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Multi-function Intelligent Relay for Distributed Generations Using Paraconsistent Annotated Logic of 4 Values

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Abstract: This paper presents the intelligent multi-function protection relay (IR) for inverter-based systems using a paraconsistent neural network. This network works with degrees of favorable, unfavorable evidence, sensitivity and time. The IR includes islanding, fault detection, fault type recognition, and selective fault blocking. The proposed multi-function APL4v IR was tested in a hardware-in-the-loop (HIL) environment. The results show that the proposed IR is superior to the traditional islanding recognition methods regarding reliability, safety and detection time.

Key words: paraconsistent neural network, islanding detection, distributed generation (DG)

1. Introduction

The Brazilian Energy Sector is under intense transformation, the decentralized and environmentally sustainable supply has driven the use of small and medium-sized generations (microgeneration and mini-generation) connected to distribution systems called Distributed Generations based on inverters (DGs). The use of DGs is beneficial to power utilities, DG owners and end-users as it improves reliability, energy quality and is economically advantageous. However, several technical conditions need to be analyzed concerning the insertion of DGs, to identify the impacts caused in the electrical network. One of these conditions is the islanding that can be classified in intentional islanding when the generation source is disconnected from the network and the unintentional islanding when short-circuit problems and device failures are detected in the distribution network.

The unintentional islanding must be detected by the DG protection system, as it can cause deterioration of the quality of energy, life risk for the maintenance teams, as well as problems in the protection of the islanded distribution system. On the other hand, undue detection may result in instability of the interconnected system in cases of heavy dependency on DGs, a decrease of the quality of the energy, attenuation of the quality of the supply, as well as the reduction of the reliability of the distribution system, besides the increase of operating costs.

The anti-islanding protection techniques can be classified according to their operational characteristics and can be classified in remote and local techniques.

Remote techniques are more reliable and efficient in detecting islanding than local techniques. However, remote techniques are little used due to the high operational cost and the need for a flawless

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communication network, and it has as a functional principle the communication between the utility, the protection devices, the switching devices of the distribution network and the DG [5].

The local techniques are divided into three classes: passive, active and hybrid [1, 2]. Among the typical active techniques, the most frequent are: Active Frequency Drift (AFD), Sandia Frequency Shift (SFS), Slip Mode Frequency Shift (SMS) and impedance measurement method. These techniques introduce into the distribution system instability that is normalized by connection to the host system or causes a disturbance that is absorbed by the interconnected system. The occurrence of the islanding arises from the loss of connection with the interconnected system and the parameters of the generations distributed as voltage, frequency, impedance suffer a variation that is used for the detection of the islanding. These techniques present deterioration in the quality of the electric energy and are associated with the generators that use inverters for the connection to the electric grid, leading to the failure of islanding detection [6].

The hybrid techniques combine low non-detection zones (NDZ) of the active methods and the non-interference in the quality of the electric energy of the passive methods. Generally, hybrid methods use a passive technique to perform a first assessment of the state of the distribution system. When an abnormality is detected, an active method is employed to force the system to a condition that characterizes the islanding.

Fault detection is another important part of DG interoperability detection. The operational rules of DGs require immediate disconnection at the beginning of any failure. Among the types of faults, those involving short-circuits are the most notable ones, standing out the lack of a single-phase line-to-ground short circuit that corresponds to 70% of this fact.

Therefore, this article proposes a multi-function Intelligent Relay (IR) for inverter-based systems, using 4-Values Annotated Paraconsistent Logic, which allows the treatment of inconsistent, indeterminate or indefinite signals. The analysis of signals using APL4v allows several problems caused by contradictory, imprecise or indefinite situations to be treated in a way that detects the fault or fault closest to its reality, in addition to analyzing the behavior of the specialists over time. This method gave rise to the algorithm called “Para-Specialist” implemented in IR.

