Methodology for relative location of voltage sag source using voltage measurements only

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Abstract
This paper presents a methodology for the relative location of voltage sags source based on voltage measurements only. Network faults are the most frequent disturbances in the electrical systems and in turn are the causes that generate most voltage sags. Thus, the proposed algorithm considers only voltage sags by network faults, and a minimum of three voltage meters is required. Power quality can be evaluated automatically using the characterizing and extracting information from voltage records. The positive sequence voltages are the descriptors used to determine the relative location of the voltage sags causes, and the methodology is applied to a simulation where its effectiveness is verified. Matlab was used for validating this methodology, and voltage records of simulated voltage sags were generated in ATP-EMTP.

Keywords: Power quality monitoring; relative location; voltage sags; positive sequence voltage; network faults.

Metodología para la localización relativa de la fuente de hundimientos de tensión usando únicamente mediciones de tensión

Resumen
Este trabajo presenta una metodología para la localización relativa de las fuentes generadoras de hundimientos de tensión y la cual se basa únicamente en mediciones de tensión. Las fallas de red son las perturbaciones más frecuentes en los sistemas eléctricos y son las causantes del mayor número de hundimientos de tensión. Así, el algoritmo propuesto considera únicamente los hundimientos de tensión originados por fallas de red y requiere un mínimo de tres monitores de tensión para su aplicación. La calidad de la potencia puede evaluarse automáticamente a través de la caracterización y extracción de información de los registros de tensión. Las tensiones de secuencia positiva son usadas como los descriptores para determinar la localización relativa y la metodología es aplicada en un caso de estudio por simulación comprobando su efectividad. Para la validación de los resultados se usa Matlab, tomando como entradas los hundimientos de tensión simulados en ATP-EMTP.

Palabras clave: monitorización de la calidad de la potencia; localización relativa; hundimientos de tensión; tensión de secuencia positiva; fallas de red.

1. Introduction

Power quality has become an important research topic due to increasing electromagnetic disturbances. In particular, voltage sags are a power quality problem that affects both power suppliers and customers. The most severe voltage sags are caused by network faults in the power system, and they propagate through the electrical system affecting loads connected away from an event source [1]. Consequently, disturbance source identification (DSI) and fault location (FL) have become important areas of investigation to improve the power quality [2-4]. DSI is the identification of event source (e.g. network faults, transformer saturation or induction motor starting) while FL is the localization of the event source within of the electrical network.

This paper is focused on electrical distribution systems. The proposed method assumes a minimum of three voltage measurements available at electrical distribution systems. These measurements are obtained from three power quality monitors, installed at strategic points of electrical systems.

Table 1.
Descriptors and rule decisions for voltage sags' relative location.

Relative Location	Network Fault if	Motor Starting if	Transformer Saturation if
Downstream	$\frac{I_{sag}{}^1}{I_{ss}{}^1} > Thr_{LF}$	$\frac{P_{pos}-P_{pre}}{P_{pre}} > Thr_{IM}$	$\frac{I_{sag}{}^1}{I_{ss}{}^1} > Thr_{TR}$
Upstream	$\frac{I_{sag}{}^1}{I_{ss}{}^1} < Thr_{LF}$	$\frac{P_{pos}-P_{pre}}{P_{pre}} < Thr_{IM}$	$\frac{I_{sag}{}^1}{I_{ss}{}^1} < Thr_{TR}$

$I_{sag}{}^1$ Current fundamental frequency component during network fault
$I_{ss}{}^1$ Current fundamental frequency component before network fault
Thr_{LF} threshold of the ratio $I_{sag}{}^1/I_{ss}{}^1$
Thr_{LF} threshold of the ratio $I_{sag}{}^1/I_{ss}{}^1$ in transformer saturation event
P_{pre} steady state active power before induction motor starting
P_{pos} steady state active power after induction motor starting
Thr_{IM} threshold of the ratio $(P_{pos}-P_{pre})/(P_{pre})$
Source: Adapted from [2,3]

Table 2.
Descriptors and rule decisions based on the sequence current magnitude.

