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Islanding detection of synchronous distributed generators

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Abstract. This paper analyses the performance of local passive islanding detection methods for synchronous distributed generators, under different grid and load scenarios. These methods monitor electrical parameters at the interconnection point of a distributed generator and detect island situation whenever these parameters change correspondingly. Lately, islanding detection research has been focused on inverter based systems. But synchronous generators still pose a challenge for study. With this aim, a low voltage distribution network with embedded synchronous generators has been modelled. The performance of frequency and rate-of-change-of-frequency relays have been evaluated, analysing the influence of power mismatch and generator characteristics on the islanding and also avoid false operation.

Key words

Distributed generation, islanding detection, synchronous generator, microgrid.

1. Introduction

Islanding is a condition that occurs when part of the electrical network is disconnected from the remainder of the power grid, but remains energized by a distributed resource. Distributed resources (DR) are demand supply-side resources that can be deployed throughout an electric distribution system to meet the energy and reliability needs of the customers served by that system. Related to DR emerges the concept of a microgrid, i.e. a group of interconnected loads and distributed energy resources, within clearly defined electrical boundaries, that acts as a single controllable entity with respect to the grid. A microgrid is able to operate either connected to the grid or islanded. However, current practices do not permit autonomous operation due to the hazards related to the operation in island. Though, regulation is being drafted by the IEEE Working Group IEEE 1547-4 for utilities and independent power producers for islanded operation [1].

Research has been carried out to study islanding detection both for unplanned islanding, due to a fault in the grid, and for future preplanned islanding and subsequent microgrid operation. Currently, no islanding detection scheme can serve all situations in a microgrid. Therefore, the method is normally selected according to the nature of the distributed generator (DG). DG technology can be inverter-based or rotating machine-based generation, both synchronous and induction generators.

The paper is organized as follows. Islanding detection methods for synchronous generator based networks are reviewed in section 2. Section 3 presents a case study, where reliability and operation times for passive islanding detection methods have been evaluated. Finally, Section 4 presents the results of the simulations carried out along with their analysis.

2. Islanding detection for synchronous distributed generators

A. *General islanding detection methods*

Islanding detection methods (IDM) fall into two categories: remotely controlled (mostly communication based) or locally built-in detection systems. Local IDMs can be classified into passive and active methods.

- *Passive anti-islanding detection methods* monitor electrical parameters such as voltage, frequency, rate-of-change of frequency, phase displacement and harmonic distortion at the interconnection point of a DG. When the DG is islanded, those parameters change and trigger the disconnection of the generator.

- *Active anti-islanding detection methods* introduce deliberate changes or disturbances to the connected circuit and then monitor the response to determine if the utility grid with its stable frequency, voltage and impedance is still connected. If the small perturbation is able to affect the parameters of the network, within prescribed requirements, island situation is detected and the DG is tripped.

To assess the suitability of an IDM, the following technical parameters should be considered: reliability, impact on the grid and operation time. IDMs should also be cost effective solutions for the DG owner and the utility. The impact on the grid and the operation time are limited by the standards in force, as well as utility requirements. IEEE standard 1547 stipulates a maximum delay of two seconds for detection of an islanding operation. Note that distribution utilities may require a faster detection, before the first reconnection attempt of the autorecloser. Table I shows protection requirements for DG connected in low voltage networks required by the Spanish electrical utility Iberdrola [2].

TABLE I
PROTECTION REQUIREMENTS FOR LV MICROGENERATION

PROTECTION UNIT	SETTING	OPERATION TIME (S)
OVERVOLTAGE (OV)	1.1 V_N	0.6
UNDERVOLTAGE (UV)	0.85 V_N	0.6
OVERFREQUENCY (OF)	51 Hz	0.2
UNDERFREQUENCY (UF)	49 Hz	0.2
ANTI-ISLANDING PROTECTION	--	0.5

B. *Review of islanding detection methods for synchronous generators*

Synchronous generators are highly capable of sustaining an island. Therefore, anti-islanding protection for synchronous generators is a more challenging problem in comparison with the inverter-based DGs, and options are limited.

Most of passive IDMs are suitable for all type of machines, and so for synchronous DGs. Unfortunately, these methods are not totally reliable due to their inherent limitations. When the power imbalance in an island is small, it may take some time for the islanded system to exhibit detectable change in electrical parameters, especially in synchronous DG based microgrids.

