CURRENT-ONLY DIRECTIONAL PROTECTION OF DISTRIBUTION NETWORKS USING LOW-COST COMMUNICATION

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Abstract

Conventional distribution protection schemes may not be suitable for evolving and future networks due to the rapid increase in distributed energy resources. This paper presents a review of selected novel protection principles for distribution networks and proposes a new and effective protection technique using only current measurements, based upon comparison between pre- and during-fault current phasors. This comparison process only requires low-cost communication systems for intermittent data transmission between measurement points. An overview of potential communication solutions is also contained in the paper. The operation of the method is tested and validated using simulated case studies of different scenarios, which demonstrate that the proposed scheme is highly effective in detecting and isolating faults, thus presenting a promising solution for protection of future active distribution networks.

1 Introduction

Electrical power systems are continuously evolving – the increasing demand for sustainable low carbon energy has resulted in the penetration of many relatively small renewable energy resources (RES), including distributed generation (DG) units and energy storage technologies, many of which are connected to power distribution networks. In addition to providing clean energy, RES can also provide many benefits such as increases in system reliability and efficiency, decreases in peak overall power demand on networks, improvements in power quality and reliability, and reductions in distribution losses [1]. However, this evolving situation also leads to a number of protection challenges being presented [2]. In microgrids, where the power flow can be bi-directional due to connection of DG units, fault levels depend on the operational mode, type, number, and capacity of DGs [4], as well as the infeed from any grid connection(s) (which may not always be connected and could also vary in strength). In addition, fault current magnitudes contributed by inverter-interfaced DGs can be limited (typically to less than 150% of their rated current [4]), and may also present highly distorted waveforms, particularly in the initial time following fault inception, which can lead to difficulties in fault detection [5]. Thus, conventional protection devices may not detect faults for all situations in future networks, or if they do, the operating time could be much longer than usual [1]. As a result, directional protection based upon voltage and current polarity measurements may be more appropriate for future electrical networks.

However, using both volage and current as inputs for fault detection may require more measurements and could require more computation power. Including voltage measurements (typically requiring three voltage transformers for three-phase system) can increase the expense associated with protection [6]. Moreover, if the fault location is very close to the relay measuring point, the voltage polarisation function may be compromised as the voltage is very low, leading to difficulties in establishing direction/phase for such 'close-in' faults [7].

During fault conditions, current phasor values typically change considerably from pre-fault values due to drastic changes in system impedances. Hence, current-only directional principles are of interest and potentially beneficial for future power systems (with high penetrations of DG and bidirectional and highly variable during-fault power flows). The work reported in [8] proposes fault detection methods based on current directions measured from signals in the time-domain. However, the results of measuring signals in the time-domain include noise, harmonics, and possibly frequency deviations. This can mean that such protection systems may mal-operate in some cases. In addition, the paper also stresses that the direction of system power flow in normal operating condition must be known prior to faults. In [6, 9], other schemes for measuring the current direction e.g., using Kalman filters and Discrete Fourier Transforms (DFT), are described as alternatives to processing signals using time-domain computation. However, Kalman filters may be unable to remove all noise, harmonics, and may be susceptible to frequency deviations. The results from Kalman filter may be incorrect [10]. Moreover, the method in [9] demonstrates operation only for balanced faults, whereas the vast majority of faults on overhead distribution systems are typically unbalanced in nature. There can be a number of problems associated with such methods in practical applications with varying fault types. [10] presents fault detection using DFT-based phase angle computation. This addresses the aforementioned noise and harmonic issues. However, the problem remains as described in [8], as the direction of power flow must be known in advance of fault inception. [11] proposes a protection method that does not require prior knowledge of initial power flows, and this method uses a "current energy variation scheme" to measure current magnitude and angle. However, no significant details of communications to enable phasor comparisons are included

In this paper, a new protection method for future distribution systems is presented. It requires only current measurements, with communications of basic data relating to the angular change from pre- to during-fault transition used to accurately identify the faulted section of the system. Case studies using MATLAB/Simulink simulation are included. The paper consists of five sections. The principle of fault identification through comparison of currents and use of communications are explained in section 2. Section 3 presents various case studies. Discussion and future work are described in section 4 and conclusions are drawn in section 5.