Downstream if	Upstream if
$\frac{|I_{Down}|}{|I_{SS}|} > 1$	$\frac{|I_{Up}|}{|I_{SS}|} < 1$

$|I_{Down}|, |I_{Up}|$ currents downstream and upstream respectively.
$|I_{SS}|$ current of non-faulted steady state.
Source: Adapted from [6]

The method determines the relative location (downstream or upstream of a monitor) of a voltage sag source.

Different methodologies for the relative location of voltage sags are usually based on voltage and current measurements. However, in some cases, there are no available current measurements or algorithms that depend only on the voltage are required. Most relevant descriptors to determine the relative location of the voltage sag source are identified and listed in some works. Also, the appropriate thresholds for discriminating the relative location of the voltage sags upstream are selected. Unlike [1], where the proposed method is limited to be applied to measurements on the transformer's primary and secondary sides, the proposed method in this work allows the estimation of the relative location of the voltage sags using voltage measurements from three or more power quality monitors located in the electrical distribution system.

The validation of the proposed methodology is performed by the simulation of voltage sags in an electrical distribution system test [5]. The test system is known as IEEE 34 Node Test Feeder and it is modeled on ATP-EMTP to generate voltage sags with a relative location previously established. This set of voltage sags is used to validate the efficiency of proposed algorithm.

2. Background

There are some methods which are used for determining the relative location of voltage sags and which primarily use voltage and current measurements. Some algorithms are presented below, and emphasis is placed on the nature of the most relevant concepts related to the proposed methodologies.

2.1. *Relative location of voltage sags source for PQ diagnosis*

In [4,5] methodologies for the relative location of the voltage sag sources are presented. These methodologies are based on the previous identification of the voltage sag causes and their characteristics. Among the causes of voltage sags are: identified network faults, the induction motor starting and transformer saturation. With this information, the descriptors and decision rules are formulated to determinate the relative location of a voltage sag source, as a shown in Table 1. With respect to the transformer saturation, initially there are some descriptors for the identification and classification of voltage sags that originated from transformer saturation [4,5].

An algorithm performs a previous classification of the causes of the voltage sags using the decision rules presented in Table 1 and determines the relative location of the voltage sag source. Some limitations found are the incorrect classification of some classes of voltage sags, such as voltage sags caused by network faults with fault impedance, multistage events, network faults in isolated electrical systems, transformer energization with load, network faults with harmonics and transformer saturation, among others.

2.2. *Relative location of voltage sag source based on the sequence current magnitude*

The methodology proposed in this article focuses on the use of ratio from the positive sequence current (RPSC), calculated before and during the voltage sag [6]. Descriptors and decision rules are shown in Table 2. This method provides an optimum performance when applied to records of real and synthetic voltage sags, mainly caused by network faults. The fundamental condition for its application is the existence of current measurements in the electrical system.

Thus, the purpose of this paper is to provide solutions for electrical distribution systems in which only voltage power quality monitors are implemented or records are collected of voltage electromagnetic events presented in the network. Currently, there are electrical distribution systems with a limited metering infrastructure, which generally focus on voltage records only. The proposed methodology may also result as an interesting tool to implement fault localization methods using a partial monitoring program, as these only measure voltage and distributed strategically in the electrical distribution system.

3. Proposed algorithm

Positive sequence current is important for the analysis of asymmetric faults in power systems because they are present in all types of network faults [7]. Therefore, this electrical variable is important for a detailed analysis of the relative location of voltage sags in the electrical distribution systems.
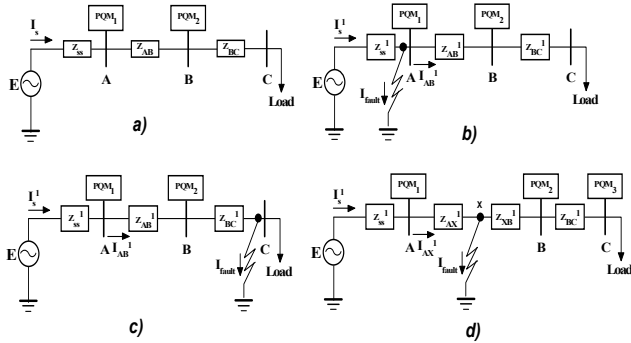
Figure 1. Radial distribution system a) One-line diagram, b); c); d) One-line diagrams of positive sequence.
Source: The authors.

