Rate of Change of Frequency Estimation Based on SOGI-PLL for Islanding Detection

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Abstract—**Distribution Grid (DG) has become the part of main equipment of the electric power system. DG supplies power to the grid and local loads. This will require proper operation in the DG equipment when islanding to improve the system's reliability. Islanding in DG systems can cause dangerous conditions for humans and equipment. The SOGI-PLL synchronization system in DG has been tested for its ability to detect voltage and frequency disturbances quickly. Passive over/under voltage and over/under frequency detection techniques for islanding detection have weaknesses against false signal problems and inefficient validation. Passive detection techniques over the time domain of monitoring oscillations in the Rate of Change of Frequency (ROCOF) have sensitivity to grid faults and false operations during non-islanding conditions. The ROCOF in a short time compares with a threshold. Grid parameter in the form of the frequency required by ROCOF is obtained from the SOGI-PLL synchronization algorithm. The simulation of the grid tie inverter system showed improved performance, reliability, and durability due to the shared advantages of SOGI-PLL synchronization and ROCOF islanding detection protection. The optimal time obtained to detect islanding is 72 ms. While in non-islanding conditions the false signal response can be overcome.**

Keywords—inverter, SOGI-PLL, islanding detection, ROCOF

I. INTRODUCTION

Distributed Energy Resources (DER) systems connected to the network must be able to identify situations of a grid fault. The ability of a distribution generator (DG) to connect to the main grid to isolate and keep active power to local loads when nuisance tripping, this operation is called islanding mode. The technique Islanding Detection Method (IDM) in islanding conditions must be detected immediately and the inverter disconnects the power grid [1].

Islanding detection can be divided into intentional and unintentional islanding. Intentional islanding is done due to scheduled maintenance for major utilities, whereas unintentional islanding can occur at any time due to regular errors or other uncertainties in the power system. IDM is generally classified into two main groups: (a) local techniques and (b) remote techniques. Anti-islanding protection can use one or a combination of types of islanding detection. Local techniques are divided into active, passive, and hybrid methods [2].

In the scenario of the active method, an external signal is injected into the system so that the DG output parameters can changes significantly during the islanding. Passive method scenario monitoring changes in parameters grid, such as voltage, current, impedance, active power, and frequency especially parameters that are outside the threshold. Each IDM method has advantages and disadvantages, in choosing the IDM method, it is necessary to attention to accuracy, reliability, cost, and side effects.

Some passive methods fail to differentiate between Loss of main (LOM) and other transient events. This is due to the sensitivity to grid disturbances that create false operations in non-islanding conditions. The islanding situation must be detected within 200 to 300 ms.

Of the various passive methods, a simple detection technique using the rate of change of frequency (ROCOF), this method is based on the derivative value of the frequency angle [3]. A high ROCOF value can affect the frequency stability of the power system. In addition, a high ROCOF value during normal system operation can activate false trip signals [4]. Metode frequency measurement, the window measurement, and different relay settings of ROCOF relays can affect the operating response [5]. The ROCOF method has the smallest non-detection zone compared to other passive methods but has a high error so an interlock function is needed.

A popular methods of synchronizing the output current of the inverter with grid voltage are T/4 delay [6] and the Second-order generalized integrator (SOGI-PLL) [7]. SOGI-PLL is a simple and efficient grid synchronization technique. SOGI-PLL is used to obtain grid information such as voltage magnitude, frequency, and phase angle. SOGI-PLL tracks the input signal even after grid fault conditions. ROCOF relays use a zero-crossing algorithm and a Discrete Fourier Transform (DFT) algorithm to measure grid frequencies. SOGI-PLL will represent the ROCOF method with a certain threshold so that the islanding mechanism of a single-phase inverter can be more selective.

Parameters for evaluating IDM performance that have accuracy, speed and effectiveness consist of Non Detection Zone (NDZ), detection time and power quality [8]. The detection time and accuracy of the ROCOF method largely depend on the specified threshold. The NDZ is smaller because it does not depend on load conditions.

RLC load is the most difficult load in islanding detection because RLC load has a high-quality factor value (Q) [9]. RLC load connected in parallel with the inverter describes the load model grid tie inverter system (Fig. 1), the resonance frequency of the RLC load has the same value as the grid frequency.

