EVALUATION OF ROCOF RELAY PERFORMANCES ON NETWORKS WITH DISTRIBUTED GENERATION

C.F. Ten, P.A. Crossley

The University of Manchester, UK (emails: Chui.Ten@postgrad.manchester.ac.uk, p.crossley@manchester.ac.uk)

Keywords: Distributed Generation, islanding, loss of mains, ROCOF, power system protection.

Abstract

Due to the increasing levels of distributed generation in the distribution network, the correct operation of loss-of mains protection is of utmost importance. Utilities have voiced their concern relating to the false operation of ROCOF relays, which are one of the most commonly employed loss-of-mains detection method. Whilst 'standard settings' are used, the performances of commercially available ROCOF relays are reported to vary considerably. This paper presents an investigation on the characteristic of ROCOF relays that contribute to their diverse operating responses. The factors investigated are frequency measuring techniques, measuring windows, time delays and the under-voltage interlock function. With the increasing penetration of DG into the network, it is becoming common to have multiple DG units connected to the same network location. Two generators connected at similar location and employing ROCOF relays with the same setting but different characteristics were simulated. When subjected to the same network disturbances, the possible interference between the two relays was analyzed.

1 Introduction

Rapid increase in the amount of distributed generation connected into the distribution network has given rise to a number of issues related to the safe and reliable operation of the network. One of the most frequent raised issues is islanding, which refers to the situation in which a portion of the distribution system remains energized by distributed generators (DG) whilst isolated from the main grid supply [1]. Due to safety concerns and the risks associated with an islanded system, current legislation has required immediate disconnection of the DG units once they have become electrically isolated from the grid supply [7]. To meet this requirement, various anti-islanding protection methods have been proposed and implemented, i.e. passive methods, active methods and communication based methods.

Rate of Change of Frequency (ROCOF) is the most commonly employed anti-islanding protection technique. However, the security of relays based on this technique is continually being questioned, as it is sensitive to network disturbances, leading to nuisance tripping. To avoid this problem, compromise has to be made between the relay's security and dependability. Nevertheless, selecting the 'right' setting is not an easy task and is made even more complicated when the performance of commercially available ROCOF relays vary considerably, despite being configured with the same settings [2].

In this paper, an investigation on the characteristic of ROCOF relays that contribute to their diverse operating responses is presented. The focus will be on their interpretations of the processed signals and the algorithm used, i.e. frequency measuring techniques, measuring windows, etc. The impact of these dissimilarities on the relay's security is analyzed.

With the increasing penetration of DG into the network, it is becoming common to have multiple DG units connected to the same network location. Two generators connected at similar location and employing ROCOF relays with same setting but different characteristic were simulated. The relays' performances when subjected to the same network disturbances are addressed in this paper.

2 Overview of ROCOF relay

ROCOF relays rely on the assumption that when islanding occurs, there is always an imbalance between the generation and load in the formed island [3,5]. Immediately after islanding, the resulting power imbalance will cause the frequency to change dynamically which, neglecting the governor action can be approximated by equation (1): [4,8]

$$\frac{df}{dt} = -\left(\frac{P_L - P_G}{2H \times S_{GN}} \times f_r\right) \qquad (1)$$

where

P_G = Output of the distributed generator
P_L = Load in the island
S_{GN} = Distributed generator rating
H = Inertia constant of generating plant
f_r = Rated frequency

ROCOF relays measure the rate of change of frequency and once the rate of change of frequency exceeds the predetermined setting, a trip signal is initiated.

Nevertheless, network transient events may also cause changes in system frequency, resulting in the incorrect operation of ROCOF relays. Utility members had declared their concerns over the false operation of ROCOF relays. In a system with significant amount of DG, nuisance tripping of these generators may directly jeopardize the integrity of the system [9].

Besides, it is reported in [2] that commercially available ROCOF relays from different manufacturers respond rather differently to the same event, even when they are configured with the same settings. This phenomenon is due to the different algorithms employed by these relays, and includes the effect of the following:

(i) **Frequency Determination Techniques**

There are generally two main algorithms used in the commercially available ROCOF devices to determine system frequency. One is based on zero crossing techniques whereas the other is based on Fourier transformation [6].

(ii) **Time Delays**

In order to increase the security of ROCOF relay and cut-down the numbers of nuisance tripping, time delays are employed in some relays. The time delay may vary from 50 milliseconds to 500 milliseconds [5].