Table 3.
Descriptors and rule decisions based on voltage only.

Downstream *if*	Upstream *if*
$V^1_{AB_{Fault}} \gg V^1_{AB_{Pre-fault}}$	$V^1_{AB_{Fault}} \ll V^1_{AB_{Pre-fault}}$

$V^{1*}_{AB_{Fault}}$ magnitude of the positive sequence voltage between nodes *A* and *B*, during the voltage sag.

$V^1_{AB_{P-fault}}$ magnitude of the positive sequence voltage between nodes *A* and *B*, before the voltage sag.

* *The superscripts 1 represent magnitudes of the positive sequence.*

Source: The authors

Similar to the work presented in [6], for the purposes of this work, only the positive sequence voltage is chosen as a variable that could determine the relative location of voltage sags source.

Fig. 1.a illustrates a one-line diagram of a radial distribution system. The network is parameterized by impedances between buses, voltage power quality monitors (PQMs) recording on the buses and finally a load. The analysis begins with the study of the behavior of the recorded voltages when a network fault occurs.

Fig. 1.b shows the positive sequence network of the system presented. An upstream network fault of the monitors is presented. By analyzing the network fault types, according to [6], if a symmetrical fault occurs then only the positive sequence voltages and currents are presented. If an asymmetrical fault occurs, the analysis contemplates the interconnecting of the positive and negative sequence networks (line-to-line faults) or the interconnecting of the positive, negative and zero sequence networks (double line-to-ground and single line-to-ground faults). In all cases the positive sequence current is presented in the network. Table 3 presents the descriptors and decision rules proposed.

According to Fig. 1.b), if the network fault originates upstream of PQM1, it is expected that the voltage V_{AB}^1 is reduced due to the decrease of current flowing through the two monitors. In this case it is expected that most of the current provided by the voltage source deviates with the fault current, so the voltage drop of positive sequence in the *AB* branch during the fault decreases in a large proportion. Furthermore, when the network fault is caused downstream of PQM1 and PQM2, it is expected that the voltage drop of positive sequence V_{A-B} increases, Fig. 1.c).

When a network fault occurs between the two monitors as illustrated in Fig. 1.d), the V_{AX}^J positive sequence voltage is increased compared to the pre-fault voltage of positive sequence due to the positive sequence fault current flow (I_{AX}^J) by this branch. This generates an increase in the positive sequence voltage V_{AB}^1 during the network fault compared with the prefault voltage V_{AB}^1-prefault, although it is clear that the ratio is lower compared to the case in which the network fault is present downstream from PQM2. Initially, using the proposed rules in Table 3, it is possible to estimate that the network fault is located downstream of PQM1 and PQM2, *thus it gives the correct result only for PQM1*. As a solution to this imprecision, a third power quality monitor PQM3 is used as a mechanism to estimate the correct relative location of the network fault.

Descriptors and rules presented in Table 3 are the basic formulation for determining the relative location of voltage sags based on voltage measurements only. The methodology proposed requires the strategic location of power quality monitors to register voltage only. These monitors should make a coordinated monitoring of the voltage events present in the network and thus apply the proposed algorithm in this work, Fig. 2. Accuracy level is improved with the availability of a large number of voltage power quality monitors in the distribution system. According to Fig. 2, a minimum of three voltage power quality monitors are required for the application of the proposed algorithm. *N* means the number of power quality monitors installed.

The proposed algorithm has several steps:
- ❖ A step for loading the voltage sags. These records are correlated, so that the same voltage sags are recorded by all monitors with their respective tags. Also, the coverage zones are defined.
- ❖ Segmentation of the voltage sags, in order to determine the segments of the signals corresponding to the fault and pre-fault states.
- ❖ Steps to calculate *RMS* sequences of the voltage sags recorded.
- ❖ Calculation of the positive sequence voltages of the signals recorded.
- ❖ Feature extraction and decision rules evaluation in the algorithm.
- ❖ Finally, diagnosis of the relative location voltage sags source.

