Power line signalling based earth fault location

Power line signalling based earth fault location

The Journal of Engineering

The 14th International Conference on Developments in Power System Protection (DPSP 2018)

Power line signalling based earth fault location

eISSN 2051-3305
Received on 3rd May 2018
Accepted on 23rd May 2018
E-First on 22nd August 2018
doi: 10.1049/joe.2018.0190
www.ietdl.org

Amir Farughian[1] ✉, Anton Poluektov[2], Antti Pinomaa[2], Jero Ahola[2], Antti Kosonen[2], Lauri Kumpulainen[1], Kimmo Kauhaniemi[1]
[1]*University of Vaasa, Finland*
[2]*Lappeenranta University of Technology, Finland*
✉ *E-mail: amir.farughian@uva.fi*

Abstract: Fault location in power networks is important as accurate information about the faulted line section expedites system restoration following a fault occurrence. A number of fault location methods have been proposed. Methods based on injecting a signal into the network and tracking it along the feeder appear to have received limited attention. In this study, fault location methods based on network signalling are examined. Two different types of approaches are presented. The first one is based on injection on a very low-frequency band, whereas the second one is based on utilising modern modulation technologies on low-frequency band, under 500 kHz, implemented on software-defined radios. The simulation results indicate the capability of the proposed methods in determining the location of a single phase-to-earth fault in medium-voltage distribution networks.

1 Introduction

As the society is getting more dependent on electricity, reliability requirements of electricity distribution are increasing. Rapid fault location is a key issue in minimising the duration of outages. There are well established techniques for locating short-circuit faults. However, the location of earth faults, especially in isolated and compensated neutral networks is still challenging. Over the years, a number of fault location methods have been used or proposed, including the following [1]:

- Impedance based methods.
- Travelling wave based methods.
- Fault passage indicator based methods
  - Indication based on normal quantities.
  - Signalling/current injection.

Impedance-based fault location appears to be an unpromising approach for earth faults. In spite of extensive research, commercial solutions are not yet available. Applications of computational fault distance estimation in compensated networks are currently limited to short-circuit faults [2].

There have been attempts to apply travelling wave based methods to distribution networks [3–8]. Reflections from different branches make these methods challenging to be applied to distribution networks. At present, no installation based on travelling-wave methods has been reported for distribution networks.

It appears that the methods based on signalling have received limited attention, even though the idea of injecting a signal to a power network in order to locate a fault is not new. Ripple control systems, for instance, have been used for decades. On the other hand, due to the increased penetration of distributed generation (DG) units into power grids, challenges regarding islanding situations are being experienced. Anti-islanding protection approaches based on signalling have been presented in [9–12].

In this paper, fault location methods based on network signalling are examined. After a literature review, two different types of approaches are presented. The first one is based on injection on a very low-frequency (VLF) band, whereas the second one is based on utilising modern modulation technologies on low-frequency (LF) band, under 500 kHz, implemented on software-defined radios (SDRs).

2 Literature review

In compensated networks, fault location based on injecting a current and tracking it along the feeder can be divided into three categories based on the type of the injected current:

i. Pulsating current injection [13, 14].
ii. DC current injection [15].
iii. Sinusoidal non-grid frequency current injection [16–18].

The pulsating methods have been investigated to a great extent and they have successfully been implemented in commercial relays. Methods based on injecting non-grid frequency currents have been examined less.

Regardless of the signal type, most of the methods share the same operational principles. The methods presented in [13–16] are based on a procedure where at first following a fault occurrence, a current signal is injected into the neutral of the network. This signal can then be detected by receivers at secondary substations along the faulted feeder and up to the faulted point. The signal is practically negligible after the fault point and therefore the faulted segment can be identified.

Different approaches are presented in [17, 18] where the signal injection is used not to be tracked but to obtain network parameters to estimate the fault distance.