(iii) **Measuring Windows**

Measuring window is defined as the number of power frequency measuring periods over which the rate of change of frequency is calculated [8]. Typical measuring windows are in the range of 40 milliseconds (2 cycles at 50 Hz) to 2 seconds (100 cycles at 50 Hz) [8].

(iv) **Under-voltage Interlock**

This function will block the ROCOF relay trip signal if the DG terminal voltage drops below a predetermined level, V_{min}. It helps to restrain the actuation of ROCOF relay during non-islanding situation such as generator start-up and short circuits [1]. Typical value for under-voltage pick-up setting is 0.8pu [5].

3 Simulation Studies

Fig. 1 shows the single line diagram of the network used for the studies described in section 3.2. It comprises a 33kV, 50Hz grid with a short circuit level of 1300MVA, represented by a Thevenin equivalent, which feeds a 11kV busbar through two parallel 33/11kV on-load tap changer transformers. The DG, connected to the 11kV feeder at bus 3, is represented by a synchronous machine equipped with automatic voltage regulator (AVR) control.

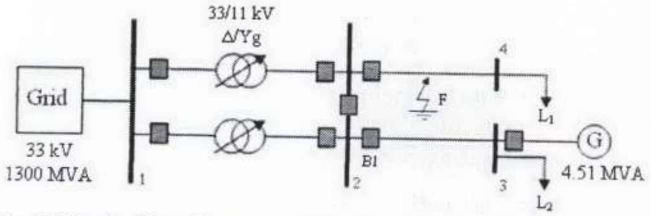

Fig. 1: Single-line diagram of simulated network.

The total simulation time is 0.75 seconds. Hence, if the relay is not activated within 0.5 seconds, it is considered that this device did not mal-operate. Due to the short simulation time, prime mover and governor control are neglected, i.e. the mechanical power is considered constant.

3.1 ROCOF Relay Model

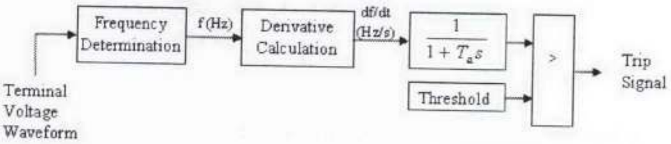

Fig 2: Structure of ROCOF relay

The model of the ROCOF relay used in the simulation studies was developed in Matlab/Simulink Software. Its operating principle is illustrated in Fig 2. The power frequency, f is determined from the DG terminal voltage waveform using a zero-crossing technique. The derived system frequency is then used to calculate the effective rate of change of frequency. This is calculated based on moving 100ms windows, according to equation (2).

$$\frac{df}{dt}=\frac{1}{5}\sum_{i=1}^{5}\frac{\Delta f_i}{\Delta t_i} \tag{2}$$

where

Δf_i = frequency variation within one cycle
Δt_i = cycle duration
i = corresponding cycle

The resulting signal is subsequently filtered by a first order function, $(1+T_a s)^{-1}$, designed to eliminate high frequency transients; where the time constant Ta represents both the time constant of the filters and the adopted measurement window. Its outcome is finally compared with the threshold value. If the former value exceeds the latter, a trip signal is initiated. Once a trip decision is made, the simulation considers it as the operating time.

It is worth noting that this is the base model implemented in the simulation studies. There is however some minor modifications on this model to represent the different algorithms and to study the effect of these differences.

For example, the frequency determination technique was changed from zero-crossing technique to Fast Fourier transform technique to represent the Fourier based ROCOF relay (section 3.2-A).

3.2 Example Simulation Results

Extensive computer simulation studies have been carried out to examine the effect of differences in the ROCOF relay's internal algorithms. For illustrative purposes, some selected examples are included in the following sections.

A. Difference in Frequency Determination Technique

These simulations were carried out to assess the differences seen by a ROCOF relay when employing different frequency determination techniques in its algorithm. In this case, a 10MW/phase load was switched on at the terminal of DG (busbar 3 in Fig. 1).

Table 1 shows the maximum values of the threshold setting at which the relay still operates. As this is not a real islanding event, both types of relay are expected to remain stable throughout the disturbance. It is seen that Zero-Crossing based relay and Fourier based relay continue to incorrectly operate even when configured with a threshold setting as high as 0.9Hz/s and 1.0Hz/s respectively.