2. Material and Methods

To develop the paraconsistent relay, the methodology applied is described below:

2.1 The Annotated Paraconsistent Logic (APL)

The IR-APL4v has as its operational principle a non-classical logic called Paraconsistent Annotated Logic (APL). Which deals with contradictions, inaccuracies of data or signals, coming from the same source or from different sources, solving these inconsistencies. For each proposition, which are symbolic sentences that define something as true or false, two degrees are associated, the degree of favorable evidence (μ) and the degree of unfavorable evidence (λ). The analysis of the degrees produces an output called the resulting logical state.

2.2 Algorithms of logical APL4V

Paraconsistent Logic algorithms for 4 values are based on the Paraconsistent Analysis Nodes (PAN). These, when interconnected, make up the paraconsistent neural network of decision-making analysis.

The PANs are algorithms extracted from the Paraconsistent Logic and form the networks of paraconsistent analysis, constituting the treatment of the islanding event. With their inputs being fed by the Evidence Degrees taken from an uncertain knowledge database, the PANs use the equations obtained from the APL methodology and obtain the results in the form of the Real Certainty Degrees (G_{RC}). These values of (G_{RC}) can be normalized to become the Degree of Evidence resulting.

The normalization of favorable and unfavorable degrees of evidence in APL algorithms produces on the output of the PAN a degree of evidence resulting μ_{ER} and an interval of evidence value φ_E, both belonging to the set of real numbers [0,1]. The symbolic representation of a PAN is shown in Fig. 1.

In PAN the value of the outcome evidence degree μ_{ER} represents the value of the resulting evidence regarding the Analyzed Proposition, and the Evidence Interval φ_E informs how much the value of the evidence signal obtained can vary, with the same Degree of contradiction presented by the evidence information applied in the entries [10, 11]. The purpose of the PAN algorithm is to analyze the values of the degrees of favorable evidence and of unfavorable evidence according to the Paraconsistent Annotated Logic of two-valued annotation (APL2v). If the system perceives a high degree of contradictory or inconsistent information, it may request more information through its specialists who will analyze the evidence through the degrees of specialties (e), the maximum degree of specialty ($e_{máx}$ = 1) and the minimum degree of specialty (e_{min} = 0) known as a neophyte. The Specialists have the role of decision-making in a manner consistent with the minimum of indecision or ignorance of the cause. The minimal specialty degree (e_{min}) neophyte due to its inexperience, I acquired the experience as the variable time (t) goes through. In this way, your specialty increases to define two logical states True or False. This analysis can be done for any level of specialty. The fourth dimension "time"

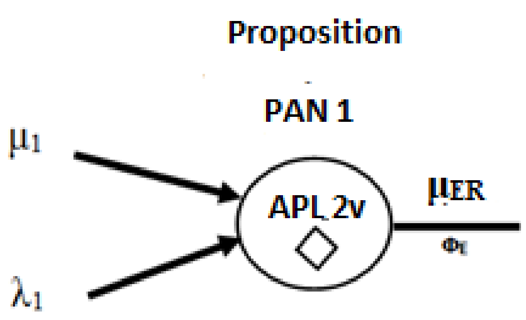

Fig. 1 Representation of a PAN (Paraconsistent analysis node).

allowed to visualize the behavior of the specialists in the decision making of the system making the extremely sensitive. Therefore, the Paraconsistent Logic of 4 Values is represented by the quadruple (μ, λ, e, t). Through the training process, according to the configuration of the distribution feeder, the islanding and fault events are simulated in real time. During the simulations, the voltage and current measurements at the common coupling point (PCC) of the DG are captured and stored for analysis by the system called the Paraconsistent Analysis Node (PAN). Based on the obtained data, the resources have patterns or characteristics of variation that during the islanding conditions and faults are calculated, as for example the frequency, rate of change of frequency, active and reactive power. After the data is processed, the proposed logic is used to find the best characteristics with high confidence and security indexes that will be incorporated into the intelligent relay (IR).

