FEASIBILITY OF ACHIEVING FAST ROCOF-BASED LOM PROTECTION – A CASE STUDY OF HONG KONG DISTRIBUTION NETWORK

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Abstract

Distributed Energy Resources (DERs) are playing a critical role in the energy landscape to facilitate the decarbonisation of energy systems. One of the key requirements for the safe integration of DERs is to ensure the Loss of Mains (LoM) protection is sufficiently dependable and secure so that it can effectively detect islanding conditions while avoiding maloperation during other non-LOM grid disturbances (e.g. faults). This paper aims to assess the feasibility of achieving fast and reliable islanding detection using a commercially available Rate of Change of Frequency (RoCoF) based LoM relay. The study is undertaken on a section of the distribution system in Hong Kong (HK) where fast LoM protection operation (<260ms) is required due to the short time delay of an existing auto-reclose scheme. Systematic evaluation of the LoM relay performance both in terms of dependability and security is undertaken using Hardware-in-the-Loop (HiL) injection implemented on a Real-time Digital Simulator (RTDS). Based on the test results and detailed analysis, it is found that: 1) the objective of achieving fast RoCoF LoM detection (i.e. the dependability requirement) is feasible with the assumed settings but the protection security may be compromised under certain fault scenarios; 2) in addition to active power, the reactive power plays an important role in the RoCoF-based LoM detection; and 3) natural frequency oscillations following the fault clearance can lead to the unwanted RoCoF operation. These factors will need to be considered during the LoM setting process to ensure the proper balance between LOM protection dependability and security.

1 Introduction

In the past decades, significant amounts of DERs (e.g. distributed generation, energy storage, etc.) have been integrated into the distribution system to satisfy the increased electricity demand and facilitate the target of global decarbonisation [1]. Compared to the conventional centralised generation, DERs are typically installed close to local loads, which reduces the power losses resulted by long-distance transmission and, with appropriate design and control, they can be used to enhance the system resilience during extreme events, e.g. severe weather conditions. However, the connection of DERs also introduces challenges to the operation of the distribution systems, one of which is to ensure the reliable detection of the LoM conditions.

LoM (also referred to as islanding) is a situation where the local network has been disconnected from the main grid, while the DERs continue supplying the local loads [2]. Such unintentional islanding could threaten the safety of the utility personnel and present risks of damage to the electrical equipment if an appropriate operation is conducted without knowing the LoM condition [3]. Therefore, the LoM protection should be implemented to detect islanding events and trip the DERs so that the islanded network can be safely de-energised.

Based on the protection principles, LoM protection can be broadly categorised into three main types, i.e. passive, active and communication-based methods. Passive methods detect the LoM events by comparing the local measurement, e.g. voltage, frequency, active and reactive power, with the pre-defined thresholds [4]. Rate of Change of Frequency (RoCoF) and Voltage Vector Shift (VVS)-based LoM protection are two of the most representative and widely used passive methods. The passive methods are relatively easy to implement and cost-effective, however, they also have inherent limitations in detecting islanding events in certain grid conditions, particularly when the power of generation and loads are matched in the local network, where LoM relays' dependability can be compromised near such operating conditions, which are also referred to as 'Non-detection Zones (NDZs)' [5]. To minimise the NDZs in the passive LoM methods, active methods were proposed in [6]–[8], where small disturbances are intentionally injected into the grid, e.g. via the use of inverters, to create specific indicators for LoM events detection. During normal operating conditions, the impact of the injected disturbances will be neglectable because of the connection of the stiff utility system, so the LoM relays will remain stable (i.e. non-operative). When the local network is disconnected from the main system, the injected disturbances can pose significant changes to the monitored electrical quantities, which can be detected by the LoM relays. Despite being able to theoretically address the NDZ issues of passive methods, the injected disturbances from active methods could compromise the system power quality and there are practical challenges in implementing the methods due to the need for resources in injecting the disturbances. Another group of LoM protection is the communication-based methods as reported in [9]–[11], where communication links are established between the DERs and the main utility grid, where the local measurements are compared with the measurements (e.g. phase angle) taken from the main grid, and the inconsistency in the measurements could be used as the LoM indicator. Compared to the passive and active methods, the communication-based methods can detect the LoM conditions faster, and more accurately, but the need for communication links will present an increase of costs, which will be a barrier for wider application in practice. Among the aforementioned solutions, presently in the industry, RoCoF-based protection is still one of the most widely applied LoM protection methods [3][4][12] and with the evolving energy landscape, it is important to re-visit the settings and the performance of LoM relays that have already been deployed widely in the systems worldwide to evaluate whether the performance can still meet the emerging system requirements.

