the conventional detection techniques may not be capable to detect such islanding scenario. To demonstrate the ability of the proposed islanding detector w.r.t. NDZ, the simulation study is carried out with 0% power mismatched in active and reactive powers.

The variation in the proposed detector ($\Psi = V_{pos} \times V_{neg} \times V_{zero}$) at different bus types: at feeder relay (R7), at DG relay (R20) and at load relay connected to bus 2 after islanding occurrence is illustrated in Fig. 4.

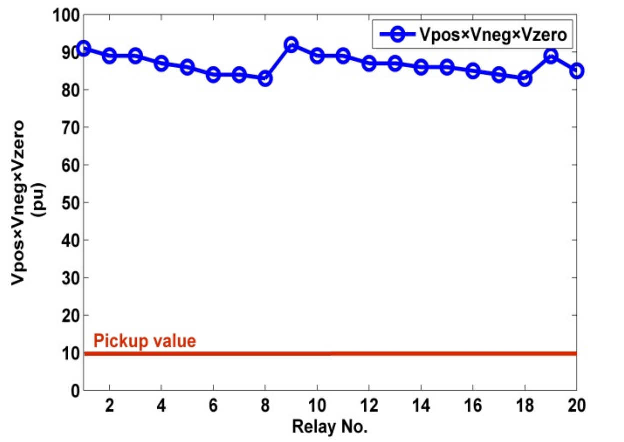


Fig. 3. Variation of proposed islanding detector for islanding occurrence at all feeder and DG relays.

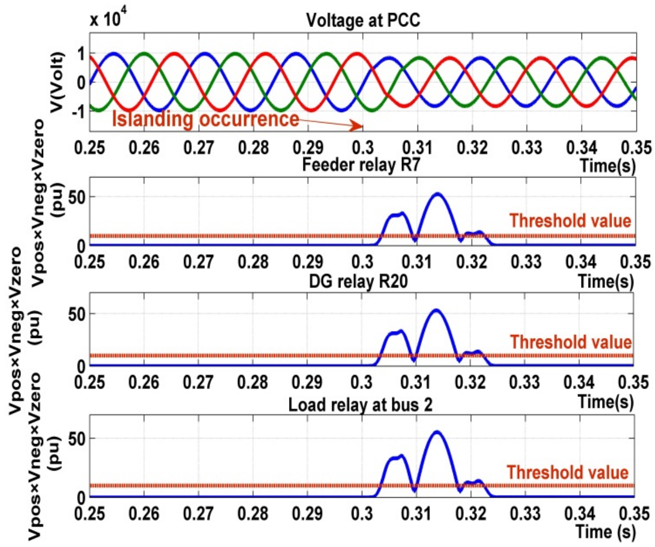


Fig. 4. Testing the proposed approach at different buses in case of islanding occurrence with zero power mismatches.

3.1.2 Load switching scenario

Load switching event is one of the disturbances, for which some islanding detection techniques may incur false operation. In this section, the behavior of the proposed method is examined under load switching (disconnection and connection of 2 MVA load at bus 4) against islanding occurrence. This case study proves the ability of the proposed method to identify the variation between load switching events and islanding cases. The variations of the proposed detector during such events are shown in Fig. 5 (load disconnecting at 0.1 sec, load reconnecting at 0.2 sec and islanding at 0.3 sec). The proposed islanding detector value is well below the threshold value for load switching (disconnection/connection). Therefore, load switching states are correctly distinguished as non-islanding events.

3.1.3 Load switching scenario under unbalanced condition

Normally, electrical power systems work in three-phase balanced sinusoidal steady-state mode. However, there are certain conditions that can produce unbalanced operations. Symmetrical components are a well-known theory of power system analysis. In addition of being a powerful analytical tool is conceptually useful and effective in monitoring and analyzing unbalances of the networks. The basic methodology for the proposed technique is to keep monitoring the unbalance in the three-phase output voltage of the network to effectively detect islanding conditions.

