Performance analysis of the ROCOF and Vector Shift methods using a dynamic protection modelling approach

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Abstract—**Due to the continually increasing levels of penetration of distributed generation the correct operation of Loss-Of-Mains protection is of prime importance. Many UK utilities report persistent problems relating to incorrect operation of the ROCOF and Vector Shift methods which are currently the most commonly applied methods for Loss-Of-Mains (LOM) detection.**

The main focus of this paper is to demonstrate the problems associated with these methods through detailed dynamic modelling of existing available relays. The ability to investigate the transient response of the LOM protection to various system events highlights the main weaknesses of the existing methods, and more importantly, provides the means of quantitative analysis and better understanding of these weaknesses. Consequently, the dynamic analysis of the protective algorithms supports the identification of best compromise settings and gives insight to the future areas requiring improvement.

Index Terms—**Distributed generation, islanding, loss of mains, power system protection.**

I. INTRODUCTION

THE growing number of Distributed Generators (DG) in the power network creates opportunities for improving overall system operational efficiencies. However it also gives rise to a number of issues related to protection and control. One of the most important aspects of connection of DG to existing networks relates to the possibility of islanded operation. An event of unintentional disconnection of a DG from the grid is known as Loss of Mains (LOM). The current legislation in the UK [1] allows the islanding of a generator under careful consideration. This, however, has not been adopted into operational practice yet. Currently the reliable detection of LOM events is required followed by the immediate disconnection of the generator from the utility network.

In recent years a number of methods for LOM detection were developed [2-6]. The most common methods widely used in the UK are Rate of Change of Frequency (ROCOF) and Voltage Vector Shift (VS). These two algorithms despite being improved and implemented in modern numerical relays, according to utility experience, provide unsatisfactory performance. The most persistent problem related to the LOM protection relays is spurious tripping. The problem occurs mostly during faults on the system – the relay misinterprets a remote fault as a LOM event and unnecessarily disconnects the generator. This possibility is sometimes resolved by the empirical adjustments of the settings to the point of stable operation. However, such an approach may lead to an improper compromise of the sensitivity of the protection to genuine LOM events.

In this paper, in order to demonstrate an accurate assessment of LOM relay operation, both under genuine LOM and fault conditions, the development of a model of a commercially available relay is reported. It contains both ROCOF and VS algorithms. Subsequently, the model has been validated and integrated within the Protection Integrated Modelling Environment (PRIME) [7] which supports testing of protection under various power system scenarios.

The paper presents dynamic simulation results of the LOM relay model subjected to typical system events, and thus supports better understanding of the necessary compromise between protection sensitivity and stability.

II. RELAY MODEL IMPLEMENTATION

The ROCOF algorithm detects the fluctuation in frequency caused by the oscillation of a machine rotor resulting from new load conditions (following loss of connection to the main grid in the event of a genuine LOM). Vector Shift (VS) detects instantaneous changes in three-phase voltage angles which occur when connection with the main grid is lost. The VS algorithm operates without any delay providing near-instantaneous tripping.

Based on available public domain data a model of the relay has been implemented in Matlab/Simulink software. A simplified block diagram of the complete model is shown of Fig. 1. In order to validate the model's dynamic behaviour its response was compared in detail with an actual relay in terms of threshold setting as well as tripping time. A secondary injection test set was used for the relay hardware testing.

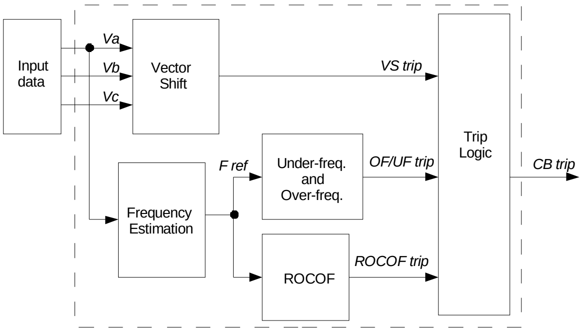

Fig. 1. Block structure of relay model

The developed model uses the 110V secondary values to calculate the rate of change of frequency as well as the sudden angle change. The input signal is adjusted to 1.2 kHz sampling rate in a pre-processing unit in order to reflect the behaviour of the modelled device.