2.1 Pulsating current injection

2.1.1 Traditional/standard pulse method: The principles of the traditional pulse method are introduced in [13]. A pulsating signal, generated by toggling a capacitor bank in parallel with the Petersen coil, is injected into the neutral of the system once a fault condition is detected which is traditionally achieved by measuring the residual current and the neutral point voltage. The change in the zero-sequence current can be measured only in the faulted feeder and from the location of the switched capacitor bank up to the fault point. The faulted segment is identified as the section between the last secondary substation in which the signal is detectable and the first secondary substation in which the signal is undetectable. The identification of the faulted segment is achieved by the

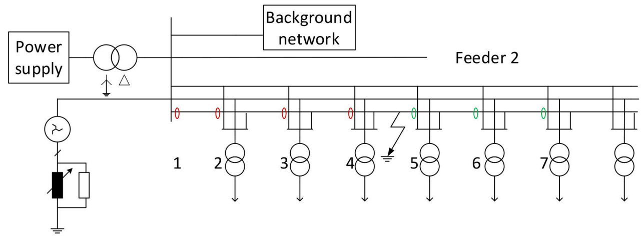

Fig. 1 *Urban compensated MV distribution network*

measurement of the zero-sequence current using relays distributed along the feeder.

It is adequate to obtain only the RMS value of the zero-sequence current. In the case of a low-ohmic earth fault, the pulses can be captured by the devices installed between the primary substation and the fault point. However, the traditional pulse method involves a number of additional requirements. One of its main disadvantages, besides its inability to detect faults other than low-ohmic faults, is the fault duration, which must be at least about 25 s [14].

2.1.2 High power current injection: To address the limitations of the traditional pulse method, a fast pulse method utilising high power current injection with a non-grid-frequency, has been developed in [14]. One of the advantages of this development is the availability of the localisation results within a second. This method has been field tested, and the results indicate the possibility of locating faults with fault resistances up to about 400 Ω [19].

2.2 Non-grid frequency current injection

The method discussed in [16] is aimed at locating faults in resonant grounded (compensated) networks. A non-grid-frequency current with the amplitude of 1 A and frequency of 183 Hz is injected to the neutral through the arc suppression coil. Fault location is realised using magnetic field detection sensors tuned to the frequency of the injected current and installed near the faulty line.

Fault location methods using injection but with different principles compared to those discussed above are proposed in [17, 18]. They are centralised methods, i.e. measurements are made at the injection end. In [17], fault distance is estimated based on measuring the network parameters by means of injecting a signal into the network. However, the validity of the proposed approach is in question as the paper lacks sufficient evidence supporting the basis of the method.

A more sophisticated algorithm is presented in [18] where two sinusoidal signals with different frequencies in the range of 4–15 kHz are used to determine the fault distance and resistance. The first signal is injected into the faulted line to obtain some feedback information. This information is used to form an equation which is referred to as 'distributed parameters equation' including the fault distance and resistance. In the equation, the admittances of transformers at the frequency of injection as well as some other parameters of the line must be known beforehand. Solving that equation yields fault location candidates. The second signal is injected in order to identify the actual fault point and rule out the false ones. This can be achieved as, unlike the false locations, the actual fault location is independent of the injected frequency in the distributed parameters equation.

As this method is based on measuring a large number of parameters, a small error in the measurement can lead to a substantial error in the fault location. This method has been field tested and the results showed the high dependency of the effectiveness of the method on the accuracy of the measurements. Also, the method has been field tested only for faults with zero-ohms resistance which is not the case in practice where the fault resistance can be up to kilo ohms in overhead lines.

2.3 DC current injection

The method presented in [15] proposes injecting DC currents into the neutral of the network for locating single earth faults. Regardless of the type of the injected current, the method shares the same principles as described earlier. However, the feasibility of the proposed method is in doubt due to insufficient evidence provided in this paper. Moreover, the amount of the proposed injected current, i.e. 100 mA and tracking it along the faulted feeder is unrealistic in electric power systems.