2.3 Feature of Extraction

The main characteristics selected in the PCC of the DG are used to form the decision-making models according to Table 1, where we can notice twenty-seven parameters associated to measured and/or calculated quantities, which are used by the extractor algorithm in order to be used by the paraconsistent neural network.

2.4 The Islanding Detection Function

In the islanding detection function, the relay logic is trained from numerous loading scenarios of the system in order to cover different system conditions and minimize its zone of non-detection by choosing the best characteristics. Breaker opening events and faults can also be recognized by the islanding function. In addition, the islanding detection function can also prevent undue disarming, since all possible non-islanding events, such as load reduction, load increase, capacitor switching, are part of the training scenarios. Therefore, the islanding detection logic is constructed with enough information to distinguish the islanding and non-islanding conditions.

Table 1 Characteristic extraction input parameters.

Parameter	Variable	Description	Dimension
X_1	F	Frequency	Hz
X_2	ΔF	Frequency deviation	Hz
X_3	dF/dt	ROCOF	Hz/s
X_4	V	Voltage	pu
X_5	ΔV	Voltage deviation	pu
X_6	dV/dt	ROCOV	pu/s
X_7	I	Current	pu
X_8	ΔI	Current deviation	pu
X_9	dI/dt	Rate of change of current	pu/s
X_{10}	P	Active power output	pu
X_{11}	ΔP	Deviation of active output power	pu
X_{12}	dP/dt	Active power output change with time	pu/s
X_{13}	Q	Reactive power output	pu
X_{14}	ΔQ	Output reactive power deviation	pu
X_{15}	dQ/dt	Reactive power output change with time	pu/s
X_{16}	$\cos\phi$	Power factor	
X_{17}	$\Delta\cos\phi$	Power factor deviation	
X_{18}	$dcos\phi/dt$	Rate of change of power factor	
X_{19}	φ	Phase angle	rad.
X_{20}	$\Delta\varphi$	Change in the phase angle difference	rad.
X_{21}	$d\phi/dt$	Rate of change of phase angle difference	rad./s
X_{22}	V_{THD}	Voltage total harmonic distortion	
X_{23}	ΔV_{THD}	Deviation of the total harmonic distortion of the voltage	
X_{24}	dV_{THD}/dt	Rate of change of total harmonic distortion of voltage	
X_{25}	I_{THD}	Current total harmonic distortion	
X_{26}	ΔI_{THD}	Deviation of the total harmonic distortion of the current	
X_{27}	dI_{THD}/dt	Rate of change of total harmonic distortion of current	

2.5 The Fault Detection Function and the Fault Type Recognition Functions

This function detects all types of symmetric and asymmetric faults within their protection zones employing different combinations of features (parameters) of DG. Through the Network of Paraconsistent Analysis (PAN) that provides secure information about which propositions with a greater or lesser degree of contradiction. With this information, the system is able to make more reliable decisions, besides having the values to act in the control of the input signals, weakening or strengthening the evidences to diminish the contradictions to produce a robust decision system and able to bring results with high degree reliability.

This function can identify four types of faults: ground fault (LG), line-fault (LL), three-phase phase fault (LLL) and line-to-ground fault line (LLG). In addition, for earth faults, the variable impedance faults are considered in the proposed relay training period to improve the adaptability of the fault detection function.

2.6 Selective Blocking Function Fault Ride Through

The proposed fault-selective blocking function is obtained through PAN analysis, using the information obtained by the islanding detection functions, faults, and recognition of the failure type.

Fig. 2 shows the functional diagram of the proposed intelligent relay. Indicating for islanding events, faults, blocking and fault identifiers. Fault logic is supervised by selective blocking logic through logic E.