A. Rate of Change of Frequency

Change of frequency is caused by the imbalance between the input mechanical power and load. Due to this imbalance after disconnection from the main grid the frequency starts to change dynamically and therefore the rate of change of frequency is often approximated in practice by the formula (1):

$$\frac{df}{dt} = \frac{\Delta P \cdot f}{2 \cdot G \cdot H} \tag{1}$$

Where:

ΔP – Change in power output between synchronised and islanded operation;
f – Rated frequency;
G – Machine rating in MVA;
H – Inertia constant.

The model of the relay utilised in this paper implements the rate of change of frequency measurement based on the following formula (2):

$$\frac{df}{dt} = \frac{f_n - f_{n-3cycle}}{T_{3cycle}} \tag{2}$$

Where:

f_n – current frequency measurement
$f_{n-3cycle}$ – frequency measured three cycles earlier
T_{3cycle} – duration of the three most recent cycles

The ROCOF value is calculated in moving 60ms windows and two consecutive calculations are required to assess if this is a permanent change. When both give a result above the set threshold the trip signal is initiated. To provide additional stability against normal load switching events and other small-scale system transients, an additional time delay can be applied.

B. Vector Shift

The Vector Shift protection algorithm is based on voltage angle measurements performed on all three phase voltages. A measurement is taken from each of the 3 phase voltages after every half-cycle and the decision is made after a full cycle. In general, a VS relay measures the same values as the under/over frequency relays, however the operating principles are different. The angle difference is calculated from the zero-crossing times between the present and the previous cycle. This gives six results at the end of each power system cycle (2 half-cycles x 3 phase voltages). If 5 of those 6 results are above the setting threshold, a trip signal is initiated. Since the VS relay compares only two consecutive results it provides fast decision-making and tripping in approximately 30ms. The use of the three phases makes the algorithm less exposed to harmonic distortion, interference and imbalanced faults. This improves protection stability and decreases the probability of spurious tripping during non-symmetrical faults.

C. Modelling environment

The PRIME software has been developed as an environment for off-line testing and development of protection algorithms. Using previously simulated or recorded data it is possible to assess the operation of the dynamic relay model in terms of operating time as well as operating thresholds.

III. TEST SYSTEM

A. Power System Model

A fragment of an existing utility network was selected for testing as depicted in Fig. 2. The model is a reflection of a typical medium voltage network with two 132/33kV feeders. The embedded generator is connected at 33kV busbar and it supplies 11kV industrial loads through 33kV/11kV transformers.

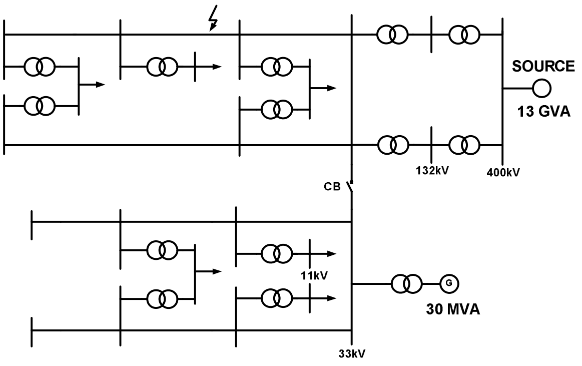

Fig. 2. Simplified diagram of the simulated network

The network model contains different voltage levels therefore it is possible to test almost every network scenario needed to assess the LOM operation. The network model has been implemented using RSCAD and simulations were carried using Real-Time Digital Simulator (RTDS) hardware [8].

B. Generator Model

To assess the relation between the LOM relay operation and generator type, two types of generators were included in the test – synchronous machine (SM) and Doubly Fed Induction Generator (DFIG) powered by wind turbine. A single equivalent machine model has been used represent a windfarm. Behaviour of the DFIG depends on the implementation of the controller algorithm – for the purposes of this paper the model presented in [10] has been utilised.

IV. EXAMPLE TEST RESULTS

A number of scenarios has been simulated and tested using the relay model in order to assess the dynamic relay performance, highlight critical cases and achieve best compromise settings. For the illustrative purposes of this paper the selected examples are included in the following sections. The settings of the relay are displayed in relevant figures.