3 Fault location based on injecting currents in VLF band

3.1 Principles of the proposed method

The principles of the method are similar to those of the pulsating method described in Section 2.1 except that the injected signal is a sinusoidal non-grid frequency current. Tracking the injected signal along the feeder can be realised by either measuring the zero-sequence current or by measuring the faulted phase current. In this paper, the latter approach is investigated. Therefore, the proposed fault location procedure is as follows:

i. The fault is detected and the faulted feeder and phase are identified by the feeder relay.
ii. The injecting device is connected in parallel to the Petersen coil, and it injects a non-grid frequency current to the neutral.
iii. Measuring devices installed along the feeder, at secondary substations, for instance, start measuring the faulted phase current. The measured current is filtered so that the desired frequency is extracted.
iv. The faulted segment is identified as the section between the last secondary substation in which the signal is detectable and the first secondary substation in which the signal is undetectable.

3.2 Simulations

The simulations are carried out in PSCAD™/EMTDC™. The network under study is shown in Fig. 1. It is an urban cabled compensated medium-voltage (MV) distribution network. The voltage level in the MV is 20 kV which is fed from a 110 kV supply network. The length of the feeder under study is 4 km and it has seven secondary substations. A single-phase-to-earth fault occurs at 2.2 km from the beginning of the feeder.

An injecting device coupled in parallel with the Petersen coil is set to inject non-grid frequency currents of the amplitude of 20 A into the neutral of the network following a fault occurrence. The power required to provide such current depends on the frequency and the neutral voltage. The neutral voltage itself depends on the fault distance and resistance. Four frequencies are examined: 168, 336, 672 and 1008 Hz. The maximum instantaneous power required to provide a 20 A current, is around 20 kW. This amount of active power is permissible as the injection process will last for a short period of time, ∼1 s.

The current in the faulted phase in the faulted feeder is measured at the secondary substations. Only for the purpose of simulation, there are measuring devices at each secondary substation. In practice, that might cost prohibitive and therefore there is limitation regarding the number of measuring devices. By using a corresponding band-pass filter, the desired frequency is extracted. Fig. 2 shows the filtered faulted phase currents measured at the seven locations indicated in Fig. 1. Four frequencies and four fault resistances ($R_F = 0.01, 1, 10, 100\ \Omega$) are investigated.

As can be seen from Fig. 2, there is a substantial difference in the signal level before and after the fault point. Therefore, the faulted segment is determined as the one between secondary substations 4 and 5.

For all the frequencies, as the fault resistance increases, the current level detected decreases. Except for $R_F = 100\,\Omega$, a threshold can be set so that the determination of the fault location in the upper level systems can be realised by comparing measurements at consecutive secondary substations. Therefore, the absolute values do not matter as long as they are above the threshold.

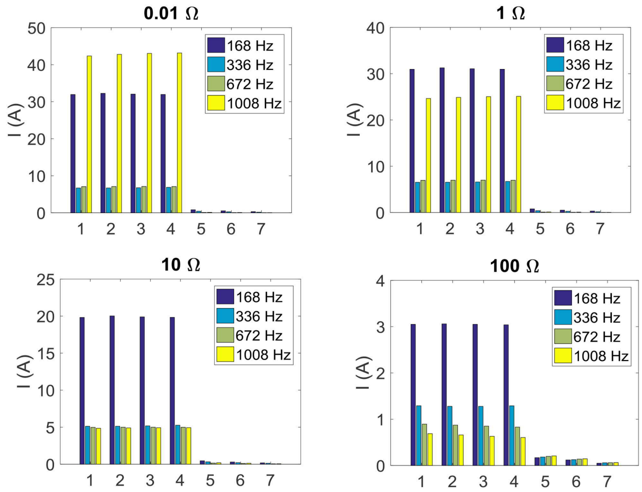

Fig. 2 *Signal detection along the faulted phase in seven locations for different frequencies and fault resistances*

