



Signal injection techniques for fault location in distribution networks

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Abstract. Over the last 50 years, fault location in transmission systems has been a subject of interest to utility engineers and researchers. Nevertheless, it has not been until the last decades that fault location in distribution networks has started to gain prominence.

Traditionally, fault location techniques for distribution networks have been classified in three different groups: fundamental frequency measurements, high frequency measurements and the use of artificial intelligence (AI). Yet despite this rigid classification, a new approach has started to be developed over the last years based on the injection of a discernible signal into the distribution systems, mainly in non-effectively grounded networks. However, even when recent developments of new grounding systems reinforce the possibility of using this kind of techniques, these are not usually cited by general reviews and overviews of fault location systems in distribution networks.

Accordingly, this paper aims to provide a general but clear overview on the existing techniques for fault location in distribution networks based on signal injection. Apart from describing the different options presented to date, the most important aspects that characterize them and the injected signal are briefly outlined, as well as a comparative performance analysis.

Key words

Fault location, signal injection, distribution systems, non-effectively grounded networks, power quality.

1. Introduction

Automated fault detection and location, as an important part of the Distribution Automation (DA) strategy, plays a crucial role in improving the operational performance of electric utilities [1]. As a result, a fast and reliable fault location system may be beneficial in many ways, e.g. improving the power quality ratios, increasing the efficiency in the daily operation, enhancing the performance of the distribution system, etc. Nevertheless, most of the research work published to date has been focused on fault location for transmission systems [2], due to the more important consequences of these types of faults.

In spite of that, free market and deregulation introduced in most of the countries have driven the fault location in distribution networks to gain prominence in the last decades. The main reason for this sudden increase is the more restrictive requirements imposed on electric utilities, in order to provide a good quality service and a continuous power supply.

According to the most outstanding reviews, surveys and overviews [3-6], fault location techniques for distribution networks have been traditionally classified in three different groups:

1. The main group is based on the phasor measurements of the fundamental frequency components of voltages and currents, using one or several measure points (apparent impedance, iterative methodologies, etc.).
2. Another group relies on using fault transients and high frequency measurements to pinpoint the fault (Wavelet theory, travelling waves, etc.).
3. The last but more recent approach focuses its research on studying the use of artificial intelligence (AI) techniques (neural networks, genetic algorithms, etc.).

Notwithstanding this classification, the past few years have been particularly prolific in new methodologies for fault location that do not specifically fit in any of the categories above. They are based on injecting a discernible signal into the distribution system, either using a different frequency to the fundamental one, DC current or pulse signal. These techniques are mainly designed to be applied in non-effectively grounded distribution systems (isolated, compensated or high impedance grounded systems), which are relatively common in distribution networks all over the world (Western and Eastern Europe, China, etc.).

Furthermore, recent developments in new grounding systems for distribution networks [7] offer new opportunities to research and apply injection-based fault location techniques. This aspect, along with the possibility of combining them with more traditional methodologies,

makes the use of signal injection a very promising approach for fault location in distribution networks.

However, concerning this type of approach, few are the papers published in English to date [8]. Besides, since the main reviews of fault location systems for distribution networks do not even mention this kind of techniques, this paper aims to shed some light on the different aspects to be taken into account when characterising and applying a signal-injection technique. The most remarkable methodologies within this group will also be fully described, highlighting some of the most relevant references of the literature.

2. Characterization of signal-injection methodologies

The use of signal-injection methodologies for fault location in distribution networks may present significant differences, even when they share a similar strategy. These differences may lie in several aspects [9]:

- Characteristics of the injected signal: sinusoidal, DC, pulse, etc.
- Procedure or device used for injecting the signal: primary winding of power transformer, fault phase voltage transformer, arc suppression coil (Fig. 1), neutral point of wye-connected capacitor set, active grounding system, etc.
- Procedure or devices used for detecting the signal: mobile detectors, instrument transformers, Hall sensor technology, remote detectors, etc.