Therefore, this paper aims to evaluate the feasibility of achieving fast RoCoF-based LoM protection via a case study of an HK distribution system. The fast LoM protection operation (i.e. <260ms in this particular case) is required due to the short time delay of an existing auto-reclose scheme of the system being studied. Presently, a practice of maintaining a minimum active power imbalance between the local network and the grid is adopted to ensure protection dependability. This paper will also evaluate whether such a practice is sufficient or necessary to achieve the required protection performance.

In the paper, realistic HiL tests of a commercially available LoM relay have been conducted considering the protection performance from both dependability and security perspectives. Systematic HiL tests are conducted using a commercially available LoM relay and covering a wide range of LoM and fault events, to evaluate the protection dependability and security under specific operating constraints of a distribution network with DERs in HK. Representative cases in the systematic tests are selected to analyse the observations and facilitate understanding of test results.

The rest of this paper is structured as follows: Section 2 presents the development and validation of the network model, and the setup of the HiL platform for testing the LoM relay; Section 3 presents the information of the studied cases and the result analysis; and the conclusions are provided in Section 4.

2. Network Model Development and HiL Setup

2.1 Network Model Development in RTDS

The single-line diagram of the developed network model is presented in Figure 1, where the studied system is connected to the 132 kV grid through two 132 kV/11 kV transformers. To emulate LoM events, it is assumed that the TR2 in the LoM studies in this paper is out of service and the LoM events are

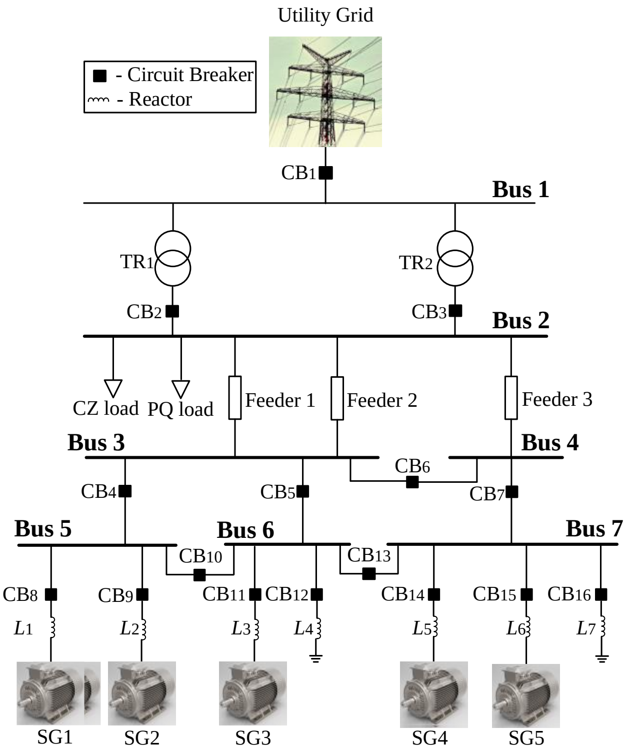


Figure 1. Single-line diagram of the investigated distributed system

triggered by the disconnection of TR1.