Some active methods have also been proposed for synchronous DGs, such as the impedance measurement, reactive power fluctuation, QC-mode frequency shift, reactive power compensation or load fluctuation [3]. Active islanding detection methods have shown to be effective, but most existing active schemes have the disadvantages of high cost, complex structure, uncommon use for all kinds of generators and degradation of power quality. To overcome these disadvantages, research has focused on hybrid detection systems, relying on more than one parameter [4], or combining passive and active methods.

However, passive IDMs, already implemented in current protection relays, have significant cost advantages for utility companies and DG owners. Therefore, this paper analyses the performance of basic anti-islanding protection methods, based on frequency variation, in order to understand the characteristics of the non-detection zones and associated risks.

C. *Performance assessment of islanding detection methods for synchronous generators*

Earlier papers have already proposed graphical tools to assess the performance of protection relays for distributed generation [5]. IDMs can also be evaluated graphically, using 'Non-Detection Zones' and performance curves. Thus, it is possible not only to identify main limiting factors that affect the performance of the evaluated IDM, but also to optimize the setting of the anti-islanding protection parameters.

- *Non-detection zones (NDZs):* NDZs can be calculated in power mismatch space (*ΔP and ΔQ*) or load parameter space. Load type, generator inertia, generator excitation control mode and relay settings are some of the factors that affect NDZs for synchronous generators [6].

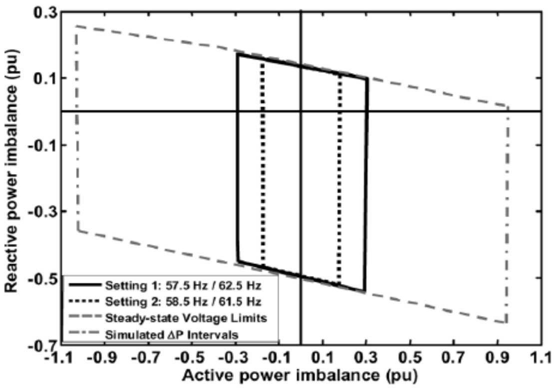

Fig. 1 NDZs for different frequency relay settings [7].

- *Performance curves:* performance curves represent the relationship between the islanding detection time versus the active power mismatch. This graphical tool is especially useful for synchronous DGs and therefore, it has been used to in our research. Limit operation times required by standards in force and by utilities will determine the critical power imbalance that the IDM under evaluation is able to detect. Power mismatches lower than the critical power imbalance make up, a non-detection zone, as indicated in Figure 2.

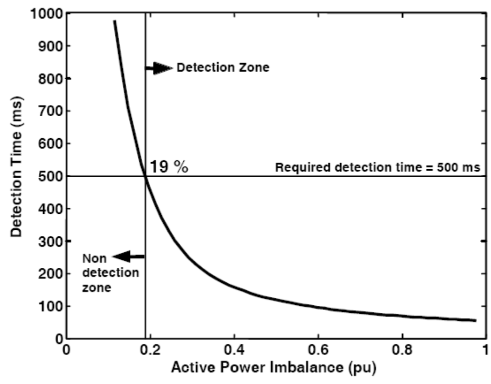

Fig. 2 Performance curve of frequency-based relays [8].

Performance indexes for islanding detection methods have been previously reviewed in [9].

3. Description of the study system

A. Test network

Fig. 3 shows a single-line diagram of the system used in this research. A low voltage, 400 V, urban distribution network with embedded synchronous generators has been modelled using the DigSilent PowerFactory software [10]. The low voltage network is connected to a 13.2 kV power grid through two 630 kVA transformers. The microgrid under study corresponds to the system linked to line L6 and it is composed as shown in Figure 3.

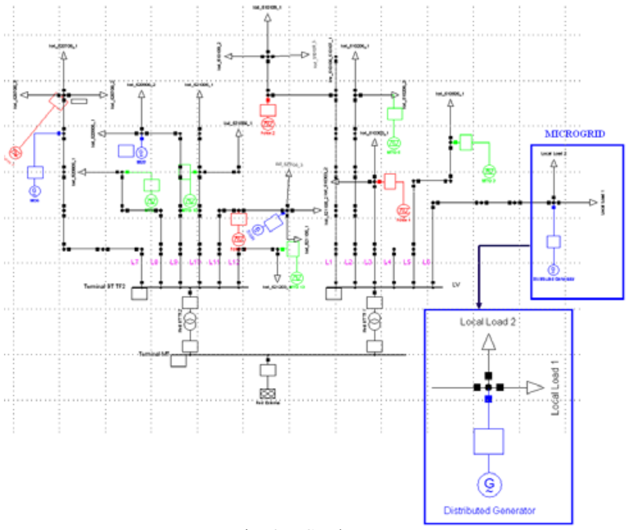

Fig. 3 Study system.