4. Testing

IEEE 34 Node Test Feeder [5] is implemented in ATP-EMTP and voltage sags are obtained from simulation of network faults (single line-to-ground SLG, line-to-line fault LLF, double line-to-ground fault DLG and three-lines fault TLF, with and without fault impedance).

4.1. Simulation

One-line diagram of test feeder is presented in Fig. 3. Five voltage power quality monitors are installed and the synthetic voltage sags are simulated and recorded.
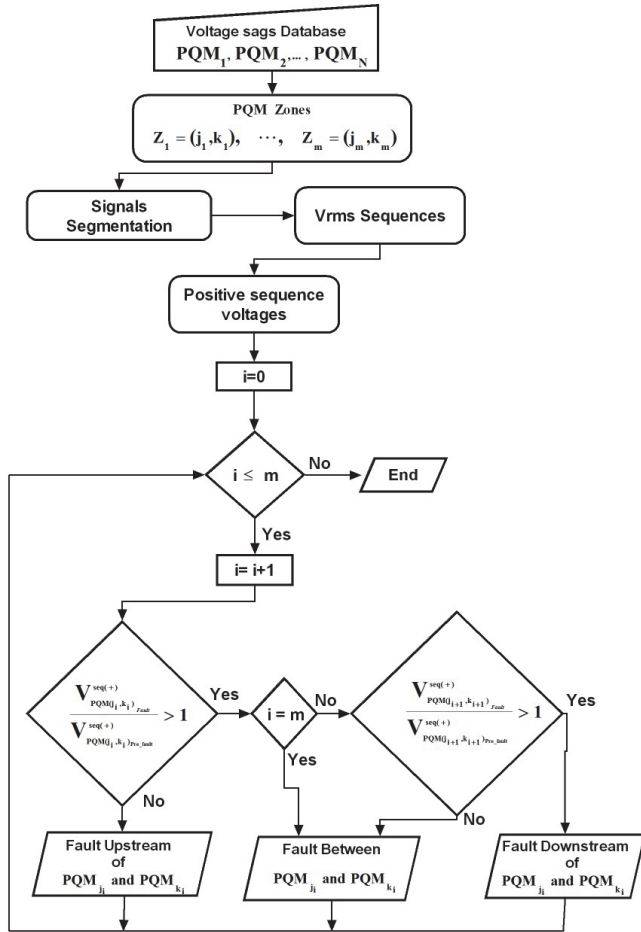
Figure 2. Proposed algorithm for relative location of voltage sags source.
Source: The authors.

In the electrical system, some "coverage zones", according to the strategic location of the power quality monitors, are defined. These zones determine the relative location of voltage events with respect to power quality monitors, as a shown in Fig. 3. For example, if network faults are presented in the nodes located in the area bounded by the black solid line, then these faults generate voltage sags that are located between PQM1 and PQM2. Table 4 shows a summary of the simulated network faults according to fault types.

4.2. Results of the proposed algorithm

The algorithm is applied to the 143 voltage sags. Table 5 presents some results of the descriptors to analyze the algorithm performance. Values taken by the descriptors are presented and the decision rules are analyzed.

Table 4.
Simulated voltage sags in ATP-EMPT.