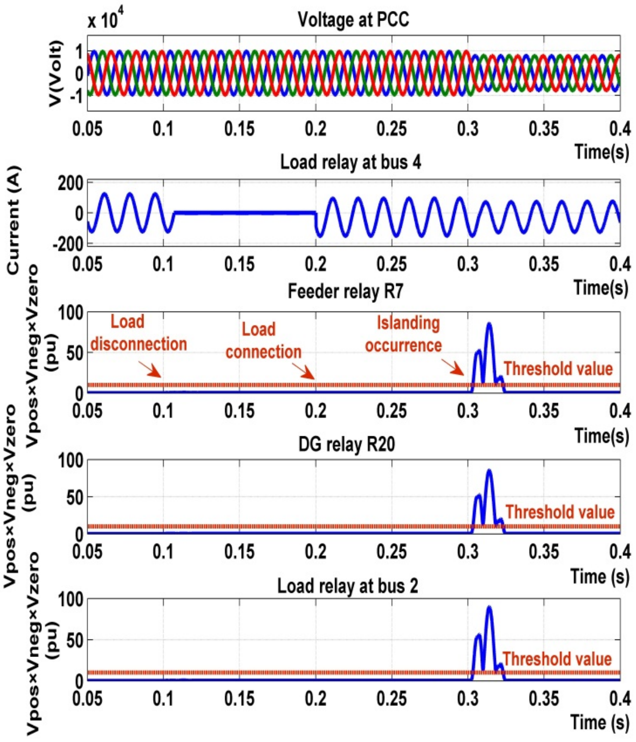


Fig. 5. Testing the proposed approach at different buses against load switching at bus 4.

To validate the reliability of the suggested islanding approach, different switching events (load connection/ disconnection and islanding conditions) are applied during unbalanced overloading condition. The loads in the network are simulated to operate in unbalanced manner to produce voltage unbalance up to 3% as shown in Fig. 6. In this figure, the load at bus 9 is disconnected at 0.1 sec, reconnected at 0.2 sec and then the islanding occurs at 0.3 sec.

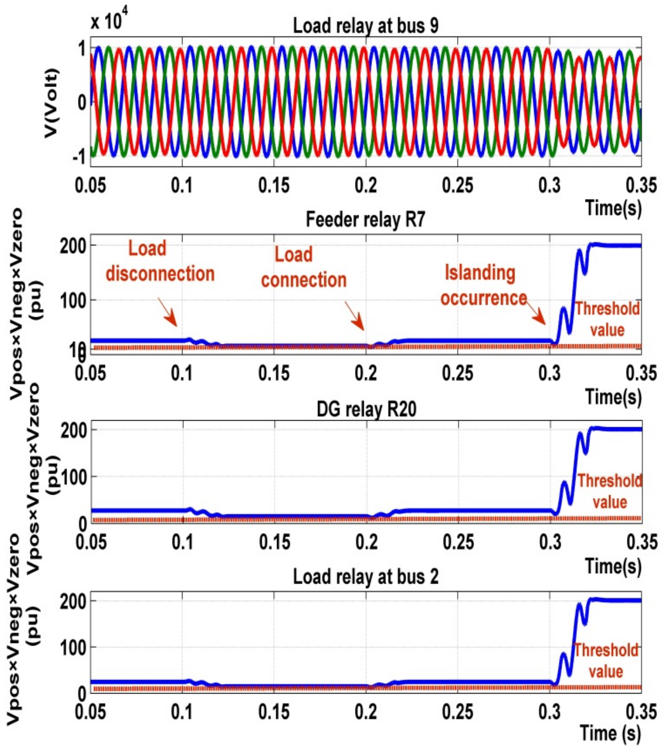


Fig. 6. Testing the proposed approach at different buses against load switching at bus 9 with 3% voltage unbalance.