The generator is a 55 kW synchronous machine. The parameters have been configured based on [11]. Table II indicates these parameters for the base case.

TABLE II
SYNCHRONOUS GENERATOR PARAMETERS

VOLTAGE (V)	400
INERTIA H (s)	0.329
X_d (p.u.)	2.02
X_d' (p.u.)	0.171
X_d''(p.u.)	0.087
X_q (p.u.)	1.06
X_q'' (p.u.)	0.163
T_{do}' (s)	0.95
T_{do}''(s)	0.078
T_{qo}'' (s)	0.045
RSTATOR (p.u.)	0.011
X_0 (p.u.)	0.038
X_2 (p.u.)	0.125

The voltage regulator of the generator has not been modelled, because the performance of voltage relays is out of the scope of this study. The modelling of the speed governor of the generator has not been considered, since the response time is slower than the actuation time of anti-islanding protection relays. Without primary control in the generator, only the inertia and damping characteristics of the machine will rule the response in frequency, after active power variations in the microgrid. Figure 4 shows frequency variation in an islanded network based on a synchronous DG, which was exporting active power before islanding occurred.

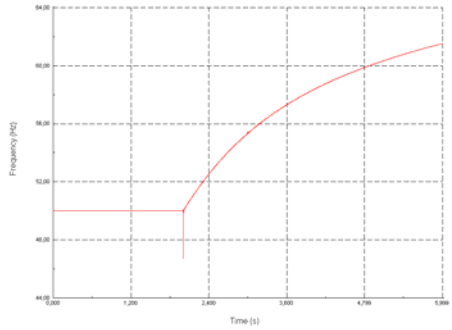

Fig. 4 Frequency variation in Hz before and after islanding with a synchronous DG.

The loads in the microgrid have been adjusted for different import/export microgrid situations.

B. IDMs under study

Every microgenerator connected to a LV network operated by electrical utilities is required to have over/underfrequency protection and over/undervoltage protection, as indicated in Table I for the Spanish distribution utility Iberdrola. Thus, the microgenerator must stop supplying power to the utility grid if the frequency or amplitude of the voltage at the point of common coupling (PCC), between the customer and the utility, strays outside of prescribed limits. Although intended to avoid any damage in consumers' equipment, the basic protection methods (under/overfrequency and under/overvoltage) contribute to the detection of islanding. Nevertheless, a specific anti-islanding protection system may be required to improve the reliability of the system. Therefore, the rate-of-change-of-frequency (ROCOF) protection function has also been implemented in this study. The threshold values for the operation of voltage and frequency relays are indicated in Table I. The settings for the ROCOF protection considered in the study have been 0.1 Hz/s, 1.2 Hz/s and 2.5 Hz/s.

The algorithm of the ROCOF relay is calculated with a measuring window of a few cycles (usually between 2 to 40 cycles) from the voltage waveform. The frequency in the system could be estimated with Fast Fourier Transform, zero crossing method or the Prony method. After calculating the derivative of the frequency, the signal is then processed by filters and the resulting measure is compared to the relay setting. Figure 5 provides the schematic diagram of the operating principle of a ROCOF relay [12].

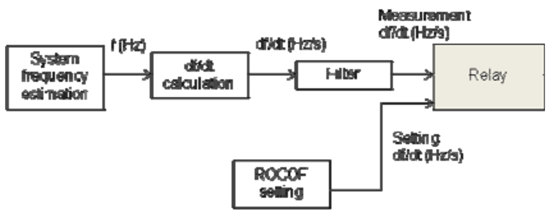

Fig. 5 Schematic diagram of a ROCOF relay.

The anti-islanding protection implemented on the distributed generator for this study, can be found in the standard library of DigSilent PowerFactory software [10].

4. Analysis of the results

This research evaluates the performance of frequency and rate-of-change of frequency (ROCOF) through performance curves. The microgrid model is shown in Figure 3. The following study cases have been simulated:

- Different power mismatch scenarios, considering exporting or importing microgrid situations.
- Influence of the generator inertia constant

Other network events, such as load change and shortcircuits, have also been simulated, to study the nuisance tripping of the anti-islanding protection unit.

A. Different power mismatch scenarios

When DGs are connected to distribution networks, traditional power flows in the grid can be reversed, as DGs supply active power (P_G) and reactive power (Q_G). Figure 6 shows the power flow for a general study case.