A. Scenario 1 - switching initiated LOM event

In this case the generator loses connection with the main grid through the opening of the remote circuit breaker (labelled CB in Fig. 2). Such event, although not very frequent, has to be considered as it poses the greatest challenge to the LOM detection method as this is imposes lesser disturbance to the frequency than an event involving a fault. This particular example relates to a situation where the generator was operating at 90% of its nominal power prior to the LOM event, and after disconnection the local load exceeded the generator output by 2.5%. This presents a particularly challenging situation given the near load/generation balance.

The simulation results for the synchronous machine and DFIG based generation together with applied settings are presented in Fig. 3 and Fig. 4 respectively. It can be noted that for the synchronous machine based generation the islanded condition could be difficult to detect when the local load matches closely the generator output. The relay remains stable even at the minimum settings of 0.1Hz/s (ROCOF) and 2deg (VS).

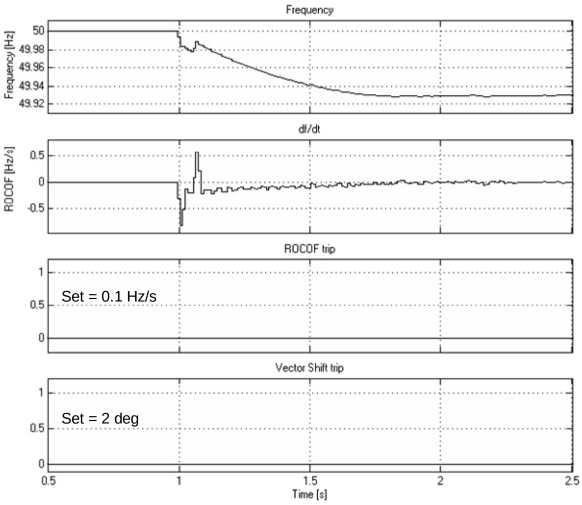

Fig. 3. Response to switching initiated LOM event – SM generator

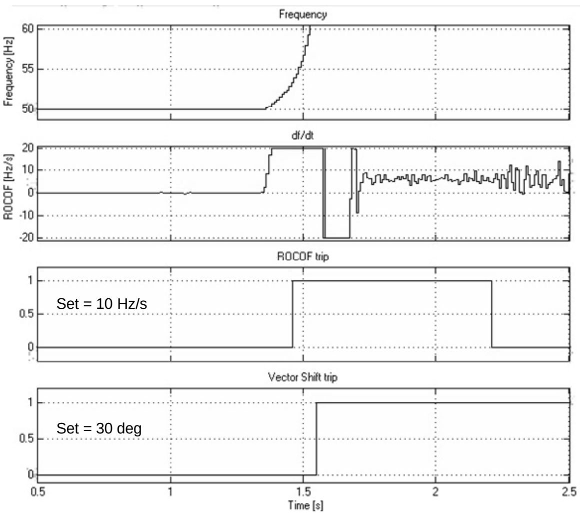

Fig. 4. Response to switching initiated LOM event – DFIG generator

On the other hand under similar conditions the DFIG based generator is practically incapable of sustaining a stable islanded operation for more than a few hundreds of milliseconds. In this scenario it has been found that the ROCOF method detects the LOM event at settings up to 10Hz/s and VS detects the event with angles of up to 30deg.

B. Scenario 2 – system fault followed by LOM event

Although the LOM event described in the previous section is possible, a more likely scenario is the loss of grid connection resulting from a fault on the interconnecting circuit. The circuit is disconnected in order to remove the fault, and the generator becomes isolated as a result. In the simulated scenario a three phase fault occurs at 1s and circuit breaker CB opens at 1.2s. The results together with associated relay settings are presented in Fig. 5 and Fig. 6 for SM and DIFIG based generation respectively. The settings represent the maximum values at which both types of protection (ROCOF and VS) still operate.