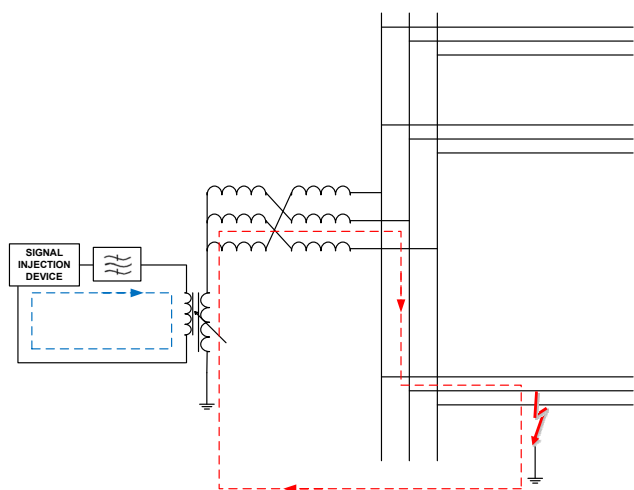


Fig. 1. Injection via arc suppression coil [9]

Regardless of the specific solution adopted, compliance with the existing regulations in the field of power quality (e.g. EN 50160, etc.) must be guaranteed. One of the main consequences that might be derived from the signal injection is the overvoltage level, which is limited to a 10% of the rated voltage of the distribution system. Basically, the decisions over the signal injection that may significantly affect the voltage level are two [10]:

- Magnitude of the injected signal: the selected value depends on the neutral grounding of the distribution system, along with its rated voltage and, under some

circumstances (ungrounded or compensated networks), the reactive capacitance of the distribution system (including the percentage of underground cable installed). Figure 2 shows the overvoltage level reached depending on the magnitude of the injected current, for a given non-effectively grounded network [10].

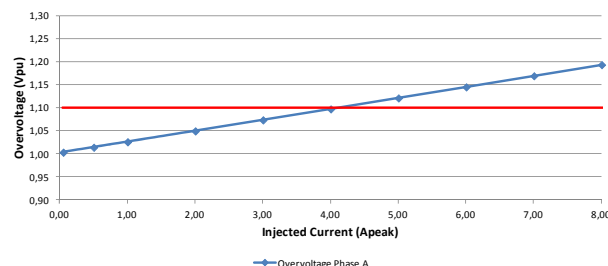


Fig 2. Overvoltage due to injected current (75 Hz) [10]

- Magnitude of the injected frequency: the higher the frequency is for a given magnitude of the injected signal, the lower the overvoltage produced will be.

In case of injecting a sinusoidal signal, some considerations should be borne in mind when choosing the right frequency:

- The injected signal should have different frequency characteristics from the inherent signal of the power system.
- The choice of the sampling frequency should take into account the fact that the power frequency signal will probably be filtered.
- In order to make it easier to process and calculate the injected signal, the sampling frequency should be a whole number multiple of the injected signal's frequency.
- In ungrounded or compensated networks, the lower the frequency is, the higher the possibilities for the fault current to close the fault path through the fault resistance [8, 11]. On the other hand, the higher the frequency, the higher the magnitudes to be measured and the easier to have precise measurements.

3. Description of injection methodologies for fault location in distribution systems

As has been stated in Section 2, there are different ways in which signal-injection methodologies for fault location can be classified. One of the possibilities is based on the approach used to accomplish the location of the fault, which is the classification criterion used in this section.

A. Handheld and portable devices

Although the establishment of a widely developed DA should be the trend for any modern distribution system, it is not always possible to precisely locate the fault in an automatic way. That is why it often becomes necessary to turn to a mobile location system, based on visual inspection and handheld devices, which should ensure efficiency and reliability. To cope with the drawbacks concerning the traditional visual inspection of the lines

(slow, expensive and unsafe), signal injection offers numerous alternatives, either using alternating current or direct current. Some of these types of location systems have been recently developed and field tested in several networks worldwide: Europe, China, etc.

Considering the previously mentioned benefits derived from a reduced frequency of injection, [12] describes the hardware and software for the signal injection system, along with an outline of the detector design (air core inductance) for fault location. Once a 60 Hz AC (350 mA) signal has been injected into the faulty phase, the fault is located using a dichotomy method by means of a signal detector. A similar strategy may be observed in [13], where the same frequency is applied for fault location and, in case of high resistance grounding systems, the method of high voltage breakdown is used. Its main disadvantage is its high level of error when used in long lines [8].

In [14] a method for compensated networks is presented. Based on the injection of a non-grid-frequency current (183 Hz, 10 A) into the faulty phase or the zero sequence system (arc suppression coil), the fault can be located through sensors that may be designed for mobile equipment or stationary equipment. To date, several field tests have been conducted using prototypes of the devices, with satisfactory results.