Five Synchronous Generators (SGs) are connected to the local system as DERs, which are represented by the Permanent Magnet Synchronous Machine (PMSM) model in RSCAD (i.e., the software package for RTDS) [13]. The rating of each generator is 2.84 MVA and the inertia constant is set to 0.28 s. In normal conditions, the active power delivered by each SG is fixed at 2 MW and all of them operate close to the unity power factor. As mentioned previously, to ensure continuous LoM protection dependability, the existing operating practice adopted in this network is to maintain the total output of the local generation at a level which guarantees at least 500kW active power imbalance between the local grid and the utility grid. This work will evaluate the effectiveness of such a practice. Two types of loads are included in the developed model to evaluate the impact of load type on the RoCoF protection performance, i.e. Constant Impedance Load (CZL) and dynamic PQ Load (PQL).

2.2 Network Model Validation with Historical Data

Before implementing the HiL test cases, the accuracy of the developed network model is validated by actual historical data from five physical tests in the network, where the RoCoF values obtained from RTDS simulation are compared with the historical measurement data. The information on the studied cases is presented in Table 1.

Cases 1 to 5 in Table 1 represent the field tests, where the generators from SG1 to SG5 are individually connected in sequence (with the rest being disconnected). In each case, the single connected generator is disconnected by tripping its corresponding CB (e.g. in Case 1, CB8 is disconnected to create a LoM event). During this process, the voltage at the disconnected generator's terminal was recorded and stored as historical data.