Technique	Maximum Trip Setting (Hz/s)
Zero-Crossing	0.9
Fast Fourier Transform	1.0

Table 1: Maximum ROCOF Trip Setting for Different Frequency Determination Technique.

When investigated further, it can be observed that the Fourier based relay sees a higher rate of change of frequency than the Zero-Crossing based relay when subjected to the same disturbance. This explains the higher maximum trip setting of the former relay.

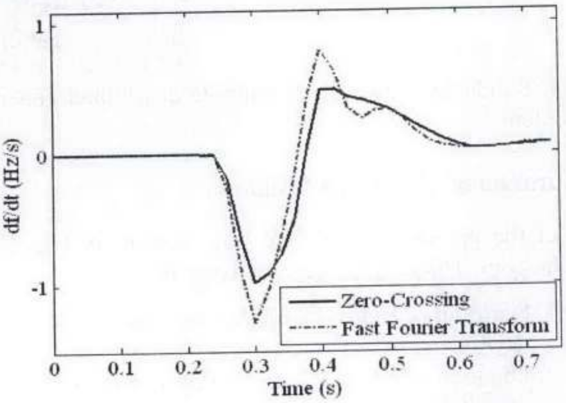

Fig 3: Comparison of Rate of Change of Frequency Using Different Frequency Determination Technique

B. Difference in Duration of Measuring Windows

The duration of the measuring windows used in the rate of change of frequency calculation directly affects the operation of a ROCOF relay. To provide a clearer idea of its impact, the following simulations were carried out. One of the parallel 33kV/11kV transformers in Fig. 1 was switched out. Three cases were analyzed:

i) ROCOF relay with measuring window of 0.04 seconds
ii) ROCOF relay with measuring window of 0.1 seconds
iii) ROCOF relay with measuring window of 0.2 seconds

The results obtained are presented in Fig. 4. From that figure, it is observed that the shorter the measuring window, the greater the rate of change of frequency, and hence the more sensitive the relay. Alternatively, the longer the measuring window, the less sensitive the relay. The main advantage of a longer window is the increase in the relays immunity to network disturbances and a reduction in the number of false trips.

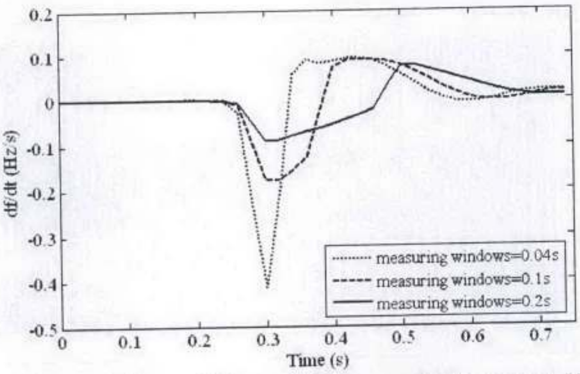

Fig. 4 Comparison of Rate of Change of Frequency Using Different Measuring Windows Duration

C. Difference in Duration of Delays

In this scenario, a 10MW/phase load was switched on at the terminal of the DG (busbar 3 in Fig. 1); ROCOF relays are not expected to operate on this non-islanding event. If they do operate, the longer it takes them to be activated is considered more desirable.

Different duration of time delays were employed in the ROCOF relay and the effect of these on the operating behaviour are portrayed in Fig. 5.

From the result, it is observed that the longer the time delays, the more resistant the relay is to network disturbances. Note: The missing bars indicate that no trip occurred within the post event simulation time of 0.5 seconds.