To reach a high percentage of unbalance in the voltage signals, extremely high unbalance in the three phase currents (around 50%) are assumed. It is worth mentioning that practically such high percentage in the current unbalance is not allowable and it will be detected by the earth fault relays. However, we went that far to prove that the proposed algorithm is applicable even under severe unbalance conditions. As described in Section 2, the islanding case is confirmed when the proposed detector ($V_{pos} \times V_{neg} \times V_{zero}$) exceeds a predetermined threshold value during one cycle and at the same time it changes during this period and does not settled at a fixed value. As shown in in Fig. 6, the proposed detector during the transient period (one cycle) is almost constant during normal operation and load switching. For more explanation, although the detector values during normal operation and load switching are as shown in Fig. 6, the proposed algorithm did not operate since the detector value is almost constant during these conditions and therefore no false islanding condition is detected. Besides, the detector values during such normal load switching are significantly small compared with the value in case of islanding condition with zero power mismatches under balanced condition (as presented in Fig. 4). Moreover, the value of the suggested detector for the duration of the islanding condition has changed to a high value (has reached 100 pu) and not settled at a constant value during the transient period (one cycle). Therefore, with unbalanced loading, the load switching states are properly distinguished as non-islanding conditions with the existing threshold value.

In addition, in Fig. 7, the four single phase DG units (0.67 MVA) are linked to different phases, where the load at bus 9 is disconnected at 0.1 sec, reconnected at 0.2 sec and then the islanding occurs at 0.3 sec. As shown, the proposed detector during the transient period (one cycle) is almost constant for normal operation and load switching. Therefore, the proposed algorithm did not operate incorrectly since the detector value is almost constant during these conditions and no false islanding condition is discovered.

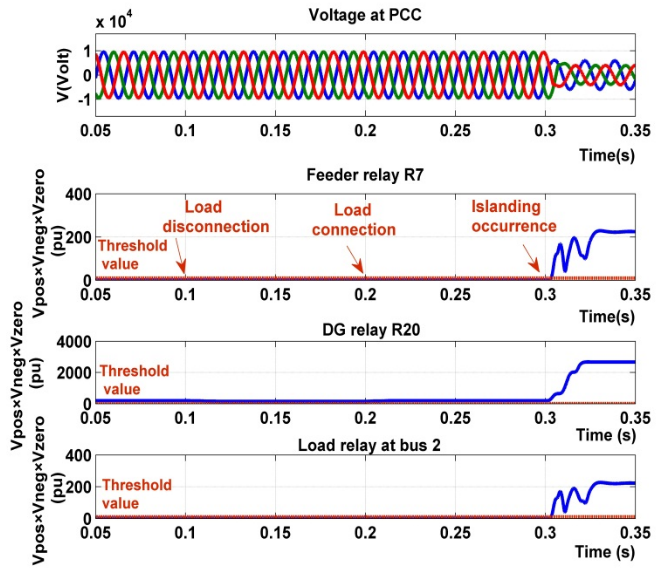


Fig. 7. Testing the proposed approach at different buses against load switching at bus 9 in case of all DG units are connected to different phases.

3.1.4 Capacitor switching scenario

Capacitors are commonly used for power factor correction and voltage sag compensation. At the in instant of capacitor switching, different parameters of the power system change, this may cause a wrong islanding detection. The proposed approach is examined in case of capacitor switching at bus 5 (connection and disconnection) against islanding occurrence. To improve the power factor from 0.9 to 0.95 lagging, 0.3 MVAR is installed. The variations in the proposed detector are shown in Fig. 8 (capacitor disconnecting at 0.1 sec, capacitor reconnecting at 0.2 sec and islanding at 0.3 sec). As illustrated in Fig. 8, switching states are correctly identified as non-islanding events.