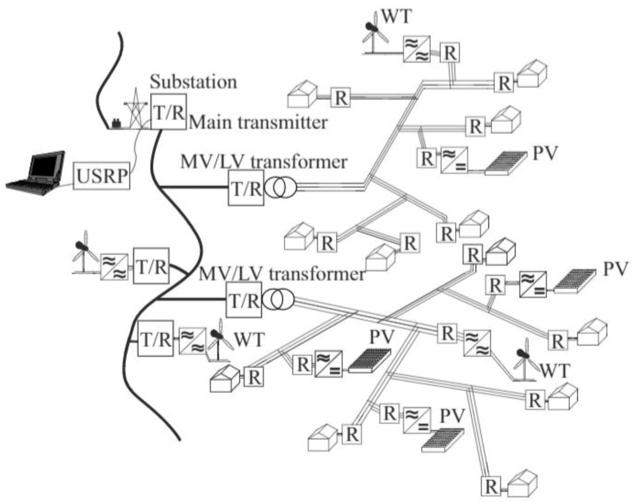

Fig. 3 *MV/LV distribution grid with an integrated PLC-based fault detection system*

For $R_F = 100\,\Omega$, only a small portion of the injected current flows through the fault path and that makes it hard to set a threshold. Moreover, currents are low and difficult to measure. However, in cabled urban networks in which fault resistances are often close to zero, that is not a problem.

For the frequency 168 Hz, in case of $R_F = 0.01$ and $1\,\Omega$, the signal level detected before the fault point, is 10 A higher than the initially injected current amplitude, i.e. 20 A. For the frequency 1008 Hz, the signal levels detected before the fault point for $R_F = 0.01$ and $1\,\Omega$ are 20 and 5 A higher than the initially injected current, respectively. This amplification is due to the resonant circuit that occurs on that particular frequency.

In addition, adding filters to extract the desired frequency causes a delay in the measuring process. For the filters used for these simulations, the fault condition should last about 0.8 s which is a disadvantage.

4 Fault location using signalling on the low frequency band

4.1 Available communication-based techniques

Power-line carrier (PLC)-based combined fault detection and LoM detection method, which we propose, is related to communication-based fault detection methods. This group includes methods, which apply Bluetooth, 3/4G mobile networks, ultra-wide band and other means of communication [20–23]. These methods are based on communication between the main power utility and distributed generators. The common operational principle behind these methods is that when the data transmission is interrupted, it is considered by the fault detection system as a grid fault and protective measures are applied [20, 21]. One of the main benefits of these methods is the possibility of transmitting operational data, which can be used for grid management purposes. Therefore, grid functionality can be extended. Moreover, compared to passive fault detection methods, communication-based techniques may provide a higher fault detection accuracy and a smaller no-detection zone. Moreover, compared to active methods, a negative impact of power quality degradation is smaller [23].

Among available communication-based techniques, a power-line communication (PLC)-based technique is attractive since the channel exists within the power lines. This way, separate communication media is not needed, and total investment and operational costs of the concept can be decreased compared, for instance, with commercial 3/4G networks, where end node would be required in every transformer and customer and DG unit.

4.2 Fault detection concept

The proposed PLC-based fault detection technique is based on continuous signalling from the primary substation through the MV grid including branches and MV/LV transformers and toward households in LV networks (Fig. 3). Modules installed at the end of MV branches, that is, MV/LV transformers combine signal transceiver functionality. Modules installed at the consumers' sites are only receivers. When the transmitted PLC signal is lost, it is considered as a loss-of-mains condition. At the same time, a grid fault does not always lead to a LoM state. Therefore, a more detailed signal analysis is needed for grid monitoring and fault detection.

We propose two techniques of signal analysis and grid monitoring. The first one is the bit-error ratio (BER) analysation. When the grid is operating in a regular mode, a transmitted signal has a stable range of BER values. Signal BER can vary, but the limits of variation are known (measured during the system commissioning phase and then continuously measured with some fixed interval) for normal conditions, and it is set in the fault detection system. When a fault occurs (the channel is under external impact or the cable is cut) the signal's BER leaves its permissible range and the system recognises the fault.