2 The Proposed Principle

2.1 Description of Method for Fault Detection/Identification

Sudden changes in measured current angles, and/or sudden changes in magnitudes (and possibly thresholds of overcurrent) may be used to initially detect that a fault exists – initiating operation of the scheme. Work is ongoing to refine the detection method and use of unbalance/negative sequences detection may also be incorporated in future. The method is further described in [12]. For the example system shown in Fig. 1, PQ loads are assumed at A and B and a fault is located between A and B. Different load types may be investigated in future, but it is not anticipated that the nature of the loads (unless they significantly re-generate power to the network during network faults) will impact upon the performance of the protection system. The phase angles of both currents will clearly change from normal to fault conditions as shown in Fig. 2.

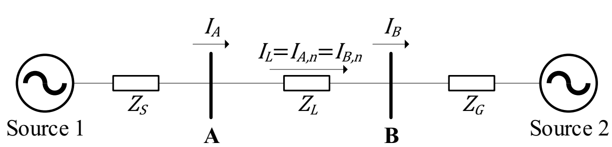


Fig. 1 Study system

The change in angles measured at bus A ($\Delta\theta_A$) and at bus B ($\Delta\theta_B$) can be stated as shown below:

$$\Delta\theta_A = \theta_{A,n} - \theta_{A,f} \quad (1)$$

$$\Delta\theta_B = \theta_{B,n} - \theta_{B,f} \quad (2)$$

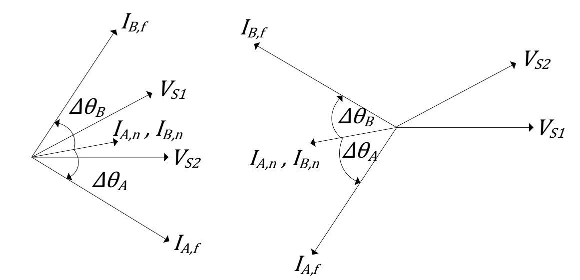
where $\theta_{A,n}$ and $\theta_{B,n}$ are the current angles with respect to some reference at bus A and bus B during normal conditions prior to the fault, and $\theta_{A,f}$ and $\theta_{B,f}$ are the current angles measured at bus A and bus B during fault conditions.

According to calculations in (1) and (2), the value of current angle change between pre- and during-fault, measured at relay A, is positive ($0° \leq \Delta\theta_A < 180°$) or can thought of as "rotating" in a clockwise (CW) direction/angle. However, the current angle change measured at relay B between pre- and during-fault rotates in a counter-clockwise (CCW) direction, or its value can be deemed negative ($-180° \leq \Delta\theta_B < 0°$).

Conversely, if system power flows from Source 2 to Source 1 prior to the fault, the current angle changes between normal and fault condition measured at bus A rotates counter-clockwise, whereas angle change measured at point B would rotate in a clockwise direction. It can be concluded that if current angle changes between pre- and during-fault condition measured at both ends of the faulted feeder rotate in opposite directions, the fault is located between on that section regardless of the direction of power flow prior to the fault.

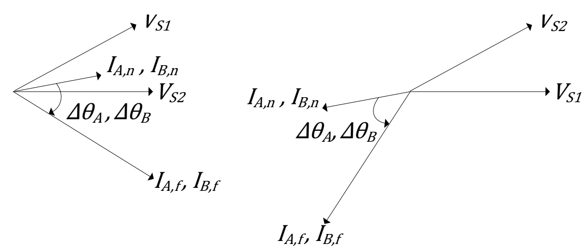
If, however, there is a fault that lies external to the feeder connecting bus A and B, the current angle changes at bus A and bus B from pre- to during-fault would both be in the same direction (either both clockwise or both counter-clockwise).