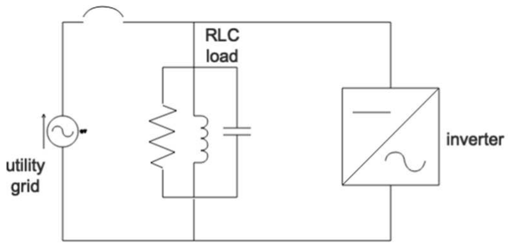


Fig. 1. A simple scheme for islanding detection analysis

Furthermore, the simulations islanding detection techniques based on frequency estimators obtained from SOGI-PLL, the frequency are used to monitor changes in the ROCOF were applied in this paper. The ROCOF threshold would be use to avoid false operation during the non-islanding situation. The rest of the paper is organized as follows. The model grid tie inverter are presented in Section II, The models ROCOF are presented in Section III, Model simulation are discussed in Section IV, Result and discussion are presented in Section V, and conclusions are presented in Section VI.

II. MODEL GRID TIE INVERTER

Grid Tie Inverter (GTI) is an inverter that works by being connected to a grid. An internal control loop of the current is designed to control the power injected into the grid. The hysteresis control system can be used to control a sinusoidal current. The synchronization between sinusoidal current inverter and grid voltage phase which estimated by SOGI-PLL algorithm. The block diagram based on an inverter connected to grid, combined with an islanding detection algorithm, is shown in Fig. 2.

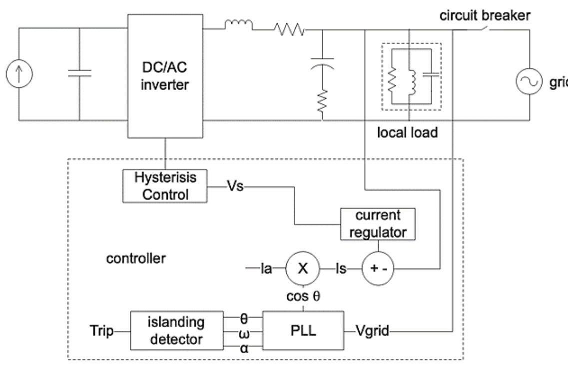


Fig. 2. Block Diagram of Grid Tie Inverter Single Phase System

A. Hysteresis Current Controller

The hysteresis control model in Fig. 3 shows the hysteresis current control signal in the inverter obtained by comparing the error values and the hysteresis limited [10].

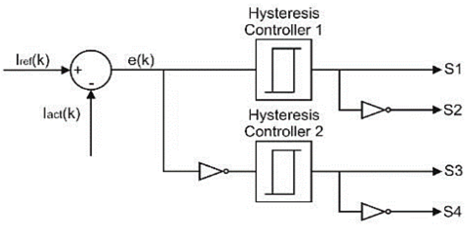


Fig. 3. Hysteresis controller block

B. SOGI-PLL algorithm

Phase Locked Loop (PLL) is used to detect phase angle, voltage magnitude, and frequency. The SOGI-PLL algorithm has adaptive-filtering characteristics in the adjustment of phase information when the grid fail. The single-phase SOGI-PLL in Fig. 4 consists of:

- SOGI - quadrature signal generator (QSG) blocks to generate orthogonal signals from the grid voltage input, i.e. Vα (grid voltage) and Vβ ($V_{quadratur}$ grid voltage) which differ phase angles 90° from Vα [11].
- The phase angle feedback control block, wherein $\omega_0$is the nominal frequency of the grid voltage and k_e is the control parameter of the filter system. Implementation into digital form is given using the Euler forward equation.

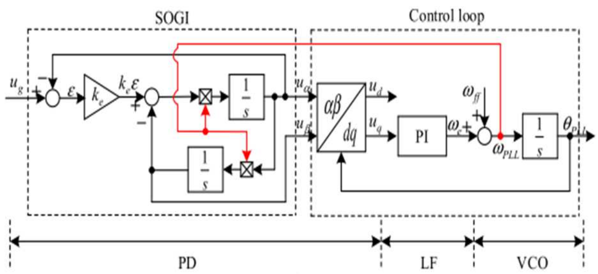


Fig. 4. Block diagram SOGI-PLL

Transformation Clark and Park convert the representation of variables: Vα and Vβ into two orthogonal variables Ud and Uq. Voltage Controlled Oscillator (VCO) consists of a sinusoidal function obtained by a linear integrator and a loop filter (LF) in the form of a first-order low-pass filter or proportional-integral controller (PI) that can affect output dynamics.