The second technique is the signal-to-noise ratio (SNR) analysation. Here the same principle as with BER is used: for a regular operating mode, signal's SNR is within a certain range. When SNR leaves this range, the system recognises the fault. Simultaneous application of both techniques can improve the total fault detection accuracy. Moreover, a possibility to independently set permissible fluctuation ranges for considered parameters allows adjusting the sensitivity of the concept.

4.3 Fault location concept

Next considered aspect is fault localisation. For this purpose, we propose to use intermediate signalling equipment. MV lines can be a few tens of kilometres. Therefore, intermediate signal transmitters/repeaters are needed to transmit the signal along the whole grid from the main substation to customers (at LV side). These intermediate transmitters can be designed as demodulating repeaters, providing fault localisation functionality.

An intermediate signal transmitter demodulates the received signal and analyses it considering two parameters: SNR and BER. If the grid is operating in a regular mode it repeats the signal. If the fault is detected it sends a new (self-made) signal, telling customers about the fault presence and providing them a personal identifier of the repeater. This unique identifier is used to establish the faulty grid segment. The accuracy of fault location equals the length between neighbour transmitters, i.e. the length between the corresponding transformer substations.

The drawback of this approach is the processing latency of the demodulating intermediate transmitter. In comparison to conventional signal repeaters, which solely work as signal replicators without signal demodulation, additional latency of the proposed operational scheme is higher. Processing latency is one of the major factors, which determine the total time, needed to detect a fault. PLC-based solutions, available today can propose fault detection within 400 ms period [20, 12]. Therefore, the designed concept should consider operation latency as a physical constraint, determining the final design.

4.4 PLC concept platform

The proposed PLC signalling concept is evaluated on the software-defined radio platform. Comparing to conventional radio equipment, SDRs are using software implementations of (de)modulators, amplifiers, filters and other radio components instead of hardware implementations. By using a software interface, it is possible to adjust radio transmission settings, such as carrier frequency, bandwidth and modulation technique according to the application.

4.5 Signalling method

Next considered aspect is a signalling modulation technique. Wide-band modulation techniques are commonly used in PLC-based systems nowadays. In comparison to narrow-band modulation techniques, these methods can provide a higher robustness against channel noise and attenuation [24, 25]. An MV/LV (20 kV/0.4 kV) distribution transformer, being an essential part of a power distribution network, is acting as a major signal attenuator, producing a 30–40 dB attenuation for PLC signal and distortion for the signal. Wide-band modulation techniques have proven their efficiency when PLC-based data transmission is performed through the transformer [12].

We propose using direct sequence spread spectrum (DSSS) and orthogonal frequency-division multiplexing (OFDM) modulation techniques in the frequency band below 500 kHz. A core principle of the implemented DSSS modulation is the following: in the signal transmitter data packet is modulated with a conventional modulation technique, such as binary phase-shift keying (BPSK). The data packet includes several synchronisation bits (also known as a synchronisation key (SK)) and data bits. At the same time, a new bit sequence is generated, which is called a spreading code (SC). A modulated signal is multiplied by this SC and then transmitted. This way the signal bandwidth is spread, which grants a lower pulse noise and attenuation sensitivity. DSSS modulation technique provides signal reception even with negative SNR and is beneficial for signalling over the distribution transformer [12, 25]. On the receiver side, a transmitted signal is decoded using the known SC and then demodulated. Data packets are processed using the SK.

OFDM modulation techniques are applying the following method: initial data bits are separated into several data streams. These data streams are then modulated using one of the conventional modulation techniques, e.g. quadrature amplitude modulation (QAM). The data rate of each carrier is relatively low, being comparable to single carrier modulation rates. Modulated signals are transmitted by using a high number of mutually orthogonal waves (OFDM signal subcarriers). An inverse FFT algorithm is applied to perform this step. The OFDM approach provides a higher spectral efficiency, comparing to conventional techniques and a higher robustness against noise [26, 27].