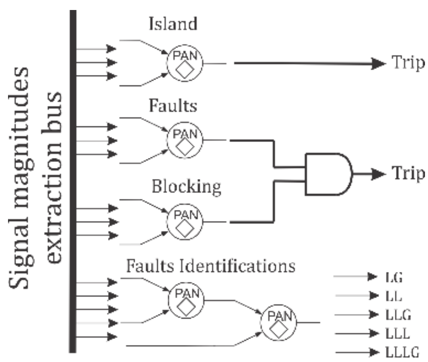

Fig. 2 Representation of a PAN (paraconsistent analysis node).

3. Results and Discussion

In order to evaluate the performance of the proposed relay, the IEEE 34 bus test network was simulated in real-time in the Typhoon-HIL equipment with two islanding situations, by opening the connection line between 800 and 802 (islanding 1) and between 830 and 854 (islanding 2) as shown in Fig. 3, where each of the DGs had the proposed relay. Two loading conditions were considered, 100% and 50%. In the first, the system load is equal to the load of the IEEE bus 34 of the original test system; in the second, the load is reduced by 50%. The tests also included two levels of distributed generation penetration: 2.5 MW and 1.0 MW, resulting in eight different situations. From these eight simulations, faults were incorporated into the 802, 830, 852 and 842 bars and two fault impedances, 0 Ω and 60 Ω, two load conditions, 50% and 100%, and two distributed generation penetration levels. A total of 2160 simulated cases were used, of which 50% were used for the training of the paraconsistent neural network and the remaining 50% were used for the recognition of islanding patterns, faults, types of faults and selective block.

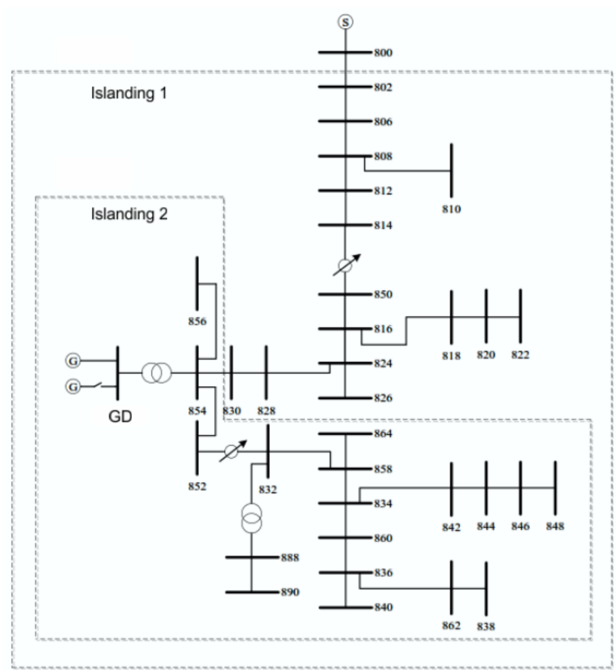

Fig. 3 Detection of islanding tested in the IEEE 34 bus test system [6].

In Fig. 4 it can be seen that the real-time simulation environment is performed on the Typhoon-HIL equipment, which serves as a coupling for the actual control of the Intelligent Relay used in the IEEE 34 bus test system.

The waveforms presented in Fig. 5 characterize two situations. The first situation, represented by Figs. 5a and 5b, shows the frequency and line voltage of phase "a" when the bar 802 is opened, respectively. These signals were extracted from the DG bar, which in turn demonstrates the penetration capacity of the proposed relay. The second situation, shown by Figs. 5c and 5d, shows the frequency and line voltage of the phase "a" When a single-phase short-circuit LG occurs in the bar 802, where it is possible to see the penetration capacity of the proposed relay.

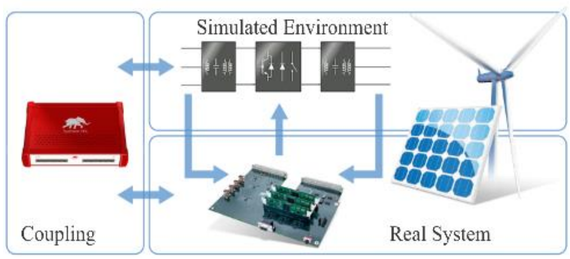

Fig. 4 Real-time system operation diagram.