C. RLC Load

RLC load as the right load model for various conditions. Load characteristics can be indicated by the load quality factor Q_f and the frequency of load resonance f_r (Hz) with the following equation:

$$Q_f = R\sqrt{\frac{C}{L}} \quad (1)$$

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

Where Q_f describes the relative amount of energy stored and energy dissipation in a RLC branch [12].

The value of inductance L and capacitance C is obtained at RLC load using formulas (3) and (4).

$$L = \frac{R}{2\pi Q_f f_r} \quad (3)$$

$$C = \frac{Q_f}{2\pi R f_r} \quad (4)$$

Resonance frequency value f_r=50 Hz used equals the grid frequency.

III. MODEL RATE OF CHANGE OF FREQUENCY

During islanding, harmonics can cause distortions in the waveform of voltage in the PCC (Vpcc). Distortion of Vpcc waves causes continuous frequency variations so that there is an increase in the ROCOF value. The change of ROCOF waveform can be used to detect islanding [13]. After the phase angle is known through SOGI-PLL, the frequency can be estimated. It can be shown that a frequency error occurred. Equation (5) formulates the frequency of mistakes.

$$\Delta f = \frac{1}{2\pi}\frac{d\theta}{dt} \qquad (5)$$

To obtain the frequency, the system frequency f0 is added to this deviation, and the resulting signal is then processed by a low voltage filter (equation 6) and multiplied by the system frequency of 50Hz [14].

$$\frac{1}{1+sT_{lP}} \qquad (6)$$

The first-order transfer function represents a low-pass filter used to remove high-frequency transients and K is the rate of frequency change after the filtration processing field [15]. The ROCOF relay works based on the speed of change, df/dt.

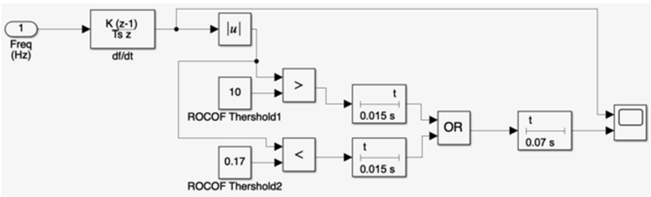


Fig. 5. ROCOF protection Simulink model

Trip signal operation occurs when the angular acceleration becomes more significant than the fixed threshold of the trip signal in the specified time interval. In Fig. 5 models the operation of the trip signal interlock with the threshold 10 Hz/s and 0.17 Hz/s.

IV. MODEL SIMULATION

The model used in the simulation is depicted in Fig. 6. Models of constant current sources connected with current source inverter single phase. The hysteresis controller is used to directly drives the inverter switches. The feedback system which is used by SOGI-PLL. CSI filter that contains inductor L and capacitor C filtering harmonics produced by CSI.

The test was carried out by the IEEE 1547.1-2005 standard, the local load was modeled as a parallel RLC circuit. The parameters of the utilized simulation model and control system are shown in Table I.

TABLE I. SYSTEM PARAMETERS

Parameters	Symbol	Value	Unit
Power Stage Parameters			
DG voltage	V_{dc}	350	V
Utility voltage	V_g	310	V_g
Utility frequency	f	50	Hz
Parameter Filters			
L_1 =5.37e-2 Mh	$R_1 = 0.02\Omega$	C_f =8.99e-5 Fμ	
Load Parameters			
$R_{load} = 17.45\ \Omega$	$L_{load} = 0.055$ h	$C_{load} = 1.82e-4\ \mu F$	
$R_{load} = 27.45\ \Omega$	$L_{load} = 0.087$ h	$C_{load} = 1.16e-4\ \mu F$	
$R_{load} = 47.45\ \Omega$	$L_{load} = 0.151$ h	$C_{load} = 6.71e-5\ \mu F$	
Control Parameters			
Current loop PI	K_{pc}/K_{ic}	0.4/44	$-/s^{-1}$
Switching Frequency	f_{pwm}	1e4	Khz
Inverter voltage gain	k_{pwm}	$\sqrt{2}$	-
SRF-PLL Parameters			
Proportional /integral	K_p/K_i	0.5/5	$-/s^{-1}$

The simulations structure and control algorithms were performed by using the Matlab / Simulink 2017b. A grid fault also included in the model. The load quality factor is determined Q_f=1 as per IEEE 1547 standard.