4.6 Concept evaluation results

Laboratory tests were performed on the test platform, including an MV/LV (20 kV/0.4 kV) distribution transformer [12]. The developed DSSS signalling mechanism was evaluated. According to the performed tests, the designed solution provides sensitivity to a variation of an SNR. SNR varies both under normal operation conditions and under a fault condition in the grid. Therefore, sensitivity to this parameter is a vital feature of the fault detection concept. Moreover, fault detection speed was evaluated by investigating signal processing latency in the receiver. According to tests, processing latency under 100 ms can be achieved, thus fault detection time below 400 ms can be provided [12, 20].

5 Conclusion

Injecting a signal and tracing it along the feeder can be used for locating faults, given that the injected signal is undetectable after the fault point. In practice, there are some considerations that have to be taken into account. Two approaches were presented. The simulation results of the first method indicate that the frequency of the injected signal is of paramount importance. It has to be chosen so that the extra amplification of the signal is avoided. In addition, the bandpass filter used to extract the injection frequency out of the measured current at receiving ends introduces a delay. That requires the fault to last about 0.8 s to be detected. In the second part of this paper, a fault detection concept employing PLC was proposed. Signalling scheme, concept components, applied modulation technique, fault detection and location algorithms were discussed. A software-defined radio was used as a concept evaluation platform. According to the tests, signal processing latency below 100 ms can be achieved when a DSSS-based signalling solution is applied.

6 Acknowledgments

The authors acknowledge the financial support provided by the European Regional Development Fund (ERDF), the Finnish Funding Agency for Technology and Innovation — Tekes (grant no. 4332/31/2014), and the industrial partners to the Protect-DG project.

7 References

[1] Farughian, A., Kumpulainen, L., Kauhaniemi, K.: 'Review of methodologies for earth fault indication and location in compensated and unearthed MV distribution networks', *Electr. Power Syst. Res.*, 2018, **154**, pp. 373–380

[2] Altonen, J., Wahlroos, A.: 'Performance of modern fault passage indicator concept'. CIRED Workshop, Helsinki, 14–15 June 2016

[3] IEEE Std C37.114-2014: 'IEEE guide for determining fault location on AC transmission and distribution lines', 2014, pp. 1–72

[4] Liang, R., Fu, G., Zhu, X., *et al.*: 'Fault location based on single terminal travelling wave analysis in radial distribution network', *Int. J. Electr. Power Energy Syst.*, 2015, **66**, pp. 160–165

[5] Borghetti, A., Bosetti, M., Nucci, C.A., *et al.*: 'Integrated use of time-frequency wavelet decompositions for fault location in distribution networks: theory and experimental validation', *IEEE Trans. Power Deliv.*, 2010, **25**, (4), pp. 3139–3146

[6] Pourahmadi-Nakhli, M., Safavi, A.A.: 'Path characteristic frequency-based fault locating in radial distribution systems using wavelets and neural networks', *IEEE Trans. Power Deliv.*, 2010, **26**, (2), pp. 772–781

[7] Sadeha, J., Bakhshizadeh, E., Kazemzadeh, R.: 'A new fault location algorithm for radial distribution systems using modal analysis', *Int. J. Electr. Power Energy Syst.*, 2013, **45**, (1), pp. 271–278

[8] Thomas, D.W.P., Carvalho, R.J.O., Pereira, E.T., *et al.*: 'Field trial of fault location on a distribution system using high frequency transients'. IEEE Russia Power Tech, St. Petersburg, 2005

[9] Kumpulainen, L., Ristolainen, I., Kimmo, K.: 'Loss-of-mains protection – still an issue with distributed generation'. CIRED Int. Conf. on Electricity Distribution, Vienna, 21–24 May 2007

[10] Pinomaa, A., Poluektov, A., Ahola, J., *et al.*: 'Analysis of channel characteristics and modeling of transformer for PLC-based loss-of-mains concept'. Int. Symp. on Power Line Communications and its Applications (ISPLC), Bottrop, Germany, 2016

[11] Voima, S., Välisuo, P., Kauhaniemi, K.: 'Power line carrier based loss of mains protection in medium voltage distribution networks'. 13th Int. Conf. on Development in Power System Protection (DPSP), Edinburgh, UK, 2016