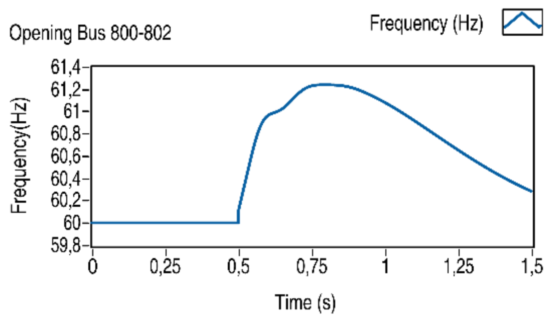

Fig. 5(a) Characteristics of signs extracted in bus DG: Frequency characteristic during bus 802 opening.

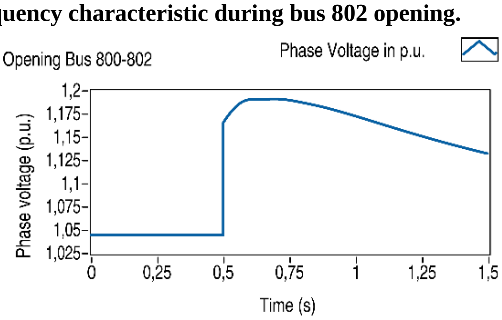

Fig. 5(b) Characteristics of signs extracted in bus DG: Characteristics of line voltage at phase "a" during the

opening of bus 802.

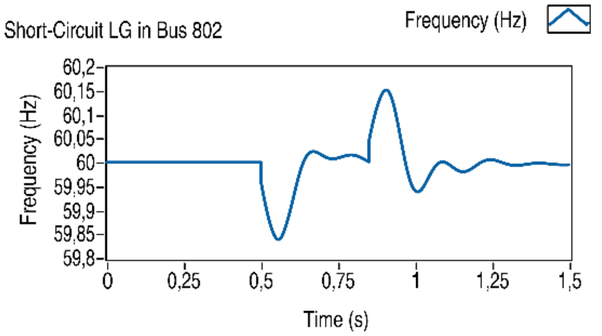

Fig. 5(c) Characteristics of Signs Extracted in Bus DG: Frequency characteristic during LG single-phase short-circuit on bus 802.

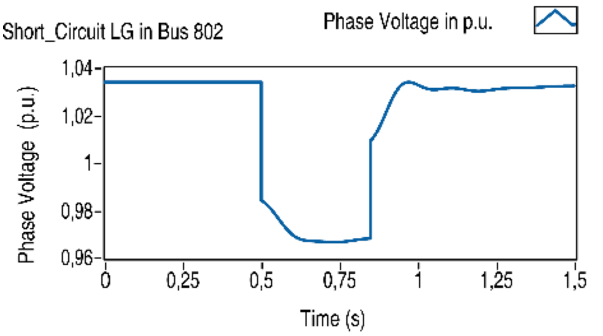

Fig. 5(d) Characteristics of Signs Extracted in Bus DG — voltage characteristic — of the line in Phase "a" during the single-phase short-circuit LG on bus 802.

A Paraconsistent Neural Network (PNN) was developed based on the PAN para-specialist algorithm. The algorithm formed by 52 PANs can analyze the islanding condition based on the classification of the deviation and the degree of pertinence of each of the deviations. These degrees of the pertinence were divided into three large groups, which relate voltage, current, and frequency, which relates the powers with cos (φ) and what relates the angle to the THD's (voltage and current). Fig. 6 shows the paraconsistent neural network. It should be noted that 3 more algorithms were constructed in order to complete the functions of the proposed relay. In this work, only the main algorithm is demonstrated. Therefore, the events of faults, blocking and fault identifiers are not displayed, but for the operation were incorporated from the controller.