V. RESULT AND DISCUSSION

The SOGI-PLL structure is to provide grid parameter references. The frequency is obtained from the PLL block. There was only one inverter operating in parallel with the load.

A. Event Loss of Main

A Loss of main event is defined as a condition in which occurs loses the inherent physical connection for part of the grid including DG and local loads with the main grid. The event loss of main is called a islanding.

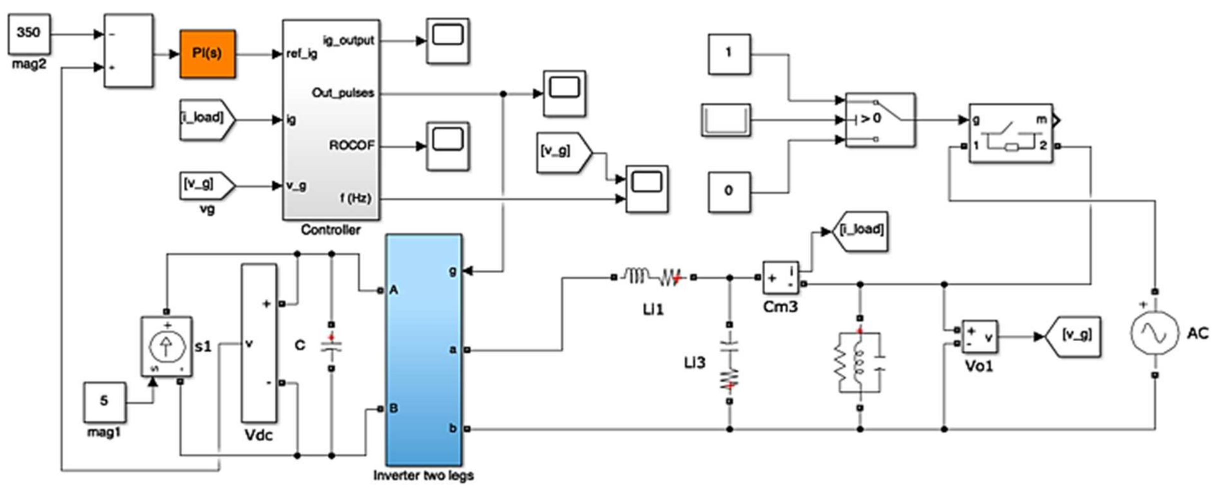
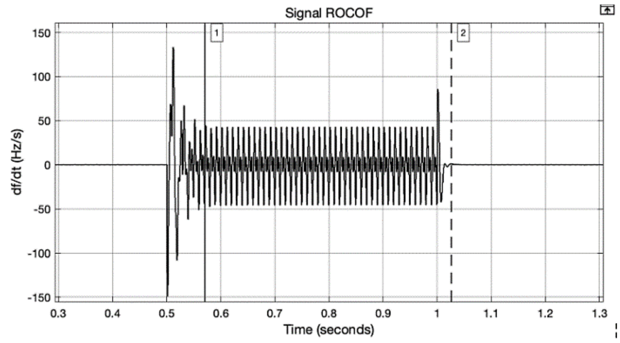


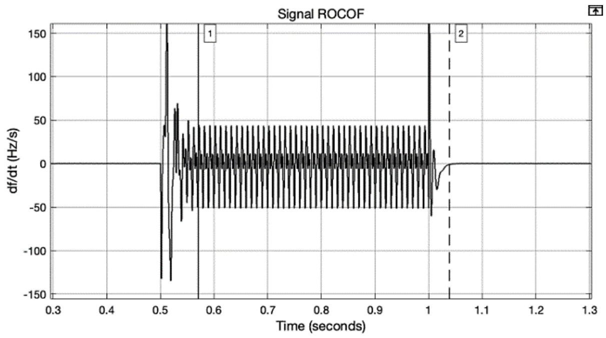
Fig. 6. Simulink model test islanding grid-connected inverter

In order to evaluate the operation of the islanding detection. The simulation with three different scenarios between local load and load generation. Situation undervoltage, power match, and overvoltage are presented:

- The load is adjusted at 36% under the inverter produced. Resistive load used to R=17,45 Ω
- The load is adjusted at 100% match the inverter produced. Resistive load used to R=27,45 Ω
- The load is adjusted at 172% over the inverter produced. Resistive load used to R=47,45 Ω



(a)



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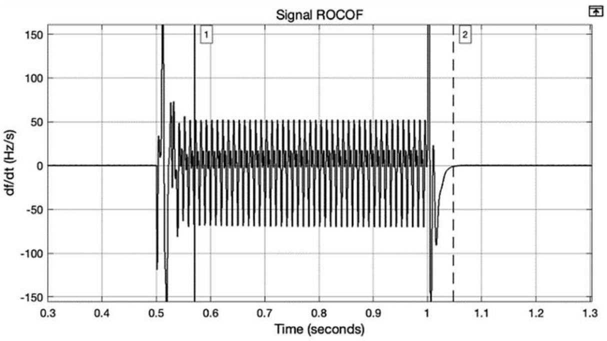

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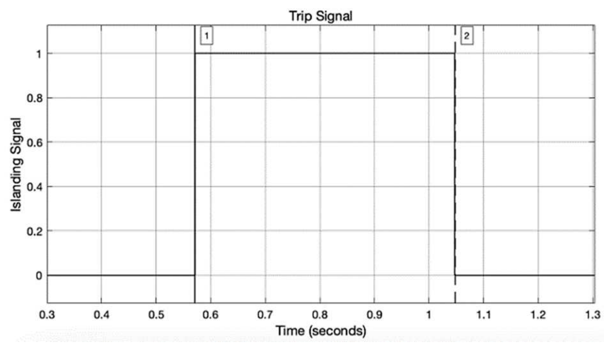


(d)

Fig. 7. ROCOF response df/dt loss of main events (a) undervoltage (b) powermatch (c) overvoltage (d) trip signal

For parallel RLC load with different resistive load, it can be seen PCC voltage and frequency also changes. At islanding conditions, the ROCOF amplitude value is observed at the PCC point of the grid tie inverter system.

The simulation islanding condition is created by opening the switch, in Fig. 8 shows is set to occur at time 500 ms, and after islanding by close the switch at the time 1000ms. The inverter would be synchronized with the grid voltage when the switch close.

From Fig. 7 (a), (b), (c) the ROCOF increased after islanding. It can be seen that large oscillations in the measured ROCOF. After islanding, the ROCOF occurrence decreases.

The islanding conditions are detected when a ROCOF threshold of 10 Hz/s with a time-delay operation at 150ms. The islanding signal in Fig. 7 (d) was able to successfully can be detected at time t=572 ms. and after islanding, the inverter takes at time t=1038 ms to synchronize with the grid voltage.

Constant current sources provides a maximum power of 1750 VA. For a small frequency deviation, the ROCOF can send a tripping signal. The load was set to match the power produced by the DG. The test results are shown that the threshold ROCOF can be used to detection for islanding operation with the small power imbalance between loads and the DG shows in Fig. 8.

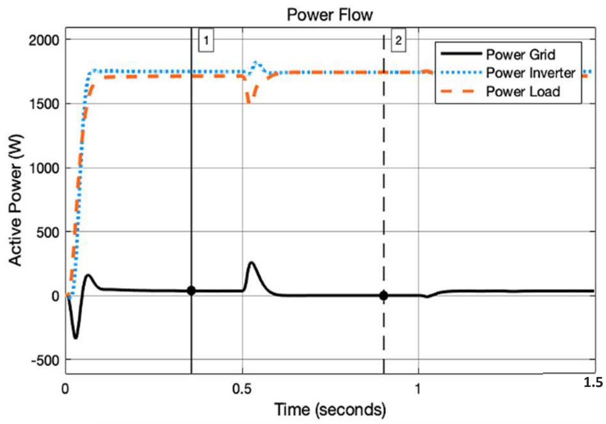


Fig. 8. Active power flow of distribution generation

The islanding condition when no load simulated in Fig. 9. shows the ROCOF increased significant after islanding into 50 Hz/s is exceed.