In summary, for external faults with respect to the feeder connecting A and B, the direction/rotation of current angle changes between normal condition and fault condition at both ends of feeder will be similar, regardless of the direction of power prior to the fault. Phasor diagrams illustrating the directions of current angle changes for internal and external fault conditions are displayed in Figs. 2 and 3.



a *b*

Fig. 2 phasor diagram of pre- and during-fault current during internal fault condition when
(a) system power flows from Source 1 to Source 2
(b) system power flows from Source 2 to Source 1



a *b*

Fig. 3 phasor diagram of pre- and during-fault current during external fault condition when
(a) system power flows from Source 1 to Source 2
(b) system power flows from Source 2 to Source 1

There is a potential issue associated with low fault current conditions, or situation where there is only infeed from one end of the feeder section. The current directional change comparison method will only be accurate when fault current infeeds from both feeder ends are relatively high. However, if fault levels are relatively low, or only one end supplies fault current, there may be issues associated with the technique described [13]. This represents ongoing and further work.

When there is infeed from only one end (or one infeed is extremely low), then a comparison between pre- and during-fault current magnitude may also be used to supplement the angular change comparison. Initial fault detection will be via measuring significant angular "jumps" and any marked increase in current – voltage is not required. This comparison is not used in situations where there may be tapped loads between the measurement points, but it can be used for confirmatory purposes in situations where infeeds are extremely weak or there is no infeed from one end. This will only require very simple low-bandwidth communications, and only when a fault is initially detected. The fault detection process is shown in Fig. 4. There remains future work to be done, but this simple method, while requiring communications to exchange simple current angle rotation/direction. Unlike differential protection, the method does not require accurate time synchronisation nor high-bandwidth continuous communication and should be relatively immune to fault level variations and network topology changes.

The method clearly requires a "moving window" and memory of prior measurements in order to establish the nature and magnitudes of angular changes. This may need a certain time duration to determine the phasor quantities and calculate any shifts in relative angles. The effectiveness, stability and reliability of the method is highly dependent on the processing techniques used to measure and derive the current phasor. There are several methods available, e.g., measuring signal directly, using Kalman filters, etc. [9]. However, by far the most popular method employs a Discrete Fourier Transform (DFT). Although this may require some time (typically one complete cycle) to provide a stable and accurate result, it is very effective in rejecting noise and harmonics and, at distribution/microgrid levels, fault clearance times in the order of hundreds of ms are acceptable – very high protection operation speeds are typically not required.

2.2 Communication Considerations

Since the fault identification algorithm must compare measurement data across multiple locations, communication between a number of relays is required – either between pairs of relays or more if multi-terminal circuits are being protected. However, data exchange will be only used during fault conditions to minimise channel use, power demand associated with communications, and bandwidth requirements (and cost). Communications will only be initiated when a fault condition is identified (as described earlier). Furthermore, only a simple '0' and '1', representing changes in pre-during fault current angles or magnitudes, will be transferred, thus reducing bandwidth and data transfer. The current measurement data processing and comparison logic are shown in Fig. 5.

From Fig. 5, if the current angle change measured at bus A from Fig. 1 rotates clockwise, then the signal of $\Delta\theta_A$ is '1', or '0' if $\Delta\theta_A$ rotates counter-clockwise [12-14]. The same concept also applies to relay B, the signal of $\Delta\theta_B$ is '1' for clockwise rotation or '0' otherwise.