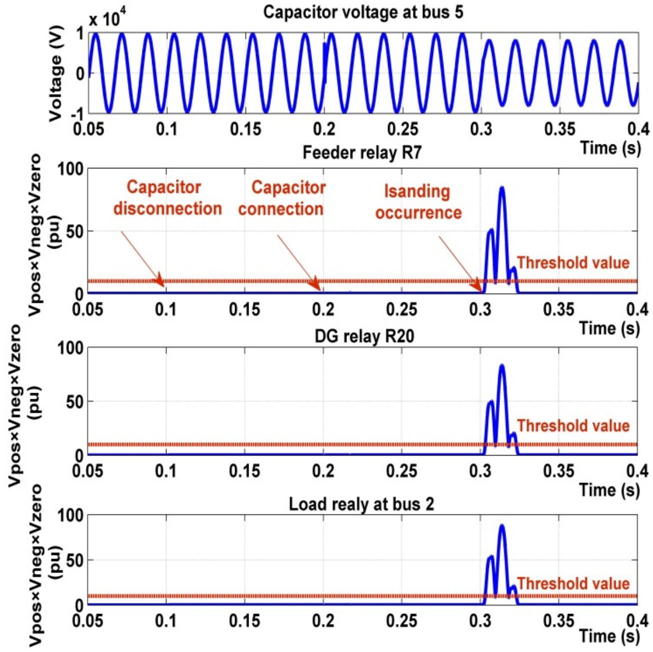


Fig. 8. Testing the proposed approach at different buses against capacitor switching at bus 5.

3.1.5 DG switching scenario

Different parameters of the electrical power system vary at the instant of DG switching (disconnecting /connecting states) which may produce false islanding detection. The performance of suggested islanding detection approach is assessed for DG (2 MVA) switching at bus 5. The approach distinguishes accurately the DG switching events from the islanding occurrence (DG is disconnected at 0.1 sec and reconnected at 0.2 sec while islanding is occurred at 0.3 sec). The proposed detector variation for the duration of the DG switching is illustrated in Fig. 9.

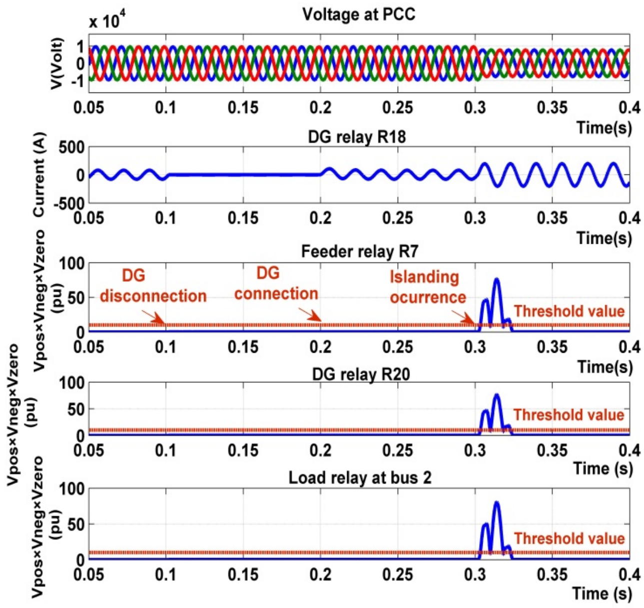
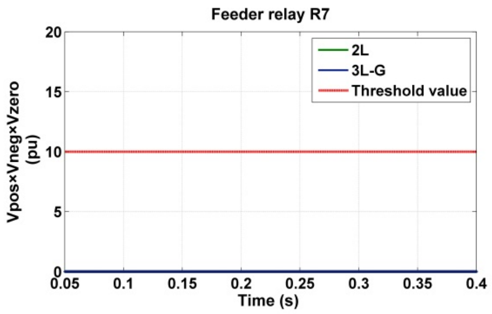


Fig. 9. Testing the proposed approach at different buses against DG switching at bus 5.