After the training of the paraconsistent neural network, based on the proposed logic, the following results are

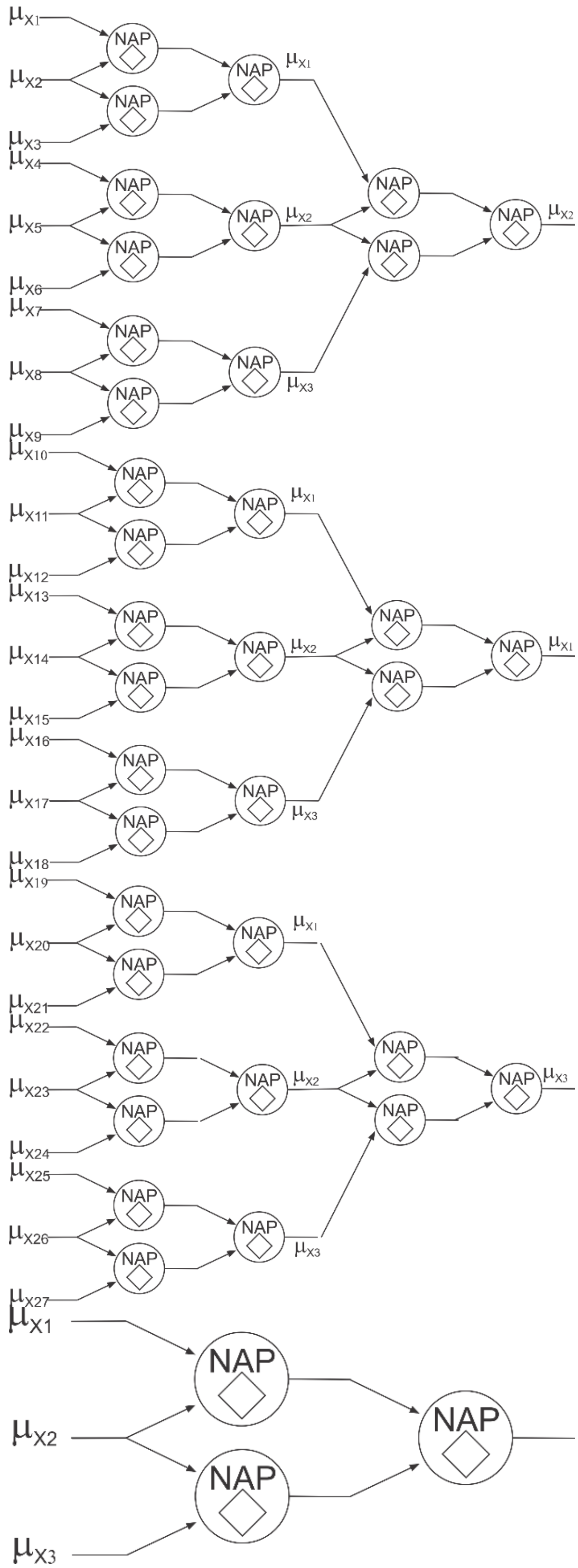

Fig. 6 Diagram of the Paraconsistent Neural Network applied in the recognition of islanding.

presented in Fig. 7, where it can be noted the performance comparisons between the proposed intelligent relay and the ROCOF and ROCOV relays.