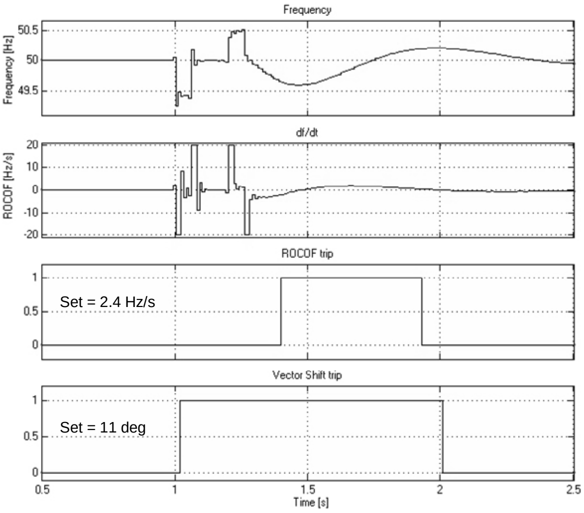

Fig. 5. Response to fault & LOM – SM generator

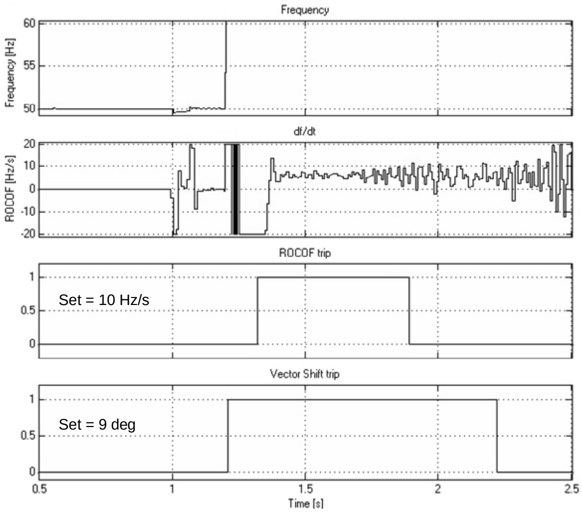

Fig. 6. Response to fault & LOM – DFIG generator

For SM based generation in scenario 2 the ROCOF operates with settings up to 2.4Hz/s and VS operates with settings up to 11deg.

For DFIG based generation the results differ significantly from those recorded with SM. ROCOF operates up to a maximum setting of 10Hz/s and VS algorithm operates with settings up to 9deg.

C. Scenario 3 – system fault on adjacent circuit

Scenario 3 presents a 3-phase fault event on an adjacent 33kV circuit, shown as F3 in Fig. 2. The fault is subsequently removed after 0.25s by circuit protection and the connection of the DG to the main grid remains possible – in this case LOM protection should remain stable. The simulation results together with associated protection settings are presented in Fig. 7 and

Fig. 8 for SM and DFIG based generators respectively. The settings represent the maximum values at which both types of protection (ROCOF and VS) still produce a spurious trip. For stability preservation higher values need to be applied.