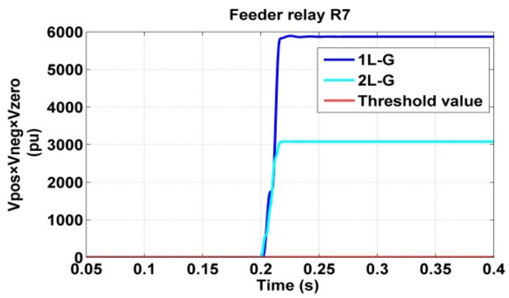
3.1.6 Short-circuit scenario

In this section, the suggested islanding detection approach is assessed during different short circuit faults including 1L-G, L-L, 2L-G and 3L-G at location F4 as shown in Fig. 10. The proposed detector is less than the threshold value before and after fault occurrence for both L-L and 3L-G faults as shown in Fig. 10-a. The variation in the proposed detector ($\Psi = V_{pos} \times V_{neg} \times V_{zero}$) after short circuit occurrence is zero since V_{zero} is zero. For both 1L-G and 2L-G, the value of the proposed detector is almost constant and higher than the threshold as long as the fault continues as shown in Fig. 10-b.

Having a constant value for the detector is completely differs from the variation occurs during islanding scenarios illustrated in previous figures.



(a) Variation of the proposed islanding detector for L-L and 3L-G faults



(b) Variation of the proposed islanding detector for 1L-G and 2L-G faults

Fig. 10. Variation of the proposed islanding detector for different fault types at feeder relay (R7).

3.2 Evaluating the proposed islanding detection technique with PV and wind DFIG

The proposed islanding detector is further assessed while the synchronous based DG at bus 9 is replaced by a PV source of 0.1 MW and wind station of 1.5 MVA.

For these two cases, the proposed method clearly identifies the dissimilarity between the islanding and non-islanding scenario of load switching of 2 MVA at bus 4. The variations in the proposed detector during such events (load disconnecting at 0.04 sec, load reconnecting at 0.08 sec and islanding at 0.1 sec) are shown in Fig. 11 and 12. It can be seen that, the proposed detector is less than the threshold value for both cases of load switching and exceeds the threshold value after the islanding occurrence. It is concluded that the proposed technique has high performance whether the network is connected to inverter based DG units or synchronous based DG units with different capacity.

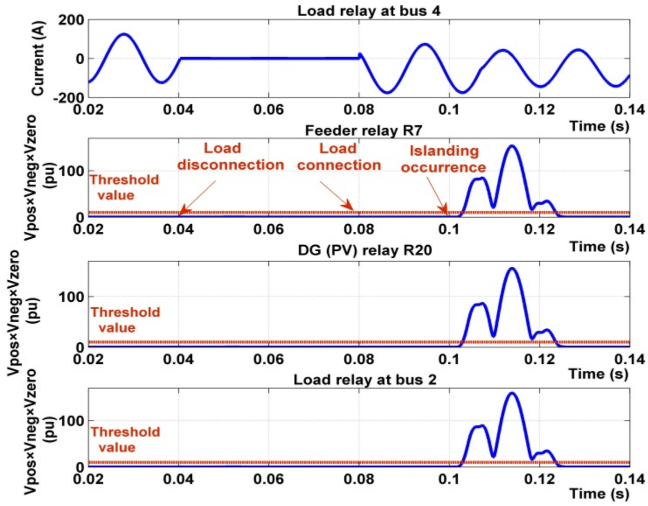


Fig. 11. Testing the proposed approach at different buses against load switching at bus 4 in case of PV (0.1 MW) connected at bus 9.

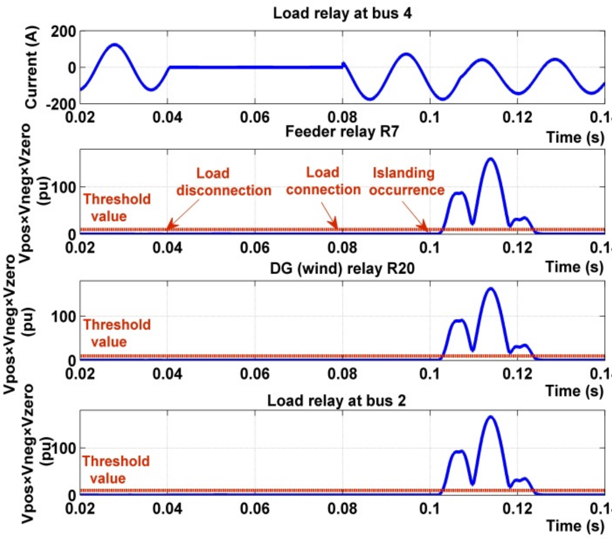


Fig. 12. Testing the proposed approach at different buses against load switching at bus 4 with a wind DFIG (1.5 MVA) connected at bus 9.