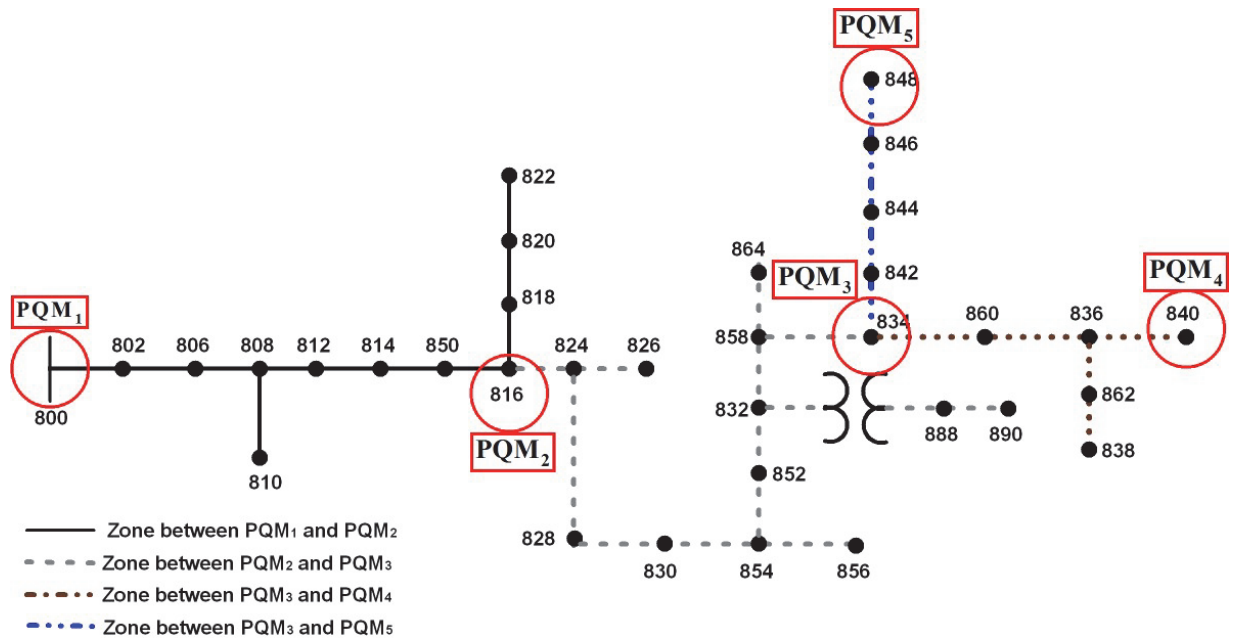| Cause		Description	Number of voltage sags
Network faults	SGL	Zero fault impedance	23
		Non-zero fault impedance	19
	LLF	Zero fault impedance	22
		Non-zero fault impedance	18
	DLG	Zero fault impedance	21
		Non-zero fault impedance	18
		TLF	22
Total			**143**

Source: The authors

Figure 3. Distribution system for simulating voltage sags in ATP-EMPT.
Source: The authors.

Table 5.
Results of the descriptors for some voltage sags.

Fault Node	N808 SLG	N820 SGL	N828 DLG	N844 TLF	N836 LLF
$V_{PQM(1\_2)pre\_fault}^{sec(+)}$	992.65	992.65	992.65	993.80	992.74
$V_{PQM(1\_2)fault}^{sec(+)}$	4016.5	2699.3	8316.7	7357.3	4118.7
$V_{PQM(2\_3)pre\_fault}^{sec(+)}$	823.04	823.04	823.04	824.02	823.13
$V_{PQM(2\_3)fault}^{sec(+)}$	670.31	741.18	1350.8	7507.1	4146.4
$V_{PQM(3\_4)pre\_fault}^{sec(+)}$	9.2754	9.2754	9.2754	9.274	9.57
$V_{PQM(3\_4)fault}^{sec(+)}$	7.6054	8.37	3.063	0.105	225.33
$V_{PQM(3\_5)pre\_fault}^{sec(+)}$	19.52	19.52	19.52	19.72	19.69
$V_{PQM(3\_5)fault}^{sec(+)}$	14.81	17.04	7.424	153.03	10.60

Source: The authors

According the results in Table 5 and the decision rules of the algorithm, the relative location results are shown in Table 6. Results estimate correctly the relative location of network fault as we can corroborate the location previously identified considering the diagram of Fig. 3 and the nodes on which performed the network faults.

Table 6.
Some results of the relative location algorithm.