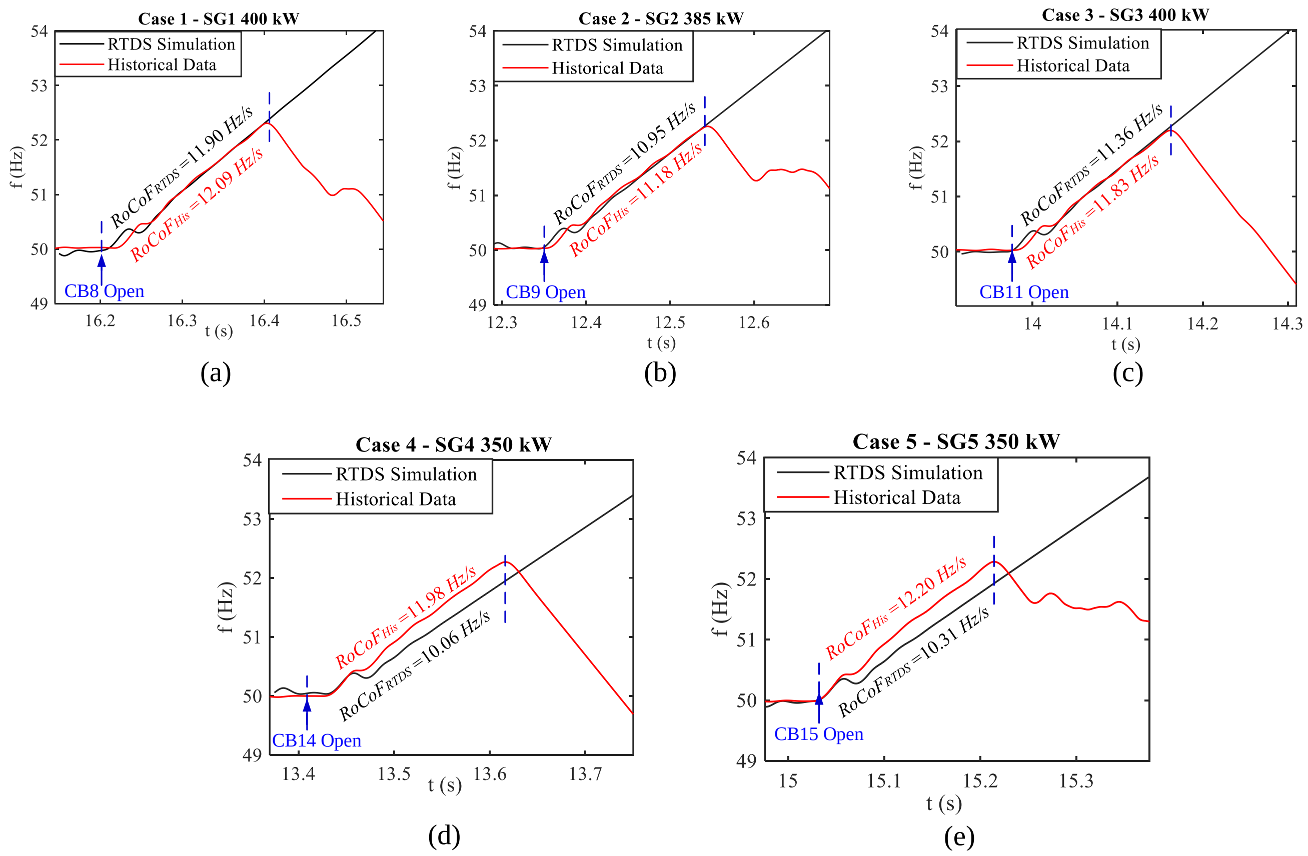


Figure 2. Validation results of, a) Case 1, b) Case 2, c) Case 3, d) Case 4, and e) Case 5

Table 1. Cases to validate the developed network model

Case	Generator Output	Initial CB status	Measurement Point
1	SG1 – 400 kW	CB1-8 closed; CBs 9-16 open	Bus 5
2	SG2 – 385 kW	CBs 1-7, 9 closed; CBs 8, 10-16 open	Bus 5
3	SG3 – 400 kW	CBs 1-7, 11 closed; CBs 8-10 & CBs 12-16 open	Bus 6
4	SG4 – 350 kW	CBs 1-7, 14 closed & CBs 8-13, 15-16 open	Bus 7
5	SG5 – 350 kW	CBs 1-7, 15 closed & CBs 8-14, 16 open	Bus 7

The cases in Table 1 are replicated in the developed RTDS network model by configuring the active power delivered from SGs and the connection of CBs in the network to be the same as historical tests. Similarly, the terminal voltage at the disconnected generator was recorded to calculate the simulated RoCoF value, and then compared with the RoCoF that was measured from the historical data.

The comparative results are shown in Figure 2, where the average RoCoF values from the RTDS simulation and historical data have been presented. The frequency in Figure 2 is calculated by the Phase-Lock Loops (PLLs) model in SIMULINK [14] and the average RoCoF values are calculated using (1), where the Δf represents the frequency deviation and the Δt refers to the time slot highlighted in the diagram. This slot corresponds to the period between the CB opening and the peak value in the historical data (i.e., the SG is disconnected during field tests after reaching the frequency peak point).

$$RoCoF = \frac{\Delta f}{\Delta t} \quad (1)$$

From the figure, it was found that RTDS simulation can achieve a relatively high level of accuracy against historical data in Cases 1, 2 and 3, while an increased error is presented in Cases 4 and 5. From a further investigation of the detailed waveforms of the measurements (not presented in the paper due to the space limit), it was found that in RTDS simulation, the system condition is always assumed to be balanced, which aligns with the historical voltage recorded in Cases 1, 2 and 3. However, in Cases 4 and 5, the input voltage from the field tests is imbalanced, which results in an increased error in Figure 2 (d) and (e).

2.3 HiL Setup for LoM Relay Tests

The schematic of the HiL setup for the LoM relay is presented in Figure 3. The distribution network as shown in Figure 1 has been developed in RSCAD and run in real-time using RTDS. The Voltage Transformer (VT) model in RSCAD was used to step down the primary voltage at the SG1's terminal, and the output secondary-side voltage is further scaled down so that it can fall into ±10 V (i.e. the required range of the GTAO card) to avoid saturation. Then, the output voltage signals from the GTAO card were amplified using a physical amplifier to the level being the same as the secondary-side voltage from the VT. The amplified voltage was then injected into the relay, which is used for the tripping decision-making. The tripping signal was monitored and transmitted back to the RTDS through the digital input/output interface, i.e., the GTFPI card.