3.3 Improving the protective relays performance using the proposed islanding detector

The capability of microgrid to work in both islanded and grid-connected modes is considered a real challenge for protection scheme because of the significant difference in short circuit levels in those modes [27]. Typically, FCL is added and located near the PCC for limiting the fault current, contributed by the main grid to the microgrid and by the DG units in the microgrid towards the main grid [25]. By using FCLs, the infeasibility of traditional DOCRs to get suitable protection coordination was overcome; however, some relays have experienced large operating times. Also, adaptive protection methods are highly dependent on the communication system. The cost, redundancy, reliability, and speed of the communication systems are vital aspects that should be considered before implementing an adaptive protection scheme, especially in large networks. Besides, the communication failure may lead to the inability of protection scheme.

In this section, the suggested islanding approach is used to toggle between the two protective relays setting groups calculated and stored in the relay for grid-connected and islanded modes based on local measurement without using FCL or communication channels. Adaptive switching between the two modes setting of protection relays increases relays' sensitivity, reliability and selectivity.

Typically, the two setting groups are obtained by optimizing relays coordination as presented in [28]. For both islanded and grid-connected modes of operation, Table 1 shows the optimum settings. The coordination time interval (CTI) between backup and primary relays is considered as 0.2 s.

Table 1. Optimum settings for the two operational modes

Relay No.	Grid-connected mode		Islanded mode	
	TDS (sec.)	$I_{pick-up}$ (pu)	TDS (sec.)	$I_{pick-up}$ (pu)
1	0.3315	0.0838	0.3503	0.0138
2	0.1898	0.0838	0.4499	0.0138
3	0.2571	0.0544	0.1696	0.0406
4	0.2997	0.0544	0.3741	0.0406
5	0.1744	0.0242	0.0784	0.0683
6	0.5029	0.0242	0.3429	0.0683
7	0.05	0.0067	0.05	0.0190
8	0.5883	0.0121	0.3944	0.0346
9	0.3289	0.0847	0.3431	0.0147
10	0.1912	0.0847	0.4435	0.0147
11	0.2412	0.0726	0.2497	0.0207
12	0.2485	0.0402	0.3747	0.0207
13	0.1542	0.0432	0.1937	0.0078
14	0.284	0.0432	0.6299	0.0078
15	0.05	0.0067	0.05	0.0190
16	0.5937	0.0121	0.3966	0.0346
17	0.6188	0.0105	0.3975	0.0337
18	0.7001	0.0106	0.4453	0.0343
19	0.4459	0.0105	0.2917	0.0342
20	0.7057	0.0106	0.444	0.0348
21	0.3876	0.1101	-	-

Table 2 compares the total operating time of the suggested approach with another approach [25] uses FCL. The results show a reduction in operating time of the suggested approach with 15.6% and 11.5% for grid-connected and islanded modes respectively.

Table 2. Comparison of total operating time for proposed scheme and the scheme using FCL presented in [25].

Mode	Total operating time (sec)	
	Proposed scheme	Scheme with FCL [25]
Grid-connected mode	32.4032 sec	38.3843 sec
Islanded mode	33.3158 sec	37.6335 sec

The features of the enhanced protection scheme in this section can be summarized by:

- The salient feature of the protection scheme is that it is autonomous adaptive and does not require communications or additional elements which means more economic operation.
- It is more sensitive as it has two pickup current settings, one for each mode of operation rather than using FCL with one pickup setting for both modes.
- Notable reduction in total operating time is achieved in both grid-connected and islanded modes.