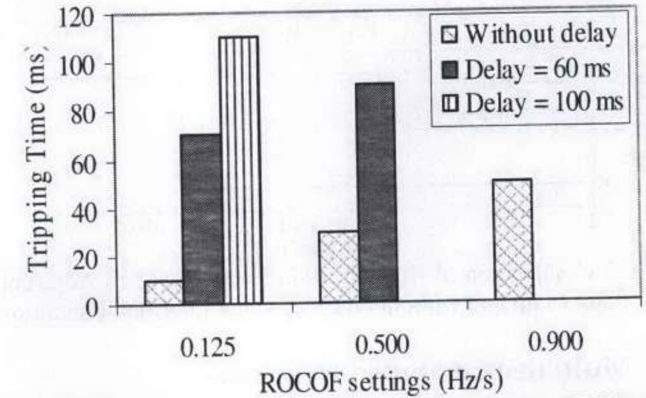

Fig. 5 Comparison of Tripping Time Using Different Duration of Time Delay

D. Under-voltage Interlock Function

To investigate the effect of including an under-voltage interlock function in the ROCOF algorithm, a three phase fault, F which lasted for 0.25 seconds was applied on feeder 2-4 (refer Fig. 1) at t=0.25 seconds. The ROCOF relays were not expected to trip due to this non-islanding event.

An enlarged version of the voltage waveform captured at the DG terminal during the disturbance is illustrated in Fig. 6, the dotted lines represent the voltage waveform if the fault had not occurred.

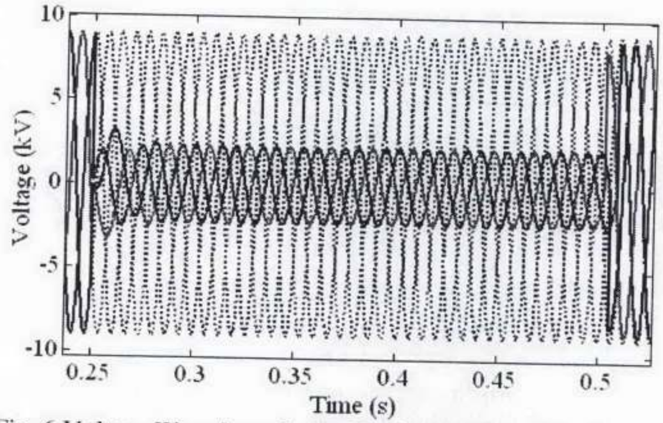

Fig. 6 Voltage Waveform during Fault at Adjacent Feeder

The result for this scenario is shown in Fig 7. It is seen that with an under-voltage interlock function, the trip decision, although not prevented, was delayed by 260 milliseconds.

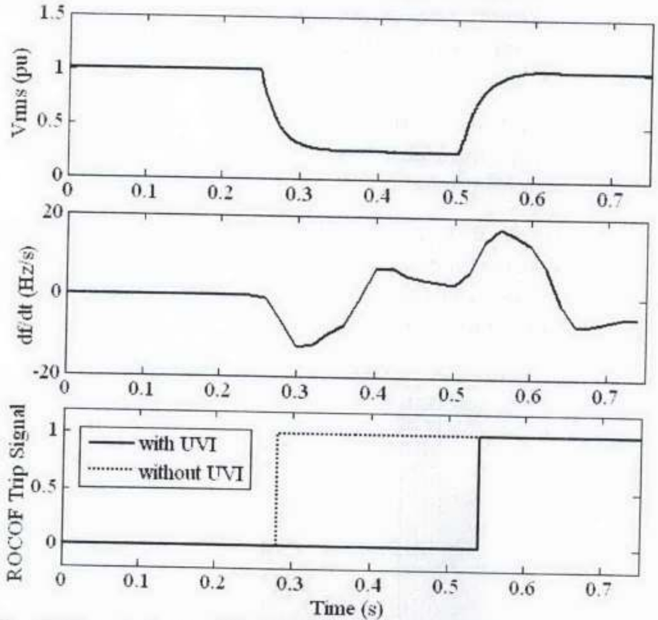

Fig. 7 Comparison of ROCOF Relay's Response to Adjacent Fault (with and without Under-voltage Interlock Function)

4 Multiple Distributed Generators

As shown in the previous section, the behaviour of a ROCOF relay depends on its operating algorithm. Hence, even if relays are configured with the same setting, different relays respond differently to the same disturbance.

Hence, the following simulation studies have been carried out to investigate the effect on stability of two relays which have the same threshold settings but different internal algorithms.

The distribution network presented in Fig. 8 was utilised to analyse cases with multiple distributed generators. This system comprises a 33kV, 50Hz grid with a short circuit level of 1300MVA, which feeds a 11kV busbar through two parallel 33/11kV on-load tap changer transformers. In this system, there are two identical synchronous generators; both with capacity of 4.51 MVA connected at bus 5 and 7. Each generator is equipped with a ROCOF relay and circuit breaker. It should be noted that there was a simulated delay of 50 milliseconds between the ROCOF's trip decision and the circuit breaker opening [1].