When current magnitude analysis is required for confirmatory purposes, the signal associated with current magnitude change is '1' when the during-fault current magnitude is higher than the pre-fault value or a '0' otherwise, although this is subject to further investigation for low fault level scenarios, high resistance faults, etc. The use of negative/zero sequence

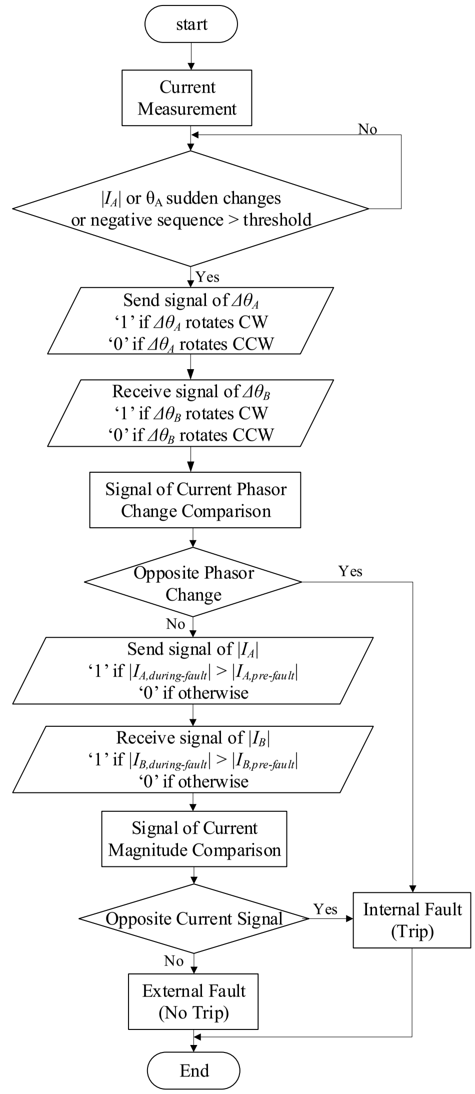


Fig. 4 The flowchart of fault detection and section identification scheme under relay A in Fig. 1

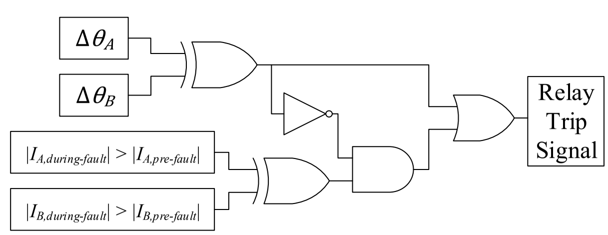


Fig. 5 Logic diagram for fault detection method

current detection to supplement the identification of faults will definitely be incorporated in the future.

Initially, following identification of a fault condition, the relay at each end of the line sections receives a signal relating to angle change from its opposite-end relay, and a comparison is made identify faulted section: as previously stated, if the angular changes are in opposite directions (or close to being opposite), then the fault is 'internal'; if the changes are similar (or not significantly different) then further current magnitude analysis is required, e.g. for single infeed situations, very high resistance faults, etc. This is subject to ongoing investigations – e.g., a further confirmatory step to establish the faulted section can be carried out using magnitudes if angular comparisons are inconclusive - if the during-fault current magnitudes (in addition to the directional changes) are significantly different, then the fault is 'Internal', otherwise no fault is deemed to be present in the section. As already mentioned, the relays do not need to exchange these data continuously. The exchange takes place only when the fault occurs and only if angular changes do not indicate an internal fault. In the event of loss of communications, a more simple but less effective graded overcurrent function could be used as backup. Simple monitoring (or self-monitoring) of the health of the communications system would be included.

Technology capable of wireless communication over a relatively large area (depending on the nature of the system) is required. It must also be cost-effective, and ideally should be a multi-use system. One suitable candidate technology may be Narrow-Band – Internet of Things (NB-IoT) due to its reach to remote and underground areas, wide coverages, and multiple connection capabilities [15]. It consumes low power, is low cost and has a long service life. Thus, NB-IoT is often used for non-real-time monitoring applications, such as electricity meter monitoring and tracking. However, according to its specification, relatively high latency (around 1.6 – 10 s) may be experienced, and this is not appropriate for protection applications – latency is still under investigation and methods for guaranteeing or specifying lower latency are being investigated.