[12] Poluektov, A., Pinomaa, A., Ahola, J., *et al.*: 'Designing a power-line-communication-based LoM protection concept with application of software-defined radios'. Int. Symp. on Power Line Communications and its Applications (ISPLC), Bottrop, 2016

[13] Druml, G., Raunig, C., Schegner, P., *et al.*: 'Earth fault localization with the help of the fast-pulse-detection-method using the new high-power-current-injection (HPCI)'. IEEE Electric Power Quality and Supply Reliability Conf. (PQ), Tartu, Estonia, 2012

[14] Druml, G., Raunig, C., Schenger, P., *et al.*: 'Fast selective earth fault localization using the new fast pulse detection method'. 22nd Int. Conf. on Electricity Distribution, Stockholm, 10–13 June 2013

[15] Qian, L., wei, W., Lijie, X., *et al.*: 'Research on fault location method of single three-phase hybrid distribution system based on signal injection method'. 3rd IEEE Int. Symp. on Power Electronics for Distributed Generation systems (PEDG), Aalborg, Denmark, 2012

[16] Raunig, C., Fickert, L., Obkircher, C., *et al.*: 'Mobile earth fault localization by tracing current injection'. IEEE Electric Power Quality and Supply Reliability Conf. (PQ), Kuressaare, Estonia, 2010

[17] Bai, Y., Cong, W., Li, J., *et al.*: 'Single phase to earth fault location method in distribution network based on signal injection principle', 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), Weihai, Shandong, 2011

[18] Han, F., Yu, X., Al-Dabbagh, M., *et al.*: 'Locating phase-to-ground short-circuit faults on radial distribution lines', *IEEE Trans. Ind. Electron.*, 2007, **24**, (3), pp. 1581–1590
[19] Tengg, C., Schoass, K., Druml, G., *et al.*: 'Evaluation of new earth fault localization methods by earth fault experiments'. CIRED 22nd Int. Conf. on Electricity Distribution, Stockholm, 10–13 June 2013
[20] Cataliotti, A., Cosentino, V., Nguyen, N., *et al.*: 'Hybrid passive and communications-based methods for islanding detection in medium and low voltage smart grids'. 4th Int. Conf. on Power Engineering, Energy and Electrical Drives (POWERENG), Istanbul, Turkey, May 2013
[21] Etxegarai, A., Eguía, P., Zamora, I.: 'Analysis of remote islanding detection methods for distributed resources'. Int. Conf. on Renewable Energies and Power Quality (ICREPQ), Las Palmas de Gran Canaria, Spain, April 2011
[22] Cataliotti, A., Cosentino, V., Nguyen, N., *et al.*: 'On the use of narrow band power line as communication technology for medium and low voltage smart grids'. IEEE Int. Instrumentation and Measurement Technology Conf. (I2MTC), Graz, Austria, May 2012
[23] Timbus, A., Oudalov, A., Ho, C.N.: 'Islanding detection in smart grids'. IEEE Energy Conversion Congress and Exposition (ECCE), Atlanta, USA, September 2010
[24] Haj, Y.E., Albasha, L., El-Hag, A., *et al.*: 'Feasibility of data communication through distribution transformers for Smart Grid applications'. 2014 IEEE Innovative Smart Grid Technologies – Asia (ISGT ASIA), Kuala Lumpur, 2014
[25] Meng, J., Marble, A.E.: 'Effective communication strategies for noise-limited power-line channels', *IEEE Trans. Power Deliv.*, 2007, **22**, (2), pp. 887–892
[26] Kikkert, C.J.: 'MV to LV transformer PLC bypass coupling networks for a low cost smart grid rollout'. IEEE PES Innovative Smart Grid Technologies, Perth, WA, 2011
[27] Dong, L., Baohui, Z., Dongwen, N., *et al.*: 'Design and implement of timing synchronization algorithm for OFDM PLC system in low voltage powerline networks'. Proc. of 46th Int. Universities' Power Engineering Conf. (UPEC), Soest, Germany, 2011