The main factors contributing to the difference in performance includes the following:

a) Duration of measuring window
b) Duration of time delays
c) Under-voltage Interlock function

For each case, the responses of ROCOF1 for different settings were obtained.

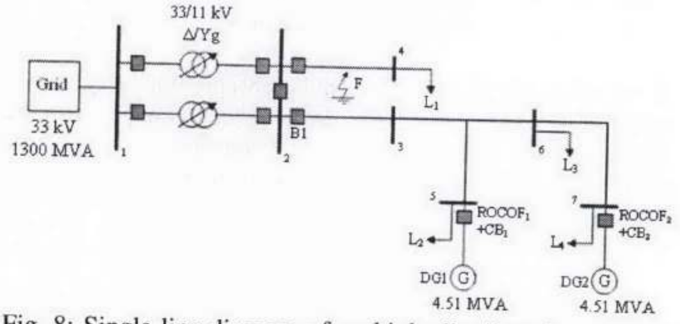

Fig. 8: Single-line diagram of multiple distributed generators system.

A. Duration of Measuring Windows

One of the parallel 33kV/11kV transformers in Fig. 8 was switched out. Three cases were analysed here:

Case 1: Duration of ROCOF2 measuring windows is less than ROCOF1.
Case 2: Duration of ROCOF2 measuring windows is same as ROCOF1.
Case 3: Duration of ROCOF2 measuring windows is more than ROCOF1

ROCOF settings (Hz/s)	**Case**		
	1	**2**	**3**
0.125	√	√	√
0.200	√	√	√
0.300	√	X	X
0.400	X	X	X

√	Trip
X	No Trip

Table 2: Results of ROCOF1's Responses for Cases 1-3

From the results shown in Table 2, it is observed that ROCOF2 with the same or longer duration of measuring windows did not interfere with the stability of ROCOF1. However, if ROCOF2 had a shorter measuring window than ROCOF1, then it easily responded to the disturbance and tripped DG2. Consequently, ROCOF1 sees a larger disturbance than expected and tripped DG1. Fig. 9 shows the frequency and df/dt sensed by ROCOF1 for the scenarios with DG2 tripped or not tripped (at setting 0.3 Hz/s).

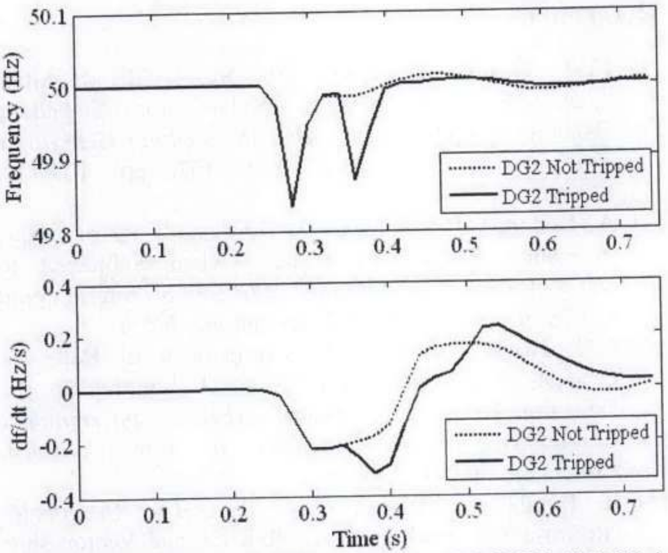

Fig. 9: Frequency and df/dt sensed by ROCOF1 if DG2 is tripped or not tripped (at setting 0.3 Hz/s)

B. Duration of Time Delays

A 10MW/phase load was switched on at the terminal of DG1 (busbar 5 in Fig. 8). The following three cases were analyzed:

Case 1: ROCOF2 with shorter time delay than ROCOF1.
Case 2: ROCOF2 with same time delay than ROCOF1.
Case 3: ROCOF2 with longer time delay than ROCOF1.

The results obtained are summarized as Table 3. The stability of ROCOF1 is not affected by ROCOF2 when the latter has similar or longer duration of time delays in its algorithm than the former.