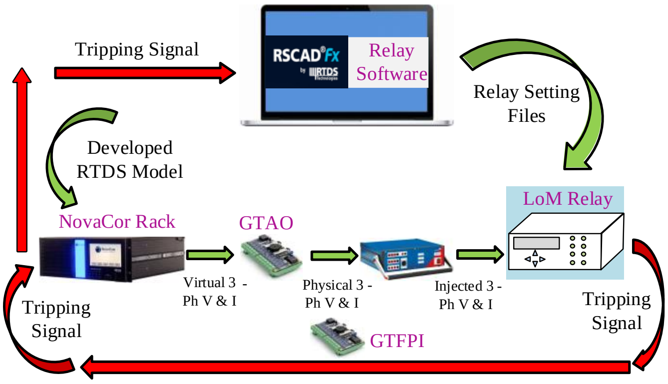


Figure 3. HiL setup for LoM relay tests

To allow the test of a large number of cases, dedicated RTDS scripts are developed to automate the aforementioned injection process and record the tripping signal, along with other associated data during the testing process, e.g. the injected voltage and current. The recorded tripping signal was further interpreted and analysed in the designed MATLAB code to evaluate if the relay had met the tripping requirements.

3. Results and Analysis

3.1 RoCoF Relay Settings and Studied Cases

The relay settings used in all tests are presented in Table 2. The value of the RoCoF threshold was established using the assumption that the real power imbalance for each generator (under all operating conditions) is 100 kW or more (i.e. 500 kW in total at least), which leads to the estimated minimum value of the RoCoF during the LoM event. After substituting the 100 kW to (2) that is used to calculate the RoCoF value under the specific active power mismatch, the minimum RoCoF is 3.1 Hz/s (i.e., $\frac{0.1 \cdot 50}{2 \cdot 2.84 \cdot 0.28} = 3.1\text{Hz/s}$) for 100 kW real power imbalance. In (2), the ΔP is the active power change during LoM events, f is the system frequency, S is the DER's rating and H is the inertia constant of the DER.

$$RoCoF = \frac{\Delta P\ f}{2\ S_G\ H} \tag{2}$$

Considering an additional sensitivity margin of 20% the RoCoF setting is set to $0.8 \times 3.1 \approx 2.5$ Hz/s. The second setting, a time delay, which enhances protection security (especially during remote faults and other voltage disturbances), is set relatively short to comply with the fast operation requirements of 260 ms in the HK distribution network which is equipped with the fast auto-reclose automation scheme. Considering the typical RoCoF measurement delay of approximately 100-120ms and an additional 20 ms time margin, the relay operational time delay is set as 120 ms.

The key objective of the test was to verify whether the assumed settings (reflecting the challenging operating requirements) can deliver the expected performance of the LoM protection. Both LoM and fault conditions are simulated to evaluate the relay's performance from the dependability and security perspectives. The detailed cases in tests are shown in Table 3 and Table 4.

Table 2. Settings of the studied relay

Setting Name	Settings
Enabled Function	RoCoF
Start Value of RoCoF	2.5 Hz/s
Operational Time Delay	120 ms

Table 3. LoM cases in the HiL tests

Parameter	Settings
Total active power of loads, P_{Total}	9 MW to 11 MW with an increasing step of 0.2 MW
Power factor of loads, pf	0.99, 0.95
Penetration level of dynamic load, PQ%	100%, 50%, 0%

Table 4. Fault cases in the HiL tests

Parameter	Settings
Transformer connection	Only TR1 connected, both TR1 and TR2 connected
Fault position	Bus 1, Bus 2
Fault types	AG, AB, ABG, and ABCG
Fault resistance	For AG, AB, ABG – 0 Ω, 5 Ω and 10 Ω For ABCG – 0.5 Ω, 5 Ω and 10 Ω