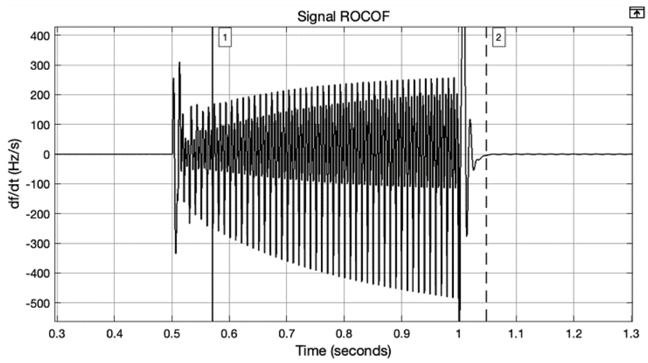


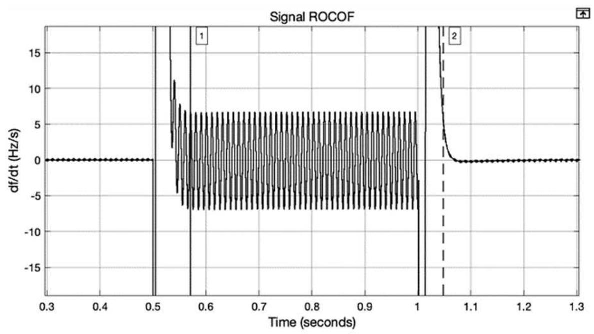
Fig. 9. ROCOF response df/dt with no load condition

B. Event Grid Fault Transient

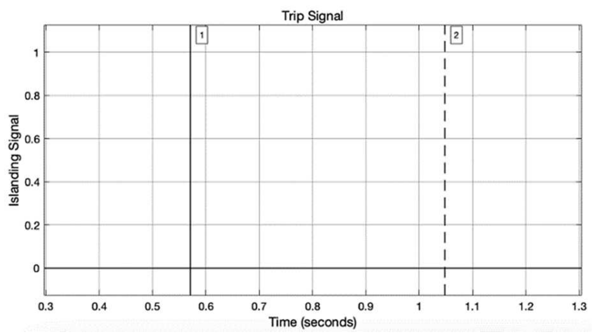
In this case study, the response of the proposed technique to grid fault transient events is presented. In distribution systems, the grid voltage is not always balanced. Following IEEE 1547 and UL 1741 regulations, over-under voltage (OUV) / over-under frequency (OUF) should not make the system trip when the voltage and frequency are within the under and overvoltage protection 88% ≤ V ≤ 110% and 49.3Hz ≤ f ≤ 50.5Hz. The grid fault transient events condition was simulated without being created by opening the switch. There are some considerations which are taken during the simulation non-islanding as follows:

- Grid fault within the tolerance limits. The grid was set the voltage of 275 V and the frequency of 49.5 Hz.
- Grid fault out of the tolerance limits. The grid was set the voltage of 270 V and the frequency of 49 Hz.
- Grid fault out of the tolerance limit. The grid was set the voltage of 250 V and the frequency of 50 Hz.

The grid fault transient events approximately occurs at time 500 ms and after non-islanding at time 1000 ms in this simulation. The local load was set to matches with the local generation. The threshold ROCOF of 10Hz/s can be used to non-islanding condition.



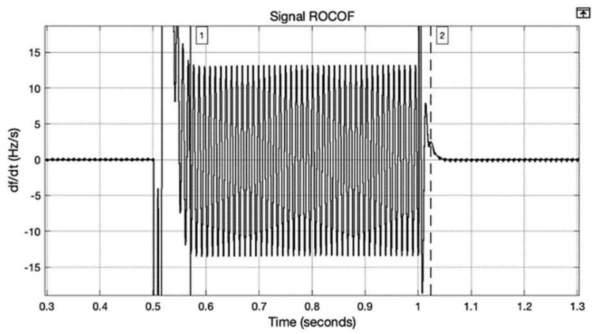
(a)



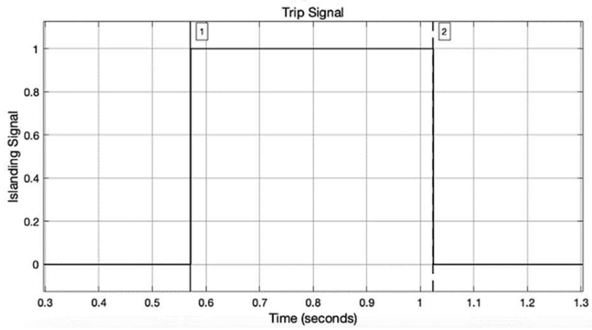
(b)

Fig. 10. ROCOF response grid fault within the tolerance limits event (a) df/dt (b) trip signals

Fig. 10. (a) depicts the simulation results of the ROCOF when non-islanding condition. The transient spikes in the ROCOF waveform would be settled down within the time delay of 150 ms, therefore in Fig. 10. (b) no false islanding was detected.