3.4 Comparing the proposed islanding detector with prevalent islanding detection techniques

Different islanding methods have been designed and executed in real applications. The most commonly used passive techniques are over/under frequency protection (OFP/UFP), over/under voltage protection (OVP/UVP) , total harmonic distortion (THD), rate of change of voltage ($ROCOV$), rate of change of voltage sequence components ($ROCOVSQ$) and voltage unbalance (VU). Although, these methods have the benefit of relatively easy execution and simple operation, they suffer from performance problems such as non-detection zone when the load mismatch is relatively small and the wrong trip due to non-islanding cases. In this section, the performance of the suggested islanding approach has been compared with most prevalent islanding detection techniques as indicated in Fig. 13. The figure demonstrates the performance of the proposed islanding detector ($V_{pos} \times V_{neg} \times V_{zero}$) compared with different islanding detection techniques (VU, $ROCOV$, THDV, $ROCOVSQ$) at bus 9 during different events: load disconnecting at 0.1 sec, load reconnecting at 0.2 sec and islanding with small power mismatch at 0.3 sec. As shown, the proposed detector ($V_{pos} \times V_{neg} \times V_{zero}$) is less sensitive for normal load switching (disconnection/connection) compared to other passive islanding techniques. Therefore, load switching cases are correctly distinguished as non-islanding events. On the other hand, the suggested approach is also more sensitive for detecting the islanding occurrence in case of small power mismatch.

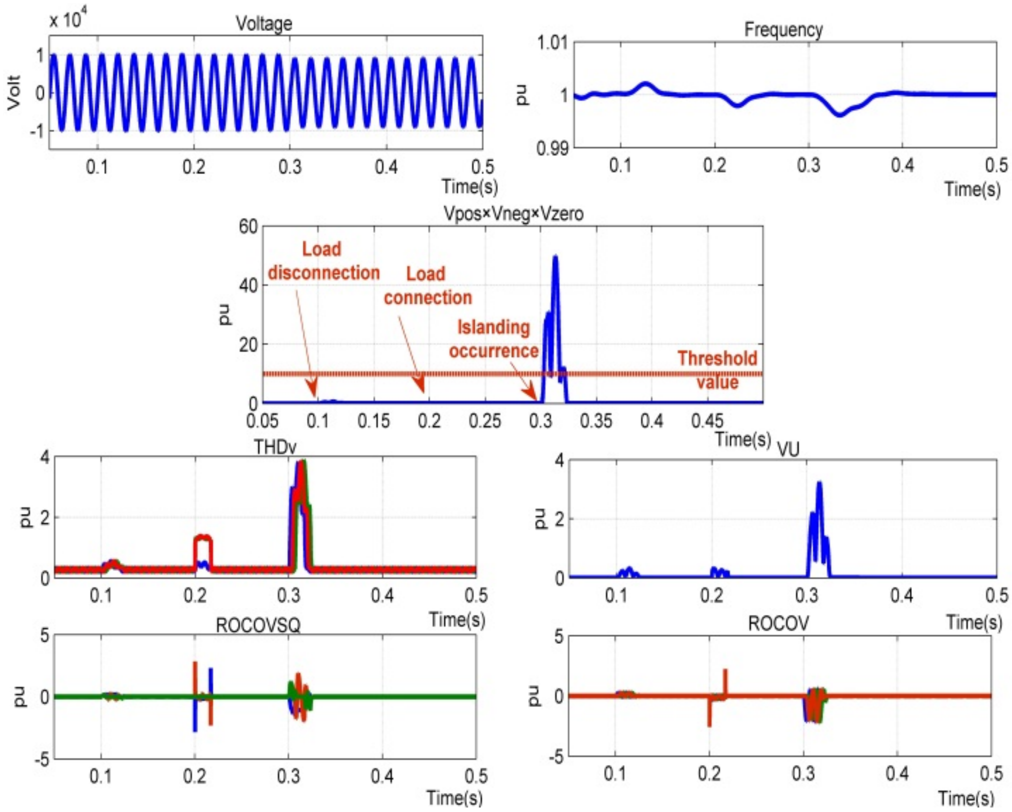


Fig. 13. Performance of the proposed approach compared to other approaches at bus 9 against load switching and islanding with small power mismatch.