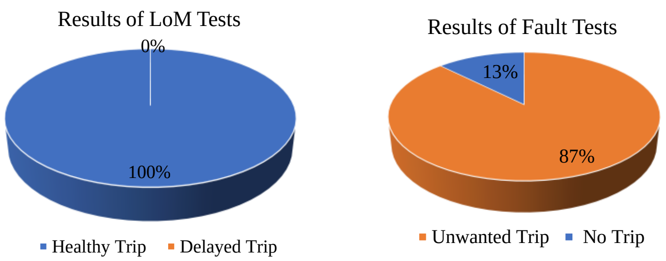
In Table 3, P_T is the total active power setting of the dynamic PQ load and constant impedance load in the network and the penetration level of the dynamic load is defined in (3), where P_{PQ} and P_{CZ} are the active power settings of dynamic and constant impedance loads. It should be noted that compared to the dynamic load that can dynamically maintain its active and reactive power to the power setting points, the actual active and reactive power consumed by the constant impedance load is also dependent on the load's terminal voltage.

$$PQ\% = \frac{P_{PQ}}{P_{PQ} + P_{CZ}} \times 100\% \tag{3}$$

For the fault cases in Table 4, the connection of the transformer can affect the equivalent impedance between the utility grid and the local distribution system. Therefore, the transformer connection status has been considered as one factor for study in the fault tests. The faults are simulated at Bus 1 (i.e., 132 kV) and Bus 2 (i.e., 11 kV) to evaluate the impact of faults at the High-Voltage (HV) and Low-Voltage (LV) sides. To focus on the cases where DERs remain stable during ABCG faults, the fault duration is configured as 100 ms and the minimum fault resistance under ABCG faults is set to 0.5 Ω.

3.2 Overview of Results from HiL Tests

A high-level summary of the results from the HiL tests is presented in Figure 4, where in total 66 LoM cases and 48 fault cases were tested.



(a) (b)

Figure 4. Relay response statistics: (a) LoM tests, (b) fault tests

For the test result presented in Figure 4 (a), the tripping action was grouped as 'Delayed Trip' if the relay operating time (i.e., the time difference between the relay trip and the occurrence of the LoM event) is greater than 260 ms, which is the maximum tolerable operating time of the LoM protection in the studied distribution network as mentioned previously to meet the requirement of a fast auto-reclose scheme. From the results, the relay can detect and trip all LoM events correctly within the required time.

Based on fault results in Figure 4 (b), the LoM protection trips incorrectly in 87% of all investigated cases (i.e., 48 cases in total). Analysis of fault conditions is presented in Section 3.4.

3.3 Analysis of the LoM Events

Three representative cases in the LoM tests are selected and shown in Table 5. In these cases, P_{PCC}, i.e. the active power flowing through the PCC (i.e., CB2 in Figure 1), is controlled to be close to 0 MW to emulate the active power balanced condition of the distribution network.

Table 5. Selected cases in LoM tests

Case	P_{Total} (MW)	pf	$PQ\%$	P_{PCC} (MW), Q_{PCC} (MVAR) (before LoM)	t_{op} (ms)	Trip Group
3	11	0.99	0%	-0.08, -4.09	124.94	Healthy
14	10.2	0.99	50%	-0.04, -4.09	139.62	Healthy
22	9.6	0.99	100%	-0.09, -4.10	149.2	Healthy