Another potential communication technology could be Long-Term Evolution Machine (LTE-M) especially enhanced Machine-Type Communication (eMTC) including LTE Category M1 (CAT M1) and LTE Category M2 (LTE M2). Compared with NB-IoT, the benefits of LTE-M are similar; remote and wide coverage, and low power consumption [16]. It is also believed to be a strong candidate to facilitate high penetrations of high numbers of IoT devices in 5G/6G future communication networks. One positive is that the latency of LTE-M is lower than NB-IoT (LTE-M latency is 10 – 15 ms [17], while NB-IoT latency is typically 1.6 – 10 s [18]). Hence, it may be more suitable for protection system application. Its operation and application will be investigated and demonstrated using real time simulation and hardware-in-the-loop (HIL) facilities in the laboratory at Strathclyde as a component of future work.

3 Case Studies and Results

To demonstrate and validate the principles of operation outlined in section 2, a 5-bus system as shown in Fig. 6 is used. This is derived from the IEEE 33 bus distribution network [19-20] and has been simulated in MATLAB/Simulink. Based on the line impedance values and R/X ratios, the system is underground cable-based. In the future, studies using overhead and mixed overhead-underground systems will be conducted, as the ratios between resistance and reactance will vary, and therefore the angle change in the measured currents will be different for faults at different locations (with different R/X ratios of line sections). The system has 3 sources connected to busses 1, 4, and 5. Every feeder between buses has a

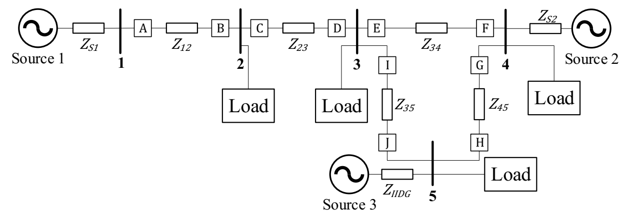


Fig. 6 Case study system

measurement point at the line ends where they connect to buses. A Fourier block is used for calculating current phase angles at A, B, and C and to remove any noise from the signals. The system voltage (line-line) is 12.66 kV and frequency is 50 Hz. The parameters of the case study system are specified in Table 1.

Table 1 Parameters in case study system

Source	Fault level (MVA)	Initial voltage angle (degree)	
Source 1	250	10	
Source 2	250	5	
Source 3	10	0	
Load			
At bus	Type	Active power (MW)	Reactive power (MVAR)
2	PQ	1.00	0.60
3	PQ	0.90	0.40
4	PQ	1.20	0.80
5	PQ	1.20	0.80
Line impedance			
From bus	To bus	Resistance (Ω)	Reactance (Ω)
1	2	0.3660	0.1864
2	3	0.4930	0.2511
3	4	0.3660	0.1864
3	5	0.3811	0.1941
4	5	0.3811	0.1941

A fault is simulated at 0.8s between bus 1 (relay A) and bus 2 (relay B), and another fault is simulated between bus 4 (relay G) and bus 5 (relay H). furthermore, the network topology is also altered to investigate the response of the protection scheme under different circumstances.

A range of different variations on the fault scenarios have been investigated, as explained below:

1) Different fault locations: 10%, 50%, and 90% of the length along each feeder section
2) Different fault resistances: 0.001 Ω, 0.1 Ω, 1 Ω, and 10 Ω

3.1 Scenario 1: 3 Sources in Services, All Circuit Breakers (CB) are Closed

An earth fault is placed on phase-C (C-E fault) at 3 different locations between bus 1 and 2 of the network in Fig. 6, and current angle changes for phase-C at relays A, B, G, and H are obtained as depicted in Fig. 7.