However, at setting 0.4Hz/s, the use of ROCOF2 with a shorter time delay than ROCOF1, improved the stability of ROCOF1. In this case, ROCOF2 responded to the disturbance and tripped DG2. The frequency and rate of change of frequency with DG2 tripped or not tripped is shown in Fig.10. It is observed that the frequency changing rate has reduced after the tripping of DG2, resulting in ROCOF1 not being activated.

ROCOF settings (Hz/s)	Case		
	1	2	3
0.125	√	√	√
0.200	√	√	√
0.300	√	√	√
0.400	X	√	√
0.500	X	X	X

√	Trip
X	No Trip

Table 3: Results of ROCOF1's Responses for Cases 1-3

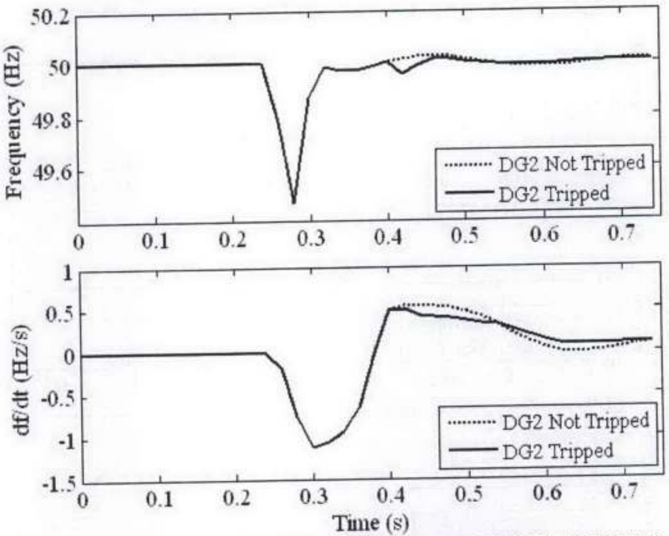

Fig. 10: Frequency and df/dt Sensed by ROCOF1 if DG2 is tripped or not tripped (at setting 0.4 Hz/s)

C. Under-voltage Interlock

A three-phase fault was applied on the adjacent feeder (feeder 2-4), shown as F in Fig. 8. The fault is subsequently removed after 0.25 seconds by the responsible circuit breaker. The following four cases were analyzed:

Case 1: Both ROCOF1 and ROCOF2 without under-voltage interlock function
Case 2: Both ROCOF1 and ROCOF2 with under-voltage interlock function
Case 3: ROCOF1 with under-voltage interlock function and ROCOF2 without under-voltage interlock function
Case 4: ROCOF1 without under-voltage interlock function and ROCOF2 with under-voltage interlock function

ROCOF settings (Hz/s)	Trip Time (ms)			
	Case 1	Case 2	Case 3	Case 4
0.125	10	290	290	10
0.500	10	290	290	10
1.000	30	290	290	30

Table 4: Results of ROCOF1 Tripping Time for Cases 1-4

The simulation results are portrayed in Table 4. It is found out that ROCOF2 with and without under-voltage interlock function does not affect the performance of ROCOF1. As shown in Fig. 11, the parameters used to initiate a trip decision did not change excessively with or without (tripped) DG2.

The false operation of ROCOF relay is due to the phase shift resulting from the fault incident (Fig. 6). However, in this case, after DG2 tripped, it is found out that the voltage waveform captured at terminal DG1 only experience magnitude changes but not phase shift (Fig. 7).

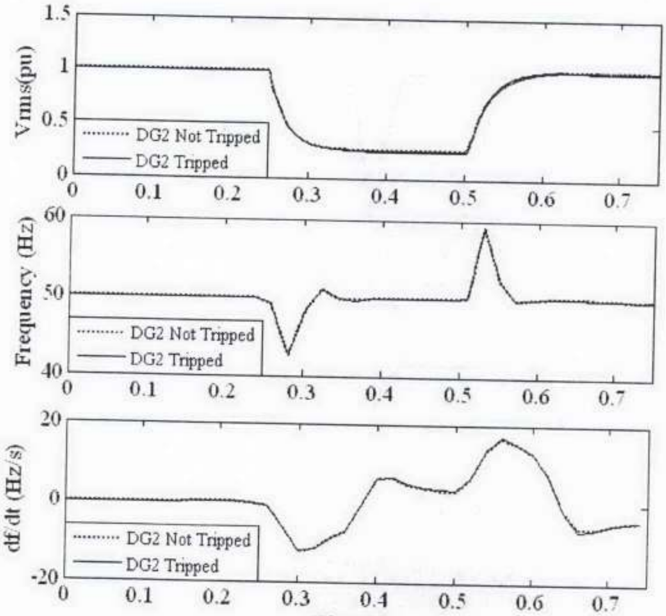

Fig. 11: ROCOF1's Response to Adjacent Fault (with or without DG2)