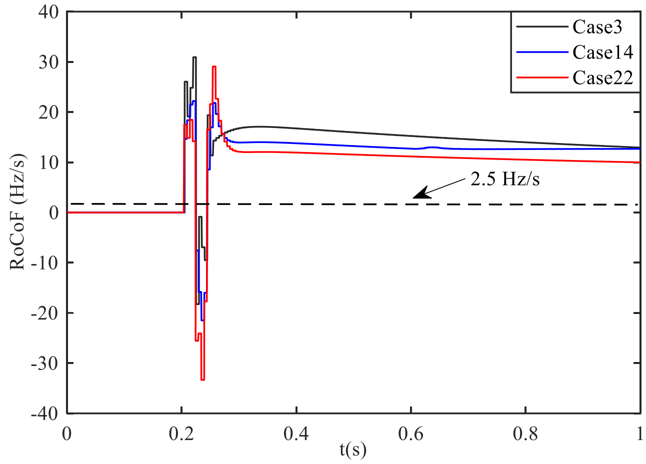


Figure 5. RoCoF values of cases in Table 5

The RoCoF values of the cases in Table 5 are presented in Figure 5, which are measured using the Phasor Measurement Unit (PMU) block in RSCAD [15] with the terminal voltage of SG1 being the input. From Figure 5, it can be seen that the RoCoF values in all cases are greater than the applied threshold, i.e., 2.5 Hz/s, therefore, the relay can trip all LoM events correctly. The RoCoF can be calculated using (2).

In the studied cases, the active power of the generation and load is matched before the LoM events, however, this condition does not hold after the loss of the utility system. As shown in Table 5, around 4 MVAR reactive power is drawn from the grid before the LoM event mainly due to the presence of the fixed inductors ($L_1 - L_7$ in Figure 1). At the LoM instant such reactive power mismatch results in an immediate voltage drop at the load terminal, which affects the active power consumed by the loads in the network, and further influences the ΔP in (2), and thus, RoCoF values seen by the relay. In this study it was noted that the reactive power imbalance is increased leading to improved RoCoF protection dependability. This suggests that the existing practice of maintaining a minimum active power imbalance (export) of 500 kW (in total for the 5 SGs), while further facilitating protection during LoM events, might not be necessary as even during a matched active power and demand condition, the reactive power imbalance as a result from local inductors will be sufficient to trigger the LoM protection within the required time frame. However, it should be noted that, if the active power imbalance is for importing power to the local network, it might compromise the protection sensitivity.

3.4 Case Analysis of Fault Events

In addition to the dependable requirements, the LoM relay should remain stable during other grid disturbances, e.g. faults. After analysing the test results, it was found that the main source behind the maloperation in Figure 4 is the voltage amplitude and frequency oscillation after the fault clearance. The cases in Table 6 are selected to demonstrate the impact of voltage swings on the RoCoF protection.

Table 6. Selected cases in fault tests

Case	Transformer	Fault Conditions	Trip Group
3	TR1 connected	Bus 1, AG, 10 Ω	Unwanted Trip
6	TR1 connected	Bus 1, AB, 10 Ω	Unwanted Trip
9	TR1 connected	Bus 1, ABG, 10 Ω	Unwanted Trip
12	TR1 connected	Bus 1, ABCG, 10 Ω	No Trip