In order to minimize the influence of the distributed capacitance, [15] uses a DC signal injection system and clamp ammeters to detect the fault path, by measuring the currents in the key branching points [8]. Moreover, in [16] the design of a DC signal detection system is also provided, which injects a 100 mA DC signal in the faulty phase that will be subsequently detected by a thoroughly described DC detector based on Hall technology. Similarly, [17] proposes a fault location methodology based on low-frequency pulses that are periodically injected (10 kV) off-line. In these cases, mobile devices are used to apply a dichotomy approach to fault location in low-current grounding systems.

B. Impedance based techniques

Nevertheless, it is quite common for distribution networks to have the possibility of taking measurements only at the substation level. In these cases, similarly to what is usually made for techniques based on measurements of the fundamental frequency components, several signal-injection methodologies have been proposed so as to obtain an approach to the apparent impedance to the fault point. This way, having a precise knowledge of the distribution network, it is possible to estimate the fault distance. Even though there may still be a problem of multiple estimations in radial systems, the unique characteristics associated to signal injection techniques may be the determining factor to correctly pinpoint the fault, discriminating it amongst the different possibilities.

One of the main lines of research in this field has been conducted by the group of P. Toman, which started in the second half of 2001 for low-current grounding systems. Firstly, their analysis [18] was based on analyzing the

advantages or disadvantages of using fundamental-frequency versus ripple control signal injection (interharmonics, mostly 216,66 Hz) in MV ringed networks. For this purpose, the theory worked out by the Haefely-Trench company was used by simulating in MATLAB the injection of a remote control signal (HDO). Once the benefits of the ripple control signal injection were tested, a known algorithm for fault location [19] was modified in order to make possible the application of the injection of a ripple control signal to a radial network [20].

Having verified the results of this strategy, the authors developed their approach to be applied in MV compensated networks. In this regard [21-23], the three ancillary balancing tunable suppression coils, connected to the busbar of the distribution substation, have an inter-harmonic frequency signal generator connected in its secondary winding. By means of the higher inter-harmonic signal injected to the affected phase, it is possible to obtain the fault distance using impedance calculations. In the 22 kV network where this fault location method has been simulated and tested, the necessary time was less than 3 minutes for faults without arc.

Another important line of research in this field has been conducted by A. Dan and his team. The authors propose a fault location methodology for compensated networks [24-27] that has been recently implemented in the Hungarian distribution systems (2 substations). Based on a current injection in parallel to the Petersen coil, it can also be used to reduce the harmonic content during sustained earth fault operation. The frequency of the injection is chosen so as not to coincide with odd order harmonics or ripple control frequencies that exist in the distribution network, although it may be composed of different frequencies (e.g. 400 and 500 Hz).

Employing real-time measurements that approximately do not take more than 1.5 seconds, simulations and field tests over a 22 kV overhead distribution network have yielded satisfactory and promising results.

Furthermore, [28] presents a methodology for fault location in ungrounded distribution systems, based on the signal injection principle. For this purpose, when the ground fault is established and the faulty phase detected, the signal injection device uses the secondary winding of the potential transformer to inject the special frequency signal into the faulty phase. This signal, whose amplitude is about 5 A, has a frequency different from the integer multiple of the fundamental frequency (interharmonics, e.g. 80 Hz). Based on the distributed parameter model, the fault distance can be obtained using the resistive characteristic of the transition resistance, derived from the measurements at the substation level.

C. Hybrid techniques

In order to apply the fault location systems based on the signal injection approach to the operation required in an automated distribution network, there are more and more

techniques that consider the use of signal injection devices, combined with other techniques or technologies.

One possibility relies on the use of C-type travelling wave (injected) analysis to calculate the fault distance from the beginning of a line and a DC signal injection system to determine the faulty section and branch [29-30]. The system takes advantage of both systems: whereas the C-type travelling wave analysis is not affected by signals generated by the fault, DC injection technique is not affected by inductance and capacitance of the lines. The detection of the injected DC signal is done with the help of hall sensor technology. A similar approach is used in [31], where an AC (60 Hz) injection system is used in combination with a DC location method [8].

Another option is to use the Continuous Wavelet Transform (CWT) to deal with the travelling wave signals generated by both the injected pulse signal and the fault itself [32], leading to the calculation of the fault distance from the bus. Using Db6 wavelet analysis by simulation, the fault location strategy has proved to be accurate.

In [33-34], the authors develop an automatic fault location system based on signal injection at a special frequency, along with GSM short messages [8]. The technique makes good use of some signal detectors fixed with the FTUs along the network. Once they detect the injected frequency, a GSM message is sent to a server, which will be responsible for the fault location. Likewise, [35] briefly outlines the use of a current source as a signal injection subsystem, a signal voltage detection subsystem and a communication subsystem (GSM) for fault section location.