According to Fig. 7, the phase-C current angle changes from pre- to during-fault conditions at all measurement locations. The value obtained at relay A ($\Delta\theta_A$) is around 51.22° to 82.96° (positive; CW) or '1' while -100.61° to -120.19° (negative;

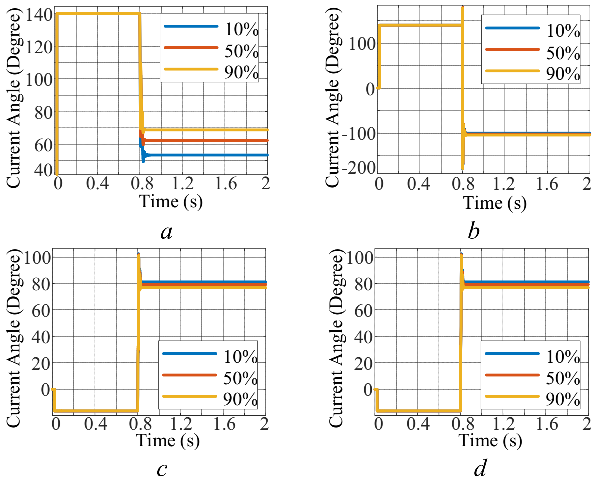


Fig. 7 Phase-C current angle measured at (a) relay A (b) relay B (c) relay G (d) relay H

CCW) or '0' is measured at relay B ($\Delta\theta_B$). Both relays G and H measure a negative phase angle change (-92.01° to -103.57°; CCW) or '0'. It can be concluded that the fault lies on the section between bus 1 and bus 2. As the angular change can conclude the fault identification, the further confirmatory step of comparison of current magnitude is not required.

Simulations of different fault location between bus 1 and 2 have also been carried out. The results for angular changes for, shown in Table 2, are similar, in that relays outside of the faulted line measure the similar angle changes, whereas those at the ends of the faulted line detect differences in the relative angle changes/directions of rotation from pre- to during-fault conditions. The operation of the proposed protection scheme is thus validated for all scenarios considered (although it is accepted that there remains many more scenarios and considerations to be investigated in the future).

Table 2 Pre- and during-fault signal values associated with faulted phase current phasor changes for varying fault locations

Fault between bus	Fault location	Signal value of current angle rotation at relay	Fault type			
			3-PH	PE	PP	PPE
1 & 2	10%	A	1	1	1	1
		B	0	0	0	0
	50%	A	1	1	1	1
		B	0	0	0	0
	90%	A	1	1	1	1
		B	0	0	0	0
4 & 5	10%	G	1	1	1	1
		H	0	0	0	0
	50%	G	1	1	1	1
		H	0	0	0	0
	90%	G	1	1	1	1
		H	0	0	0	0

Further investigations were conducted to establish the impact of varying fault resistance. The results of this are displayed in Table 3.

3.2 Scenario 2: 1 Sources at Bus 1, Open CB Between Bus 3 and 5

This situation represents a single-infeed scenario, and the analysis of angular changes must be supplemented with confirmatory analysis of current magnitudes from the pre- to during-fault transition. The

Table 3 Pre- and during-fault signal values associated with faulted phase current phasor changes for varying fault resistances

Fault between bus	Fault impedance	Signal value of current angle rotation at relay	Fault type			
			3-PH	PE	PP	PPE
1 & 2	0.001 Ω	A	1	1	1	1
		B	0	0	0	0
	0.1 Ω	A	1	1	1	1
		B	0	0	0	0
	1 Ω	A	1	1	1	1
		B	0	0	0	0
	10 Ω	A	1	1	1	1
		B	0	0	0	0
4 & 5	0.001 Ω	G	1	1	1	1
		H	0	0	0	0
	0.1 Ω	G	1	1	1	1
		H	0	0	0	0
	1 Ω	G	1	1	1	1
		H	0	0	0	0
	10 Ω	G	1	1	1	1
		H	0	0	0	0

results illustrating fault current magnitude changes from pre- to during-fault in the faulted phase for varying fault locations and fault resistances are shown in Table 4 and Table 5. When the fault is between bus 1 and bus 2, all current angle changes are '1' or the angle changes are all clockwise. Accordingly, the confirmatory current magnitude change analysis is initiated.