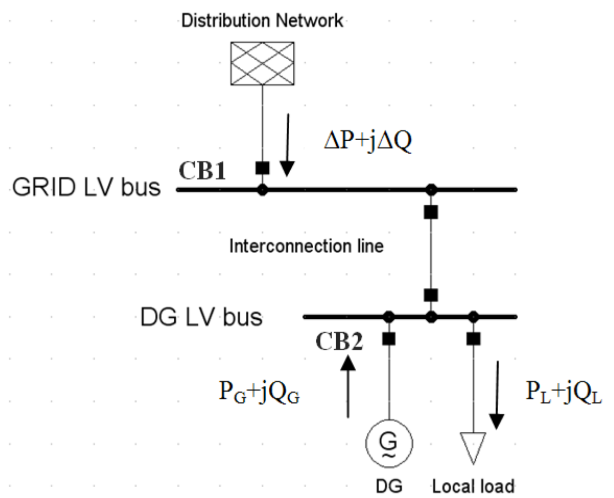

Fig. 6 Power flows in the microgrid under study.

The local load consumes P_L active power and Q_L reactive power. In a normal operation situation, the active and reactive power supplied by the distribution network are denoted by ΔP and ΔQ, as indicated in Equations (1) and (2).

$$\Delta P = P_L - P_G \quad (1)$$

$$\Delta Q = Q_L - Q_G \quad (2)$$

Previous to islanding, the microgrid can export power ($\Delta P<0$, $\Delta Q<0$), import power ($\Delta P>0$, $\Delta Q>0$) or be self-sustained. This power mismatch will determine the subsequent variation in frequency, for active power imbalance, and in voltage, for reactive power imbalance, for a synchronous machine. As power mismatches get smaller, variations in electric parameters will be less significant.

The base case for the simulation is described in Section 3. Besides, the DG has been configured with an inertia constant of 0.329 s, and generating 30 kW with 0.8 inductive power factor. Separate simulations have been carried out for active and reactive power mismatches in the microgrid, varying the demand of the local load.

The active power mismatch in the microgrid varies the frequency, according to the swing equation. Therefore, for large imbalances, the under/overfrequency protection trips (UOF). But with small active power imbalances, considering ΔP normalized with P_G, the operation time of this passive IDM is too high and unacceptable. Table III shows the results for an exporting microgrid with an UOF protection. The critical imbalance has been defined for detection times over 300 ms, which corresponds to an active power mismatch of -0.133 p.u. for the base case.

TABLE III
FREQUENCY RELAY OPERATION

P_L (kW)	$\Delta P/P_G$ (p.u.)	DETECTION TIME (ms)	DETECTION UNIT
30	0	No detection	--
28.5	-0.05	No detection	--
27	-0.1	396	OF
24	-0.2	228	OF
21	-0.3	177	OF
18	-0.4	156	OF
15	-0.5	147	OF
12	-0.6	139	OF
9	-0.7	135	OF

The simulations have been repeated for an importing microgrid where, after islanding, the frequency decreases depending on the active power imbalance. Thus, islanding can be detected by underfrequency protection units. Table IV shows the results for an importing microgrid with an UOF protection. The critical power imbalance corresponds to an active power mismatch of -0.143 p.u. for the base case.

TABLE IV
FREQUENCY RELAY OPERATION

P_L (kW)	$\Delta P/P_G$ (p.u.)	DETECTION TIME (ms)	DETECTION UNIT
30	0	No detection	--
31.5	0.05	No detection	--
33	0.1	415	UF
36	0.2	238	UF
39	0.3	186	UF
42	0.4	161	UF
45	0.5	144	UF
48	0.6	132	UF
51	0.7	124	UF

The performance of the ROCOF relay has been tested for the same power mismatch scenarios. Figure 7 shows the performance of a ROCOF protection unit, with a threshold of 0.1 Hz/s., compared to the underfrequency relay (settings in Table II) for an importing microgrid.

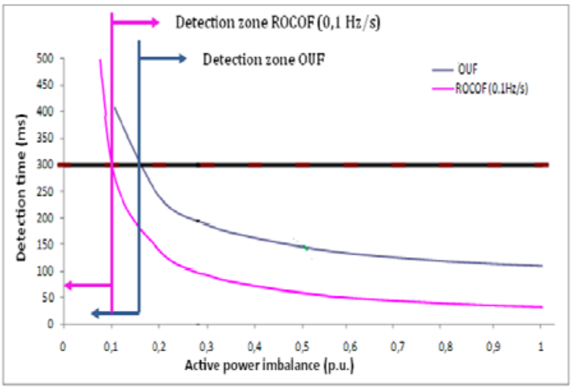

Fig. 7 Active power imbalance vs. detection time for UOF and ROCOF.