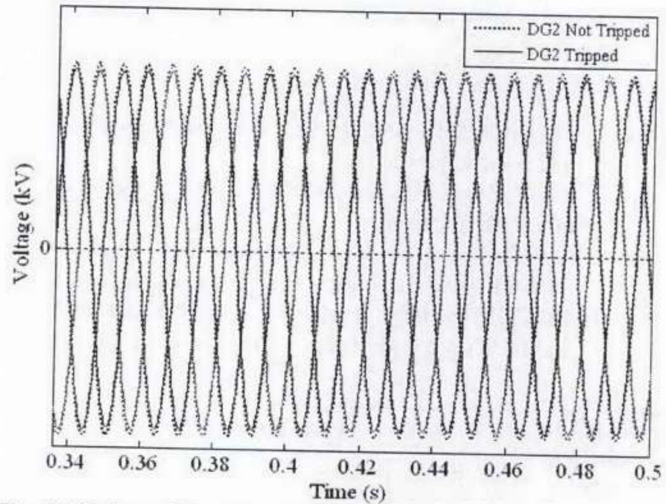

Fig. 12 Voltage Waveform if DG2 is tripped or not tripped

5 Conclusion

This paper has showed that ROCOF relays with different internal algorithms can perform very differently to the same event. It is important to note that even with the implementation of those functions into the relay's algorithm; it cannot completely prevent the mal-operation of ROCOF relay towards non-islanding events. A compromise in the setting is still required to provide a balance between the security and dependability of this relay.

For the case of multiple distributed generators, it is seen that the relays' stabilities are affected when they operate together. Even though being configured to the same threshold setting, the less stable relay may lead the more stable relay to incorrectly trip. This often happen when the less stable relay trips the DG unnecessarily, resulting in larger frequency transient which subsequently trip the other generator as well. However, this may not always be the case. As shown, the tripping may also helps to improve the other ROCOF relay's stability.

References

[1] C.M. Affonso, W. Freitas, W. Xu, L.C.P. da Silva. "Performance of ROCOF Relays for Embedded Generation Applications", *IEE Proceedings-Generation Transmission Distribution*, **Vol. 152**, pp. 109-114, (2005).

[2] A. Beddoes, P. Thomas, M. Gosden. "Loss of Mains Protection Relay Performances when Subjected to Network Disturbances/Event", *CIRED 18th International Conference on Electricity Distribution*, (2005).

[3] C.G. Bright. "COROCOF: Comparison of Rates of Change of Frequency Protection. A Solution to the Detection of Loss of Mains", *IEE 7th International Conference on Developments in Power System Protection*, pp. 70-73, (2001).

[4] R. Bugdal, A. Dysko, G.M. Burt, J.R. McDonald. "Performance Analysis of the ROCOF and Vector Shift Methods Using a Dynamic Protection Modelling Approach", *15th International Conference on Power System Protection*, pp. 139-144, (2006).

[5] X. Ding. "Synchronized Phasor Measurement and Islanding Operation of Distributed Generation", Faculty of Engineering and Power System, the Queen's University, Belfast, (2006).

[6] Econnect Ltd, "Assessment of Islanded Operation of Distribution Networks and Measures for Protection", DTI, UK, (2001).

[7] Electricity Association. "Engineering Recommendation G.59/1: Recommendations for the Connection of Embedded Generating Plant to the Regional Electricity Companies' Distribution Systems", Electricity Association, London, (1991).

[8] N. Jenkins, R. Allan, P. Crossley, D. Kirschen, G. Strbac. "Embedded Generation", the Institution of Electrical Engineers, London, (2000).

[9] R.A. Walling, N.W. Miller, "Distributed Generation Islanding-Implications on Power System Dynamic Performance", *IEEE Power Engineering Society Summer Meeting*, **Vol. 1**, pp. 92-96, (2002).