Fault Node	N808 SLG	N820 SGL	N828 DLG	N844 TLF	N836 LLF
$\dfrac{V_{PQM1\_2Fault}^{sec(+)}}{V_{PQM1\_2Pre\_fault}^{sec(+)}}$	4.04	2.71	8.37	7.4031	4.14
$\dfrac{V_{PQM2\_3Fault}^{sec(+)}}{V_{PQM2\_3Pre\_fault}^{sec(+)}}$	0.81	0.9	1.64	9.1103	5.03
$\dfrac{V_{PQM3\_4Fault}^{sec(+)}}{V_{PQM3\_4Pre\_fault}^{sec(+)}}$	0.82	0.90	0.33	0.0114	23.54
$\dfrac{V_{PQM3\_5Fault}^{sec(+)}}{V_{PQM3\_5Pre\_fault}^{sec(+)}}$	0.75	0.87	0.38	7.7604	0.5
Results of the algorithm	*Down of* **PQM₁**	*Down of* **PQM₁**	*Down of* **PQM₁** **PQM₂**	*Down of* **PQM₁** **PQM₂** **PQM₃**	*Down of* **PQM₁** **PQM₂** **PQM₃**
	Between **PQM₁** **PQM₂**	*Between* **PQM₁** **PQM₂**	*Between* **PQM₂** **PQM₃**	*Between* **PQM₃** **PQM₅**	*Between* **PQM₃** **PQM₄**
	Up of **PQM₂** **PQM₃** **PQM₄** **PQM₅**	*Up of* **PQM₂** **PQM₃** **PQM₄** **PQM₅**	*Up of* **PQM₃** **PQM₄** **PQM₅**	*Up of* **PQM₄**	*Up of* **PQM₅**

Source: The authors

Table 7.
Confusion matrix with the results obtained from test case.

Relative Location	Area PQM1-to-PQM2	Area PQM2-to-PQM3	Area PQM3-to-PQM4	Area PQM3-to-PQM5	Total
True Positives (TP)	41	58	19	19	137
False negatives (FN)	0	0	0	6	6
False positives (FP)	0	6	0	0	6
True negatives (TN)	102	79	124	118	423
True Positive Rate (TPR)	1	1	1	0.76	**0.958**
False Positive Rate (FPR)	0	0.07	0	0	**0.0139**

Source: The authors

Table 7 presents the overall performance of the algorithm. The confusion matrix validates the effectiveness of the algorithm in identifying the relative location of voltage sags caused by network faults. The results show that the algorithm is 95. 8 % efficient in the relative location of network faults, and has an error percentage of 1.39 % in the estimation of the same faults.

For cases in which the relative location estimation was not correct, it is found that the reason is that network faults that occur at the boundaries of two consecutive areas generate positive sequence voltages that are not too high in the faulted feeder. Fig. 4 shows the positive sequence voltages in the coverage zones when network faults occurred at node 842. Only the six misclassified events correspond to network faults at the node 842. These positive sequence voltages are calculated from the voltage between power quality meters.

Fig. 4.a and Fig. 4.b show expected behaviors, as the fault current flows through the coverage zone bound for PQM2-PQM3 but not flow across the zone bound for PQM3-PQM4. Fig. 4.c exhibits unexpected behavior because the sequence voltage should be increased during the voltage sag.

Table 8 shows the values of the descriptors for the all network faults simulated at node 842.

Table 8.
Results for network faults at node 842.

Type of network fault	Descriptors			
	$\dfrac{V_{PQM1\_2Fault}^{sec(+)}}{V_{PQM1\_2Pre\_fault}^{sec(+)}}$	$\dfrac{V_{PQM2\_3Fault}^{sec(+)}}{V_{PQM2\_3Pre\_fault}^{sec(+)}}$	$\dfrac{V_{PQM3\_4Fault}^{sec(+)}}{V_{PQM3\_4Pre\_fault}^{sec(+)}}$	$\dfrac{V_{PQM3\_5Fault}^{sec(+)}}{V_{PQM3\_5Pre\_fault}^{sec(+)}}$
SGL	2.6819	3.0711	0.7321	0.8049
LLF	4.2487	5.1658	0.493	0.8613
DLG	4.7804	5.82	0.4824	0.9646
TLF	7.4645	9.1881	0.002	1.3381
SGL-Z$_f^*$	2.55	3.0279	0.8107	0.8073
LLF-Z$_f$	4.1401	5.0258	0.5086	0.8674
DLG-Z$_f$	4.8587	5.9284	0.3917	0.9706