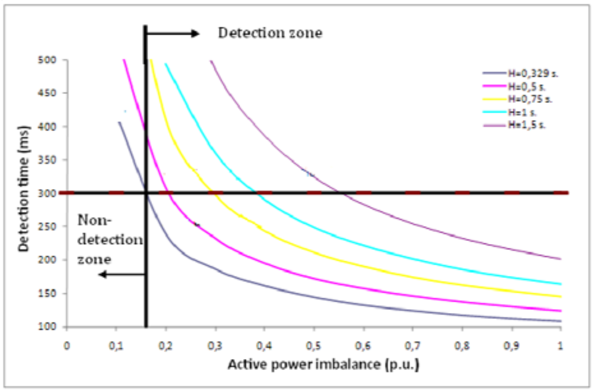

Fig. 8 Active power imbalance vs. detection time for UOF relay, considering different values of inertia.

As it can be seen, ROCOF is proven to be faster than the underfrequency unit, but it strongly depends on the setting in Hz/s. The critical active power imbalance in the microgrid or NDZ is shown to be smaller. Other simulations have been carried out with the ROCOF unit set to 1.2 Hz/s and detection times are higher, as the variation of the active power mismatch has to be faster than with 0.1 Hz/s.

B. Synchronous generator inertia

The equation of motion of a synchronous machine is given by the swing equation (3).

$$\frac{2 \cdot H}{\omega_0} \cdot \frac{d^2\delta}{dt^2} = T_m - T_e - \frac{K_D}{\omega_0} \cdot \frac{d\delta}{dt} \qquad (3)$$

where the notations used in (3) are as follows:

H inertia constant (s);

ω_0 system angular frequency (rad/s);

δ angular position of the rotor (rad);

T_m mechanical torque supplied by the prime mover in Nm;

T_e electrical torque output of the alternator in Nm;

K_D damping coefficient.

So, any active power imbalance in the microgrid results in a frequency variation. The magnitude of the frequency deviation depends on the inertia constant of the generator and the damping factor K_D. In our research, the damping factor of the synchronous machine has been dismissed. As for the inertia, the frequency deviations will be smaller as the inertia of the machine increases.

The simulations carried out in this research verify this principle, as detection time for UOF and ROCOF protection functions have been longer for high inertia generators. Figure 8 shows the results for the UOF protection and the non-detection zone for a synchronous DG with the base case values.

Aforementioned results have been confirmed for the ROCOF protection, set with different thresholds, as shown in Figure 9. Very similar values have been obtained for the different setting values, always dependent on the inertia of the machine, as ruled by the swing equation.

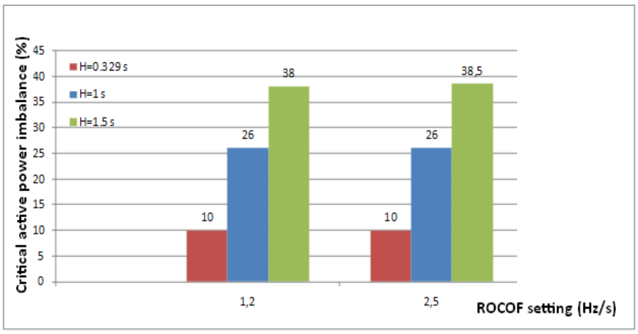

Fig. 9 Critical power imbalance for ROCOF function applied in synchronous distributed generators with different inertia constants.

C. False tripping

A suitable IDM must be reliable and therefore, able to distinguish undesirable island situation from other normal operations, such as active power imbalance due to significant local load change. The threshold value of the anti-islanding protection unit has also to be set reliably to prevent the tripping of over/underfrequency and the rate-of-change-of-frequency protection units with inherent frequency variations in the system. Otherwise, in a system with high penetration level of DG, generalised tripping of these generators may lead to dynamic problems [13] .

In the study case, local load active power changes in the microgrid and three-phase shortcircuits at the beginning of line L6 have been simulated. Then, the operation of the ROCOF unit has been observed for different setting values. Table V shows the threshold value for the ROCOF setting that prevents a false tripping, based on the study cases analysed.