In [9], the authors also use wireless signal detectors, installed at each switch point, to detect the injected AC signal, whose frequency is never an integer multiple of the fundamental frequency. In [36], the advantages of using FTUs to locate the fault area are used too [8]. However, there are certain requirements to take into consideration regarding the FTU disposition distance.

Besides, with regard to the way that the information provided by the FTU can help to locate the fault section, and considering the signal detectors fixed to FTU as nodes, [37] proposes to use the Graph theory along with a fault judgement matrix to determine the section between two nodes in which is likely to be the fault.

Similarly, [38] describes the advantages of the “Petersen Coil Trial System” for fault location in a 20 kV distribution network. Once the fault passage indicators (FPI) distributed along the network have identified the faulty section, a signal is pulsed from the arc suppression coil in order to pinpoint the fault by means of a portable fault passage locator.

4. Extended advantages of injection systems

When using signal injection systems in power distribution networks, not only are they applied to locate the fault, but they can also be used to enhance the performance and

protection over the network in which they are installed [8].

One of the main function in which these injection systems can be useful is single-phase fault detection or feeder selection, therefore providing a global strategy in order to achieve a global fault assessment within a DA system [39-40]. Other important and interesting applications would be distributed capacitance measurement, fault extinction, etc., even though in some cases they require the use of specially designed grounding systems [41].

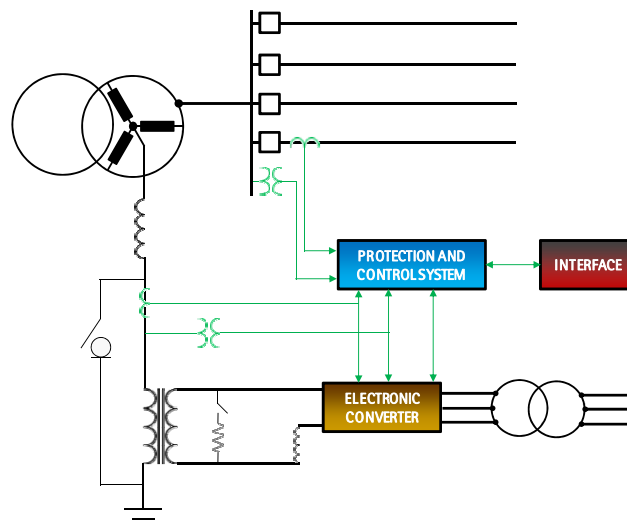


Fig 3. Electronic active grounding system [41]

5. Conclusion

As it has been previously stated, the use of signal injection techniques in distribution systems may well open the door to a new alternative for single-phase fault location, especially in non-effectively grounded networks.

Besides, this type of approach allows the application of a wide variety of techniques (Table I outlines the main characteristics of the most remarkable ones cited in this paper), some of which may be boosted due to recent developments of new grounding systems, along with the possibility of merging them with some more traditional methodologies.

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Table I. – Main characteristics of fault location techniques based on signal injection

	Injected signal	Injection system	Detection system	Methodology/device
[12]	AC (100-200 mA @ 60 Hz)	N/A (microprocessor)	Air core inductance (racket)	Dichotomy method
[14]	AC (<10 A @ 183Hz)	Arc suppression coil	Mobile or stationary sensors (Hall)	N/A
[16]	DC (100 mA)	N/A	Mobile DC sensor (Hall)	Dichotomy method
[17]	Pulse (10 kV @ low freq.)	N/A (microprocessor)	Mobile sensor	Dichotomy method
[18, 20-23]	AC (interharmonics, 216,66 Hz)	Ancillary suppression coils	Substation measurements	N/A
[24-27]	2xAC (400 & 500 Hz)	Petersen coil	Substation measurements	N/A
[28]	AC (interharmonics, 5 A @ 80 Hz)	Voltage transformer	Substation measurements	N/A
[29-30]	C-type travelling wave DC (<200 mA)	N/A	Hall sensor technology	Dichotomy method
[32]	Pulse	N/A	N/A	CWT (Db6)
[33]	AC (special freq.)	Voltage transformer	Signal detectors @ FTU	GSM messages
[37]	N/A	N/A	Signal detectors @ FTU	Graph theory Judgement matrix
[38]	Pulse	Petersen coil	Fault passage indicator Portable passage locator	Communication system

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