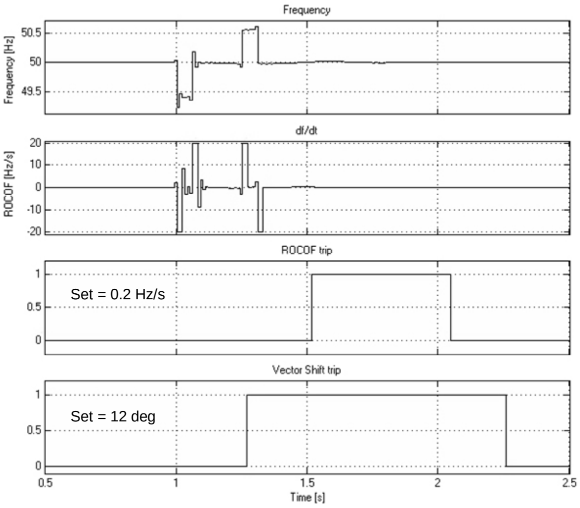

Fig. 7. Response to adjacent fault – SM generator

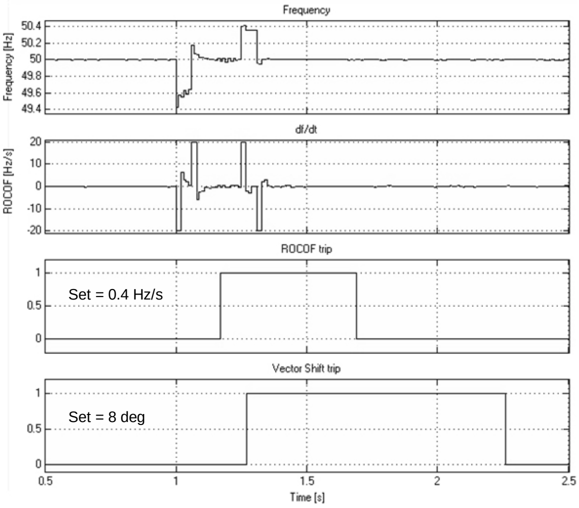

Fig. 8. Response to adjacent fault – DFIG generator

It has been observed that for SM based generation both ROCOF and VS protections are more likely to operate as a result of the clearance of the fault rather than its inception. It has been noted that ROCOF operates with the setting of 0.1Hz/s at fault inception and up to 0.2Hz/s as a result of the post-fault transient as shown in Fig. 7. Similarly, VS operates at with the setting of 11deg at fault inception and up to 12deg for post-fault disturbance.

For DFIG based generation, the ROCOF responds to the fault with settings up to 0.4Hz/s (fault inception only). VS operates with settings up to 7deg setting at fault inception and 8deg after the fault clearance.

D. Scenario 4 – system frequency excursion

Apart from the frequency deviations caused by system faults in the vicinity of the generator, there are occasional frequency excursions resulting from transmission system events. According to an engineering technical report [9] the rates of change of frequency of up to 0.16Hz/s can be expected in the UK transmission system. In order to test stability of the LOM protection under such conditions a test signal has been simulated where frequency increases with a fixed rate of 0.16Hz/s for 0.5s and then decreases with the same rate for another 0.5s.

The results together with associated minimum settings are presented in Fig. 9 and Fig. 10 for SM and DIFIG based generation respectively.

During the frequency disturbance on the network VS algorithm remains stable, whereas the ROCOF operates with settings up to 0.2Hz/s. Since the frequency is imposed by the system there is no difference in performance between SM and DIFIG based generators.

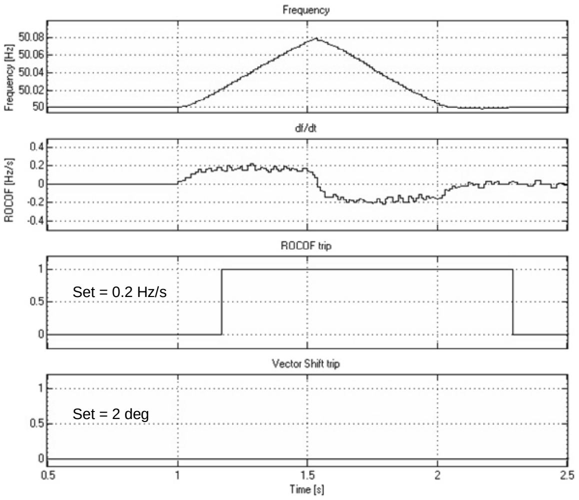

Fig. 9. Response to system frequency excursion – SM generator

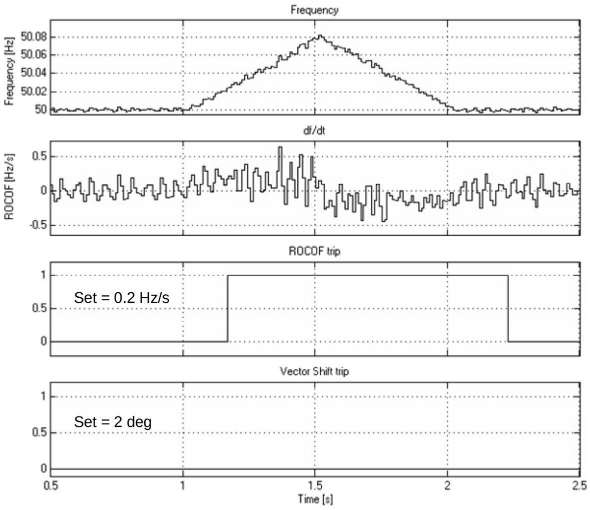

Fig. 10. Response to system frequency excursion – DFIG generator

V. DISCUSSION

The utilisation of the dynamic relay model presented in this paper provided a deeper understanding of the relay behaviour under varying system conditions which is not possible with load flow or vector based static approach.