TABLE V
ROCOF OPERATION

EVENT	SETTING VALUES
20% LOAD INCREASE	-1.13 Hz/s
20% LOAD DECREASE	1.13 Hz/s
30% LOAD INCREASE	-0.75 Hz/s
30% LOAD DECREASE	0.75 Hz/s
THREE-PHASE SHORTCIRCUIT	0.98 Hz/s

However, these setting values could be too high and not operate for islanding situations. Therefore, other factors should be considered to lock the tripping of the ROCOF relay, as mentioned in [14].

5. Conclusions

Synchronous generators are highly capable of sustaining an autonomous microgrid operating in island. Therefore, anti-islanding protection for synchronous generators is a challenging issue. A microgrid based on a synchronous DG has been modelled and different study cases have been simulated to assess the performance of frequency and ROCOF relays. The influence of power mismatch and generator characteristics on the islanding detection has also been studied. The results of the study show that ROCOF relays are an efficient tool for high-speed islanding-detection. However, setting selection must be carefully carried out in order to guarantee a fast detection without risk of false operation. Events in the network other than island operation, such as load change and shortcircuits, should not trip the anti-islanding protection.

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References

[1] H. Mohamad, H. Mokhlis, A. H. A. Bakar, and H. W. Ping, «A review on islanding operation and control for distribution network connected with small hydro power plant», *Renewable and Sustainable Energy Reviews*, vol. 15, n. 8, pg. 3952-3962, Oct. 2011.

[2] «Esquema conexión para Instalaciones de Microgeneración a la red de BT (Venta y autoconsumo)», *www.iberdrola.es*. [Online]. Available: www.iberdrola.es.

[3] T. Funabashi, K. Koyanagi, and R. Yokoyama, «A review of islanding detection methods for distributed resources», in *Power Tech Conference Proceedings, 2003 IEEE Bologna*, 2003, vol. 2, pg. 6 pp.

[4] K. El-Arroudi, G. Joos, I. Kamwa, and D. T. McGillis, «Intelligent-Based Approach to Islanding Detection in Distributed Generation», *Power Delivery, IEEE Transactions on*, vol. 22, n. 2, pg. 828-835, 2007.

[5] W. B. Gish, W. E. Feero, and S. Greuel, «Ferroresonance and Loading Relationships for DSG Installations», *Power Engineering Review, IEEE*, vol. 7, n. 7, pg. 75-76, 1987.

[6] J. C. M. Vieira, W. Freitas, Wilsun Xu, and A. Morelato, «An Investigation on the Nondetection Zones of Synchronous Distributed Generation Anti-Islanding Protection», *Power Delivery, IEEE Transactions on*, vol. 23, n. 2, pg. 593-600, 2008.

[7] J. C. M. Vieira, W. Freitas, Wilsun Xu, and A. Morelato, «An Investigation on the Nondetection Zones of Synchronous Distributed Generation Anti-Islanding Protection», *Power Delivery, IEEE Transactions on*, vol. 23, n. 2, pg. 593-600, 2008.

[8] J. C. M. Vieira, W. Freitas, W. Xu, and A. Morelato, «Evaluation of the distributed generators frequency protection due to changes in the anti-islanding requirements», presented at the Power Engineering Society General Meeting, 2006. IEEE, 2006, pg. 6 pp.

[9] A. Etxegarai, I.Zamora, P. Eguia, and X. Txakartegi, «Performance of anti-islanding protection for distributed resources», presented at the Conferencias Hispano Lusas de Ingeniería Eléctrica (CHLIE), Ponta Delgada-Açores, 2001.

[10] «DigSILENT PowerFactory». Version 14.0.520.0.

[11] W. B. Gish, «Small Induction Generator and Synchronous Generator Constants for DSG Isolation Studies», *Power Delivery, IEEE Transactions on*, vol. 1, n. 2, pg. 231-239, 1986.

[12] Bohan Liu, D. Thomas, Ke Jia, and M. Woolfson, «Advanced ROCOF protection Of synchronous generator», in *Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES*, 2011, pg. 1-6.

[13] R. A. Walling and N. W. Miller, «Distributed generation islanding-implications on power system dynamic performance», in *Power Engineering Society Summer Meeting, 2002 IEEE*, 2002, vol. 1, pg. 92-96 vol.1.

[14] C. M. Affonso, W. Freitas, W. Xu, and L. C. P. da Silva, «Performance of ROCOF relays for embedded generation applications», *Generation, Transmission and Distribution, IEE Proceedings-*, vol. 152, n. 1, pg. 109-114, 2005.