Fig. 7a compares the proposed relay with the ROCOF relay in DG1 with the settings of 0.1 Hz/s and 0.25 Hz/s varying the active power given in p.u., it is observed that the proposed relay results in any range of active power corresponds to 100% accuracy. In Fig. 7b the comparison of the proposed relay with the ROCOV relay in DG1 with the 0.07 V/s and 0.1 V/s adjustments by means of the variation of the reactive power given in p.u., it is noted that the relay result proposed in any variation of the reactive power corresponds to 100 % accuracy. Fig. 7c compares the proposed relay with the ROCOF relay in DG2 with the settings of 0.1 Hz/s and 0.25 Hz/s by varying the active power given in p.u., it is noted that the proposed relay results in any active power range corresponds to 100% accuracy. In Fig. 7d the comparison with the proposed relay with the ROCOV relay in DG2 with the 0.07 V/s and 0.1 V/s adjustments by means of the variation of the reactive power given in p.u., it is noticed that the result of the proposed relay in any variation of reactive power corresponds to 100 % accuracy.

The consolidation of the comparison of the Multifunction Intelligent Relay with the ROCOF relay is shown in Fig. 7e and, finally, Fig. 7f shows the consolidated comparison between the proposed intelligent relay and the ROCOF relay where the reliability rate was 100%.

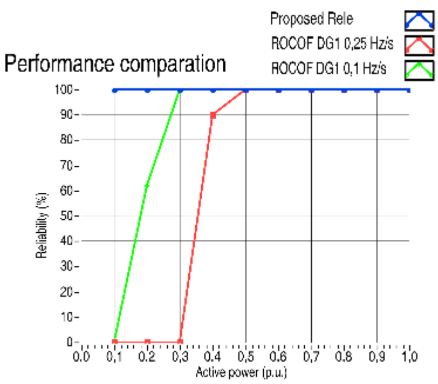

Fig. 7(a) Comparison of performance of the proposed relay: Comparison of the proposed relay with the ROCOF relay in DG1.

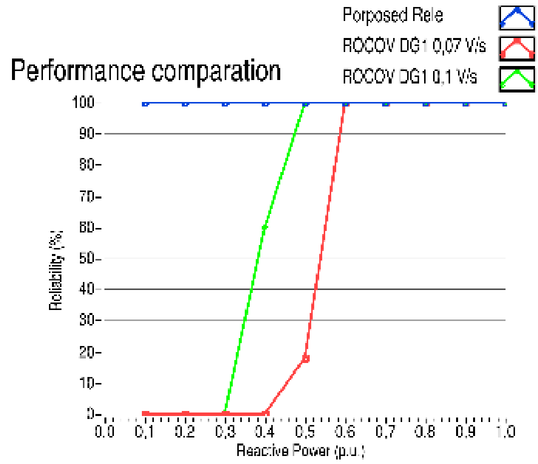

Fig. 7(b) Comparison of performance of the proposed relay: Comparison of the proposed relay with the ROCOV relay in DG1.

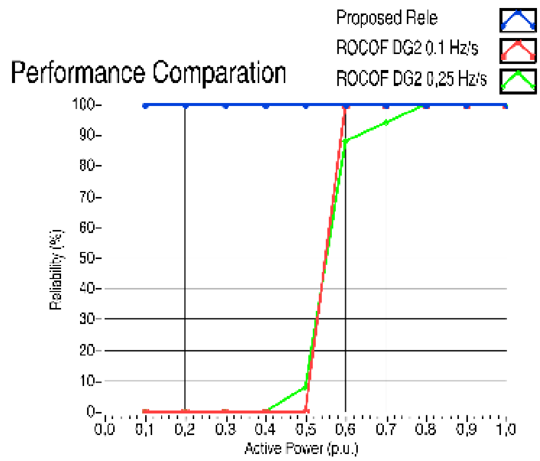

Fig. 7(c) Comparison of performance of the proposed relay: Comparison of the proposed relay with the ROCOF relay in DG2.