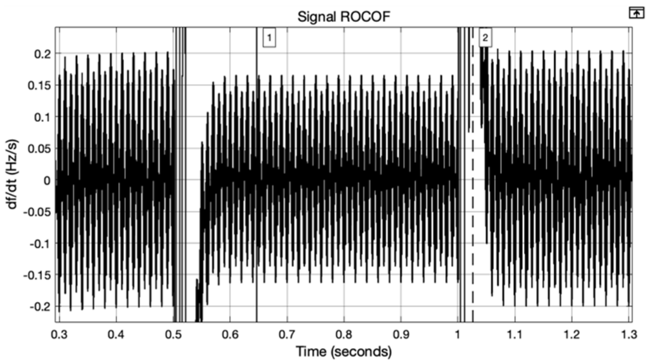
(a)



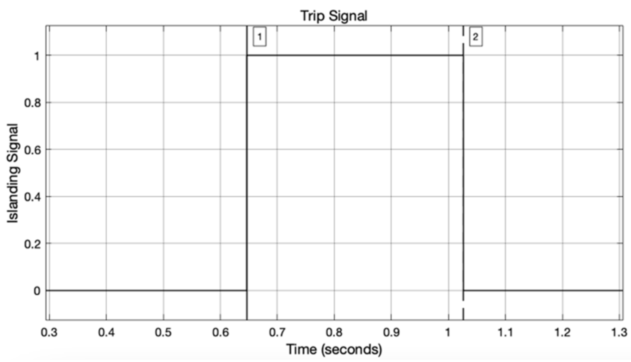
(b)

Fig. 11. ROCOF response grid interference undervoltage conditions of 270V and under the frequency of 49Hz (a) df/dt (b) trip signal

Fig. 11. (a), (b) shows experimental results for islanding detection when the grid faults. The grid fault was set to voltage decreases ≤ 88 % and frequency ≤ 49.3Hz. The ROCOF increase after grid fault. The voltage decreases conditions are detected when a ROCOF threshold of 10 Hz/s.



(a)



(b)

Fig. 12. ROCOF response grid voltage fault undervoltage condition 250V (a) df/dt (b) trip signal

From Fig. 12 (a) The ROCOF decrease after grid fault. The grid fault was set to voltage decreases ≤ 88 % and frequency = 50 Hz. The voltage decreases conditions are detected when a ROCOF threshold of 0,17 Hz/s with a time-delay operation at 150ms. In Fig. 12. (b) shows islanding was detected. In the case, the threshold ROCOF is different with the other event.

VI. Conclusion

This paper presents investigates the ROCOF base on frequency estimator by SOGI-PLL used to islanding detection. The method is monitors the frequency measuring algorithms by SOGI-PLL and the threshold ROCOF can be used to detects islanding when the ripple content exceeds a threshold for a certain amount of time. In the grid-connected inverter model, the synchronize by SOGI-PLL can be utilized the ROCOF to detect islanding. In this paper, loss of main and grid fault transient events for inverter connected grid are demonstrated. The proposed method was verified only for distribution systems with one DG.

The proposed method can offer an islanding detection time within 72 ms by the ROCOF threshold of 10 Hz/s, which is much faster than the international standard IEEE 1547. Therefore, the proposed detection method can provide protection islanding for the inverter system and stop false trips during non-islanding conditions.

This method improves the reliability of the method traditional passive anti-islanding and makes sure the correct detection of islanding operation of the distributed generation. The ROCOF can be provide useful reference to verify for islanding detection due to the algorithm has the smallest non-detection zone.

References

[1] I. V. Banu, M. Istrate, D. Machidon, and R. Pantelimon, "A study on anti-islanding detection algorithms for grid-tied photovoltaic systems," in 2014 International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2014, 2014, pp. 655–660, doi: 10.1109/OPTIM.2014.6850940.