Z$_f^*$ With fault impedance (2 Ohms).
Source: The authors

According to Table 8, Fig. 2 and Fig. 3, the values in the shaded cells in the last column should be greater than unity for correct classification. Thus, the algorithm locates the fault in the area precedent to the failed area, where it is estimated that the relative location of the faults is between PQM2 and PQM3. It is due to the overvoltage low of positive sequence between the 834 and 842 nodes, because being a short length from PQM3, the positive sequence voltage is not large enough to estimate the relative location between PQM3 and PQM5. During the fault, the positive sequence voltage between PQM3 and PQM5 is less than the respective pre-fault voltage, Fig 4.c.

5. Conclusions

This work proposes a methodology for the relative location of the voltage sags source using voltage measurements only. An advantage of this method is based on voltage measurements only, considering that, in many cases, the current measurements are not available in the electrical distribution systems.
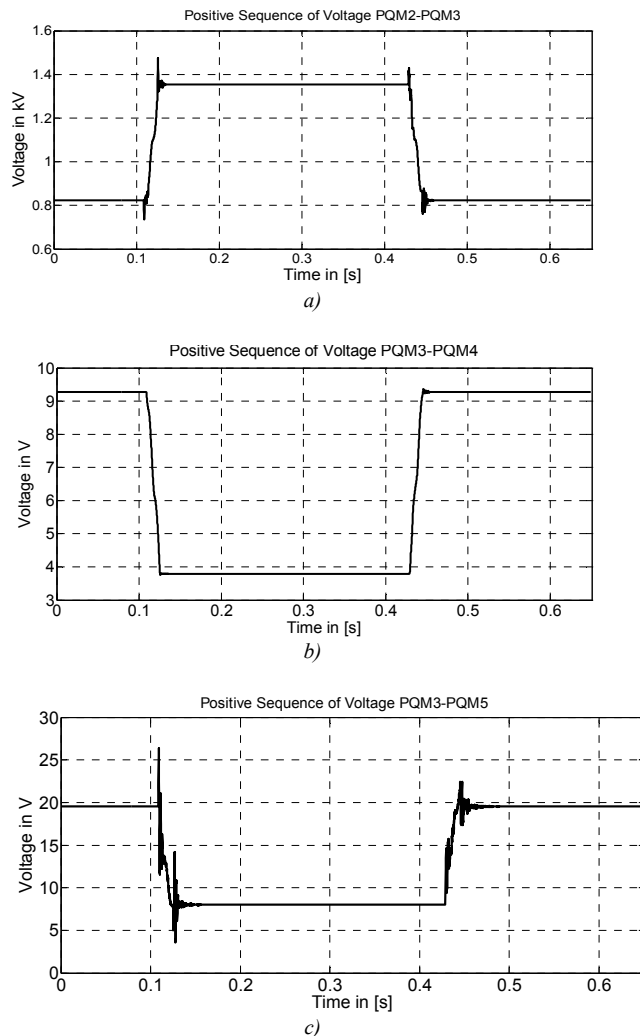

a)

b)

c)

Figure 4. Positive sequence voltages between power quality meters.
Source: Authors.

The proposed algorithm is useful for automatic location of the electrical faults in distribution systems. An extensive database of voltage sag records can be analyzed automatically and its implementation is innovative using the information recorded by monitoring equipment for more advanced analysis of the power quality. The decision algorithm is easy to understand and analyze by a user.

Some disadvantages are that this methodology is not applicable to systems, which have single voltage measurement equipment. Also, data processing equipment with this methodology requires a representative memory capacity when calculating the positive sequence voltage and RMS values. Erroneous results are obtained for electrical faults at the nodes near to boundaries between two coverage zones. It concluded that erroneous results are mainly due to the distance of occurrence of the network faults with respect to the meters, but not due to the fault impedance or network fault type.

This new methodology for the relative location of voltage sags allows responsibility to be assumed for the occurrence of disturbances in electrical systems for electrical utilities of transmission and distribution. This is a starting point for electrical utilities, allowing the implementation of new methodologies to reduce these disturbances in the network, thus ensuring a good power quality for the end user.

Acknowledgements

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