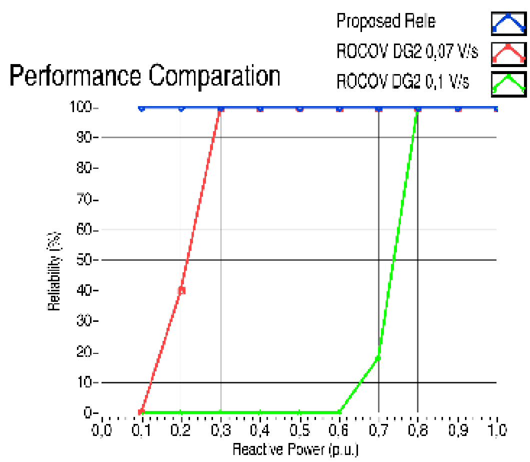

Fig. 7(d) Comparison of performance of the proposed relay: Comparison of the proposed relay with the ROCOV relay in DG2.

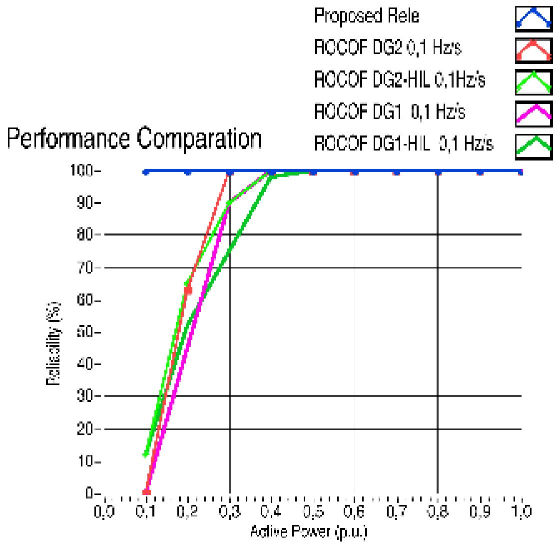

Fig. 7(e) Comparison of performance of the proposed relay: Comparison of the proposed relay with the ROCOF relay in DG1 and DG2.

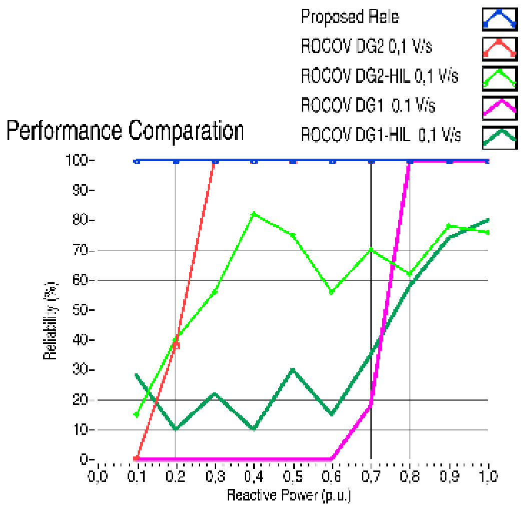

Fig. 7(f) Comparison of performance of the proposed relay: Comparison of the proposed relay with the ROCOV relay in DG1 and DG2.

4. Conclusion

The proposed intelligent relay was efficient when compared to traditional ROCOF and ROCOV islanding recognition methods. It was observed that the ROCOF relay and ROCOV relay failed to recognize islanding whenever the active or reactive power was low, in the order of 0.1 to 0.5 p.u.. The proposed relay in any power operation responded in a very relevant way since achieved 100% accuracy. Due to the nature of the PAN, the processing speed of islanding and fault recognition is fast, in the order of 10.3 to 45.8%. Another is that the computational cost of the algorithm is very low because it involves simple mathematical operations that can be applied to digital signal processors.

Appendix

A nomenclature list, if necessary, to guide the reader in reading the article.

APL	Annotated Paraconsistent Logic
AFD	Active Frequency Drift
DG	Distributed Generation
μ_{ER}	degree of evidence resulting
G_{RC}	Real Certainty Degrees
IR	Intelligent Relay
φ_E	interval of evidence value
NDZ	Non-detection zones
SFS	Sandia Frequency Shift
SMS	Slip Mode Frequency Shift
PAN	Paraconsistent Analysis Nodes
PNN	Paraconsistent Neural Network

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