[2] M. S. Kim, R. Haider, G. J. Cho, C. H. Kim, C. Y. Won, and J. S. Chai, "Comprehensive review of islanding detection methods for distributed generation systems," Energies, vol. 12, no. 5. pp. 1–21, 2019, doi: 10.3390/en12050837.

[3] S. Bifaretti, A. Lidozzi, L. Solero, and F. Crescimbini, "Anti-islanding detector based on a robust PLL," IEEE Trans. Ind. Appl., vol. 51, no. 1, pp. 398–405, 2015, doi: 10.1109/TIA.2014.2330063.

[4] T. Bašakarad, N. Holjevac, I. Kuzle, I. Ivankoviü, and N. Zovko, "Rocof importance in electric power systems with high renewables share: A simulation case for croatia," in IET Conference Publications, 2020, vol. 2020, no. CP780, pp. 72–77, doi: 10.1049/icp.2021.1239.

[5] B. Liu, X. Ni, G. Yan, B. Li, and K. Jia, "Performance of ROCOF protection in PV system," in Asia-Pacific Power and Energy Engineering Conference, APPEEC, 2016, vol. 2016-Decem, pp. 454–457, doi: 10.1109/APPEEC.2016.7779545.

[6] I. Setiawan, T. Andromeda, M. Facta, Hermawan, and S. Handoko, "Implementation and performance analysis of a single phase synchronization technique based on T/4 delay PLL," Int. J. Renew. Energy Res., vol. 8, no. 1, pp. 585–591, 2018, doi: 10.20508/ijrer.v8i1.7282.g7332.

[7] Royan, T. Andromeda, M. Facta, and I. Setiawan, "Comparison of SOGI-FLL with SOGI-PLL for Single-Phase Grid- Connected Inverters," vol. 005, no. 201 9, pp. 3–7, 2019. doi: 10.1051/e3sconf/201912514005

[8] J. Hmad, H. Trabelsi, and S. Rhili, "ROCOF Anti-islanding strategy based on frequency tracking observer for three phase DG inverter," in 2018 15th International Multi-Conference on Systems, Signals and Devices, SSD 2018, 2018, pp. 281–286, doi: 10.1109/SSD.2018.8570601.

[9] W. Bower and M. Ropp, "Evaluation of islanding detection methods for utility-interactive inverters in photovoltaic systems," Sandia Rep. 2002, no. November, pp. 24–38, 2002, doi: 10.2172/806700.

[10] S. Jena, B. Mohapatra, and C. K. Panigrahi, "Realization of double band hysteresis current controller for single phase grid connected pulse width modulated voltage source inverter," 2016, doi: 10.1109/MAMI.2015.7456579.

[11] M. Ciobotaru, R. Teodorescu, and F. Blaabjerg, "A New Single-Phase PLL Structure Based on Second Order Generalized Integrator," in 37th IEEE Power Electronics Specialists Conference, 2006, pp. 1–6, doi: 10.1109/PESC.2006.1711988.

[12] M. Malakondaiah, K. K. Boddeti, B. R. Naidu, and P. Bajpai, "Second harmonic impedance drift-based islanding detection method," IET Gener. Transm. Distrib., vol. 13, no. 23, pp. 5313–5324, 2019, doi: 10.1049/iet-gtd.2018.6838.

[13] B. Guha, R. J. Haddad, and Y. Kalaani, "A passive islanding detection approach for inverter-based distributed generation using rate of change of frequency analysis," Conf. Proc. - IEEE SOUTHEASTCON, vol. 2015-June, no. June, 2015, doi: 10.1109/SECON.2015.7133024.

[14] B. Liu and D. Thomas, "ROCOF protection in distributed system with noise and non-linear load," in 2011 10th International Conference on Environment and Electrical Engineering, EEEIC.EU 2011 - Conference Proceedings, 2011, pp. 2–5, doi: 10.1109/EEEIC.2011.5874715.

[15] J. C. M. Vieira, W. Freitas, Z. Huang, W. Xu, and A. Morelato, "Formulas for predicting the dynamic performance of ROCOF relays for embedded generation applications," IEE Proc. - Gener. Transm. Distrib., vol. 153, no. 4, p. 399, 2006, doi: 10.1049/ip-gtd:20045205.