The fault current magnitude measured at relay A exceeds the pre-fault magnitude while others do not, because the majority of the available current flows to the fault location as expected. Similarly, phase-fault current magnitudes measured at all relays except relay H are higher than the pre-fault magnitude if the fault occurs between bus 4 and bus 5. In such cases, the faulted section is identified using analysis of current angle changes and a further confirmatory step involving analysis of current magnitudes.

Table 4 Pre- and during-fault signal values associated with magnitude changes of faulted phase current phasor for varying fault locations

Fault between bus	Fault location	Signal value of current magnitude change at relay	Fault type			
			3-PH	PE	PP	PPE
1 & 2	10%	A	1	1	1	1
		B	0	0	0	0
	50%	A	1	1	1	1
		B	0	0	0	0
	90%	A	1	1	1	1
		B	0	0	0	0

4 & 5	10%	G	1	1	1	1
		H	0	0	0	0
	50%	G	1	1	1	1
		H	0	0	0	0
	90%	G	1	1	1	1
		H	0	0	0	0

Table 5 Pre- and during-fault signal values associated with magnitude changes of faulted phase current phasor for varying fault resistances

Fault between bus	Fault impedance	Signal value of current magnitude change at relay	Fault type			
			3-PH	PE	PP	PPE
1 & 2	0.001 Ω	A	1	1	1	1
		B	0	0	0	0
	0.1 Ω	A	1	1	1	1
		B	0	0	0	0
	1 Ω	A	1	1	1	1
		B	0	0	0	0
	10 Ω	A	1	1	1	1
		B	0	0	0	0
4 & 5	0.001 Ω	G	1	1	1	1
		H	0	0	0	0
	0.1 Ω	G	1	1	1	1
		H	0	0	0	0
	1 Ω	G	1	1	1	1
		H	0	0	0	0
	10 Ω	G	1	1	1	1
		H	0	0	0	0

4 Discussion and Future Work

A current-only protection scheme for future distribution systems has been described and demonstrated using case studies. The system requires only currents, and no voltages, as measurement inputs, and requires only simple communications to communicate the nature/direction of changes in measured current phase angles (from pre- to during-fault) between locations – with a further confirmatory check using detected changes in fault current magnitudes being available in certain scenarios (this is the subject of future work). It has also been proposed that relatively simple, low-cost communication technologies such as LTE-M or NB-IoT could be used – this will be demonstrated in the near future via laboratory experiments.

As noted in the paper, further work is required to refine the initial fault detection method (based on current magnitude and/or phase angle "jumps"), particularly for scenarios where infeeds are weak or non-existent from certain locations in the networks. Conditions such as very high impedance faults and more complex interconnected networks must also be studied.

Networks with inverter-interfaced distributed generator (IIDG) units will also affect fault current magnitudes, directions and angles in future system [4-5]. This will also be investigated as a part of future work, as well investigating both grid-connected and islanded modes for networks. Further work on investigating and demonstration communications technologies, evaluating performance in back-up mode and where communications is lost, and demonstrating practical implementation using hardware-in-the-loop (HIL) prototypes using real time simulation capabilities at the University of Strathclyde, will also be conducted.

5 Conclusion

The paper has presented various case studies to demonstrate and confirm the operation of a novel fault detection and faulted feeder identification algorithm using solely current measurements. Investigations of a variety of network topology and operating conditions has been conducted to confirm the robustness of the algorithm. There remains future work to be done, as outlined in the previous section, but this simple method, while requiring communications to exchange simple current angle data (importantly, only during faults), is much simpler than differential, does not require accurate time synchronisation nor high bandwidth continuous communication, and should be relatively immune to fault level variations and network topology changes. A significant amount of future work is required, but the initial analysis and results are promising.

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