In particular the simulations highlighted some weaknesses of existing LOM protection methods such as the difficulty of recognising switching initiated LOM event under balanced local load and generation conditions (Scenario 1). On the other hand both methods can operate reliably if the LOM event is a result of a system fault (Scenario 2). Another issue indicated by the relay model was the compromised stability under system faults – spurious LOM tripping. It has been demonstrated through simulations that the ROCOF method is particularly sensitive to the frequency transient following the clearance of a remote fault whereas VS method, although fast acting, responds to faults (especially balanced) in the vicinity of the generator regardless of whether they result in LOM or not. The marginal settings achieved in scenario 2 (sensitivity) and scenario 3 (stability) are very similar and leave no room for compromise.

The relay model also provided an insight into the differences in relay responses, and therefore, different requirements for settings, when different generation technologies are in place. It has been demonstrated in Scenario 1 that the required settings to ensure sensitivity of protection are much higher in the case of DFIG based generation than those with SM based generation. Consequently it is easier to achieve an acceptable compromise between sensitivity and stability for DFIG based generators. In the example case studies presented in this paper the compromise for DFIG based generator can be reached as follows:

- for ROCOF method between 0.4Hz/s (marginal value to ensure stability as shown in Fig. 8) and 10Hz/s (maximum value to preserve sensitivity as shown in Fig. 4);
- for VS method between 8deg (marginal value to ensure stability as shown in Fig. 8) and 30deg (maximum value to preserve sensitivity as shown in Fig. 4).

For synchronous machine generation the compromise is much more difficult to achieve as the required settings for the sensitivity of the LOM protection are very low if there is a real possibility of near generator/load balance. Further studies involving realistic generation and load profiles may reveal further opportunity for the best compromise settings.

It has been observed that the dynamic response of the generator during post fault clearance period has often a greater impact on the local frequency variation than the transient during the fault. When assessing the stability of the LOM protection under system faults it is therefore important to consider the time period following the fault clearance.

Additionally, careful examination of the results presented by the relay model highlighted some opportunities for LOM protection improvement. Comparing the frequency responses of the SM to switching initiated LOM in Fig. 3 and a fault event in Fig. 7 it can be seen that there is a significant difference in dynamic frequency response of the SM to these two events. When LOM occurs the frequency tends to drift from the nominal value in an asymptotic manner, whereas when the remote fault is cleared without the loss of connection the frequency on the generator terminals stabilises rapidly following a short damped oscillation around the system frequency. This indicates that perhaps a method based on frequency or integrated voltage angle can be more effective that the current approach based on the rate of change of frequency. As shown by scenarios 1 and 3 the measured rate of change of frequency can be high in both cases leading mainly to unnecessary spurious tripping.

VI. CONCLUSION

The paper presented a dynamic model of the ROCOF and VS algorithms. The simulations of the typical system events highlighted a number of issues associated with these methods, relating to both sensitivity and stability. The analysis of the detailed transient response of the relay facilitates better understanding of the principles and factors having a decisive impact on the performance of protection algorithm. The relay model can also assist in achieving the best compromise settings for a particular application (e.g. based on specific generation technology). Additionally, the analysis of the dynamic relay responses supports the identification of opportunities for further improvement of the LOM methods.

VII. ACKNOWLEDGMENT

The authors would like to express their gratitude to ScottishPower for providing data and professional expertise for this work.

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IX. BIOGRAPHIES

Rafał Bugdał was born in 1977 in Poland. After graduation from the University of Lodz in 2001 he started the research for the PhD in the Institute of Electrical Power Engineering, Lodz, Poland. In 2004 he moved to University of Strathclyde, UK where he continues his PhD studies. His research activities are power system operation, dynamics and control.

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James R. McDonald (M'90) was born in Glasgow, UK in 1957. He received the BSc, MSc, and PhD degrees from the University of Strathclyde, Glasgow, UK. He was appointed to the Rolls-Royce Chair in Electrical Power Engineering in 1994 and he was made Head of Department in 2003. His activities lie in the areas of power system protection and management, expert systems applications in power engineering; and, energy management. He was published many technical papers and is the co-author of two books.