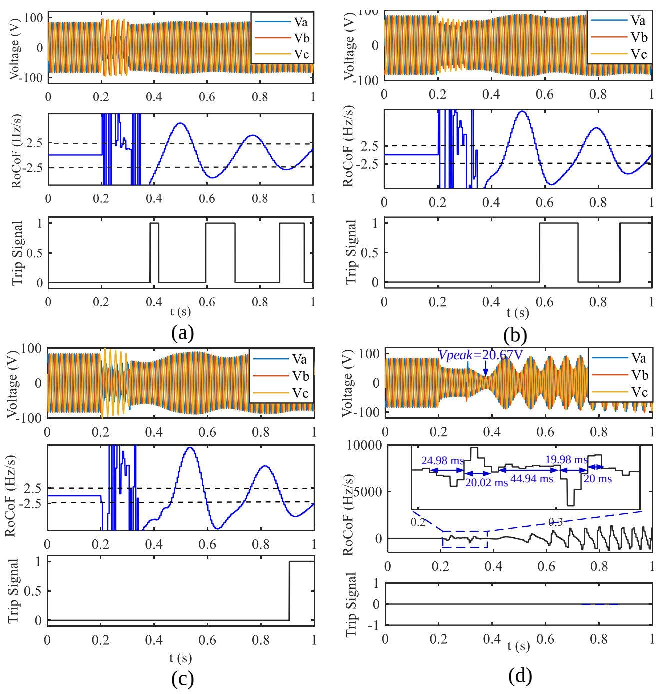


Figure 6. Results of fault cases, (a) Case 3, (b) Case 6, (c) Case 9, and (d) Case 12

The voltage, RoCoF and relay tripping signal for the cases in Table 6 are presented in Figure 6. According to the relay manual, the relay will be activated when the measured RoCoF exceeds the applied threshold, and the internal timer will start counting at the same time. If the measured RoCoF magnitude drops below the threshold during this period, the timer will be reset. The relay will trip when the timer's output is greater than the configured delay setting, i.e., 120 ms in this study. The RoCoF values in Figure 6 are the outputs from the RTDS rather than the values directly from the actual relay measurement, which is not typically accessible. Therefore, the estimated RoCoF from RTDS might be not the same as the values used in the relay.

The faults in this section are applied at 0.2 s. The duration of applied faults is set to 100 ms, which is considered as the upper limit for main protection schemes on the HV side, e.g. differential and zone-1 distance protection, to isolate faults in the 132-kV system. From the results in Figure 6 (a) to (c), it was found that the LoM relay can remain stable during faults, but it could be tripped by the frequency oscillation following the fault clearance, which leads to the swing of the measured RoCoF values. In Figure 6 (d), it is shown that during the initial cycles, the duration where the magnitude of RoCoF exceeds the threshold is less than 120 ms. As a result, the relay is not activated to initiate a trip. After that, the peak value of the secondary-side voltage drops to 20.67 V, which is approximately 23% of the nominal voltage. It is considered that this voltage reduction could have triggered the low voltage blocking logic of the physical relay, which blocked the tripping signal raised by the RoCoF element inside the physical relay. To enhance the relay performance and prevent maloperation during the voltage swing, the adjustment can be adopted by either increasing the RoCoF settings or implementing a longer time delay. Considering the fast LoM operation requirements in this particular application increasing the RoCoF threshold seems to be the only option, and further study will be required to determine the most suitable settings.

4. Conclusions

In this paper, realistic HiL tests have been conducted to evaluate the RoCoF protection performance. To ensure accurate modelling of the investigated distribution system, the RoCoF measurements obtained from the RTDS simulations were compared with the historical field-test data. The validated network model was then subjected to comprehensive HiL tests to obtain a wide overview of the LoM relay performance under both LoM and fault conditions. The test results show that the RoCoF relay can always trip correctly during all LoM events, but it trips incorrectly in 87% of the fault cases. Further detailed analysis of the test results led to the following key observations and recommendations:

1) In addition to active power, the balancing condition of the reactive power during LoM events significantly impacts the RoCoF protection's performance. Any reactive power imbalance affects the voltage level during the LoM event, which in turn, influences the active power demand from the loads, especially those characterised as fixed impedance.
2) Voltage frequency oscillation observed after the fault clearance often leads to the maloperation of the RoCoF relay. This effect accounts for most cases of unwanted non-LoM event operations.
3) In the study of the HK network, due to significant (and continuous) reactive power import from the grid, the dependability of the RoCoF protection is naturally enhanced. With the existing setting, the study suggested that it is feasible to achieve the fast LoM operation required by the auto-reclose scheme. It also indicates that there is a potential for a higher RoCoF setting leading to a reduced number of unwanted operations during non-islanding events.

The optimal setting of the RoCoF LoM relay depends on many different factors, including the level of acceptable dependability and security, the nature of loads, etc. Therefore, further testing with additional information on the actual system condition would be required to achieve the optimal settings.

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