In addition, Table 3 demonstrates a brief comparison between different passive techniques and the proposed technique. The suggested passive approach has the merit of not suffering from any false detection for the tested scenarios and not having any NDZ. All relays in the network including relays at DG unit buses, feeders and loads can detect the islanding case with only one threshold value. The threshold value is determined based on simulated islanding event with zero power mismatches for all relays. The proposed technique improves the protection performance by updating the relay settings based on local measurement. Also, being a passive technique, it does not disturb the power quality of the network. On the other hand, some of published techniques are faster than the proposed technique with less than one cycle [15], [17].

4. Conclusion

In this paper, a new islanding detection approach is proposed based on the product of voltage sequence components. The extensive simulation results proved that the technique is able to distinguish all non-islanding events including capacitor switching, load switching, DG switching and short circuit occurrence from the islanding situation.

The benefits and key contributions of the proposed approach as compared to the state-of-the-arts can be summarized as follows:

- A passive approach is proposed for islanding detection based on a new suggested sensitive islanding detector.
- All relays in the network including relays at DG unit buses, feeders and loads can detect the islanding case with only one threshold value.
- The proposed passive detection technique has no NDZ even with zero power mismatches.
- The threshold value for all relays is determined based on a simulated islanding event with zero power mismatch compared to other techniques that require different simulation studies for determining a threshold value at each DG terminal.
- It has excellent performance whether the network is connected to inverter-based DG units or synchronous based DG units.
- The proposed detector is less sensitive for normal load switching (disconnection/connection) compared to other passive islanding techniques.
- The proposed technique offers an autonomous adaptive protection scheme based on local measurements.
- The proposed islanding technique improves the protection performance of the islanded microgrid since the protection relays switch between the two modes settings following the successful islanding detection.
- The simulation results for coordination indicated a notable reduction in operating time for the two modes of operation compared with the schemes using FCL.

Table 3. Comparison between the proposed islanding detection approach and different passive approaches.

The technique	NDZ	Threshold simplicity	Detection location	DG type	Detection time
Under/over voltage [6]	Large	Simple	DG relay	Inverter-based DG	4 ms to 2 sec
Under/over frequency [6]	Large	Simple	DG relay	Inverter-based DG	4 ms to 2 sec
Rate of change of reactive power (***ROCORP***) and voltage (***ROCOV***) [7]	Large	Complicated	DG relay	Synchronous based DG	0.25 sec
THD of current and ***ROCORP*** [8]	Large	Complicated	DG relay	Inverter-based DG	60 ms
Phase angle between current and voltage [9]	Medium	Complicated	DG relay	Synchronous and inverter-based DG units	One cycle
Power spectral density [10], the rate of change of frequency dependent impedance [11], harmonic grid impedance [12]	Less than UF/OF	Complicated	DG relay	Inverter-based DG	Less than 0.24 sec
Voltage unbalance and THD of current [13]	Small	Complicated	DG relay	Inverter-based DG	Within 2 sec
Sequence components of current [14]	Zero	Complicated	DG relay	Synchronous and inverter-based DG units	Up to 0.2 sec
Rate of change of positive sequence of voltage and current signals [15]	Small	Complicated	DG relay	Synchronous and inverter-based DG units	10 ms
Wavelet and S-transform based method, wavelet singular entropy-based method, probabilistic neural network-based method, and data mining based intelligence approach [17]	None	Complicated	DG relay	Synchronous and inverter-based DG units	Less than one cycle
Proposed islanding detection technique $\Psi = \boldsymbol{V_{pos}} \times \boldsymbol{V_{neg}} \times \boldsymbol{V_{zero}}$	Zero	Simple (one threshold value for all relays)	At all relays to improve the protective relays performance based on local measurements only	Synchronous and inverter-based DG units	One cycle

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