A New Algorithm for Relative Location of Voltage Sags Based on Voltage Measurements Only

J. Blanco, J.F. Petit, G. Ordóñez P and V. Barrera.

***Abstract*— This paper presents a tool easily implemented for relative location of voltage sags based on voltage measurements only. Voltage sags caused only by network faults are considered in this work. The algorithm automatically operates for assessing power quality, characterising and extracting information from voltage records obtained from monitors in distribution systems. It is required measurements of a minimum of three monitors located on the electrical distribution system. The positive sequence voltages are the descriptors used to determine the relative location of the voltage events. Finally, the proposed method is applied to a simulation case and it is verified that the method can be helpful to determine the relative location of the voltage sags. MATLAB was used for validating this methodology, receiving voltage records of simulated voltage sags in ATP-EMTP.**

***Index Terms*— Power quality monitoring, relative location, voltage sags, positive sequence voltage, network faults.**

I. Introduction

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, to improve power quality, it is important to identify the source of disturbance and fault location becomes an important area of investigation [2][3][4]. The identification of the disturbance source consists in locating and identification of event source. Distribution systems are usually configured in a radial pattern while in transmission systems, the buses form a connected grid with monitoring instruments located at substations [4].

This paper is essentially concerned with electrical distribution systems. The proposed method assumes a minimum of three voltage measurements available at electrical distribution system. These measurements are obtained of three power quality monitors installed at strategic points of electrical systems. 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 from the voltage and current measurements. However in some cases, there are not available current measurements and algorithms that depend only on the voltage measurements are required. In those works are identified and listed the most relevant descriptors that can determine the relative location of the voltage sags source. Also, the appropriate thresholds for discriminating the relative location of the voltage sags upstream or downstream of the measuring equipment are selected. Unlike of [1], where the proposed method is limited to be applied to measurements on the transformer's primary and secondary sides, the method proposed 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 algorithm proposed is performed by the simulation of voltage sags in a test electrical distribution system [7]. This test system is known as IEEE 34 Node Test Feeder and it is modeled in ATP-EMTP for to generate voltage sags with a relative location previously established. This set of voltage sags is used to validate the efficiency of algorithm proposed.

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II. Background

There are some methods which are used for determining the relative location of voltage sags and which primarily use voltage and current measurements. Below are presented some of these algorithms more representatives, emphasizing on the nature and the most relevant concepts related to the proposed methodologies.

A. *Relative Location of Voltage Sags Source for PQ Diagnosis.*

The works [2] and [3] present a methodology for the relative location of voltage sags source. This methodology is based on the previous identification of the different causes of the voltage sags 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 (1).

For network faults:

$$\begin{aligned} &Downstream \quad if \ \frac{I_{sag}{}^{1}}{I_{ss}{}^{1}} > Thr_{LF} \\ &Upstream \qquad if \ \frac{I_{sag}{}^{1}}{I_{ss}{}^{1}} < Thr_{LF} \end{aligned} \tag{1}$$

Where:

$I_{sag}{}^{1}$ Fundamental frequency component of the current before network fault

$I_{ss}{}^{1}$ Fundamental frequency component of the current during nertwork fault

Thr_{LF} threshold of the ratio $I_{sag}{}^{1}/I_{ss}{}^{1}$

For induction motor starting:

$$\begin{aligned} &Downstream \quad if \ \frac{P_{pos}-P_{pre}}{P_{pre}} > Thr_{IM} \\ &Upstream \qquad if \ \frac{P_{pos}-P_{pre}}{P_{pre}} < Thr_{IM} \end{aligned} \tag{2}$$

Where,

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 $(P_{pos} - P_{pre})/(P_{pre})$

Respect to transformer saturation, initially it is formulated some descriptors for the identification and classification of voltage sags originated by transformer saturation, according to the following rules shown in (3).

$$Transformer\ saturation \quad if \quad \frac{\Delta I_2}{\sum_{h=2}^{7} \Delta I_h} > Thr_H$$
$$Other\ causes \quad if \quad \frac{\Delta I_2}{\sum_{h=2}^{7} \Delta I_h} < Thr_H \tag{3}$$

Where,

h order of harmonic content.

ΔI_h change of harmonic current whose order is h.

Thr_H threshold of the ratio $\Delta I_2 / \sum_{h=2}^{7} \Delta I_h$.

Subsequently the rules for determining the relative location of voltage sags caused by transformer saturation are formulated.

$$Downstream \quad if \quad \frac{I_{sag}{}^1}{I_{ss}{}^1} > Thr_{TR}$$
$$Upstream \quad if \quad \frac{I_{sag}{}^1}{I_{ss}{}^1} < Thr_{TR} \tag{4}$$

Where

$I_{sag}{}^1$, $I_{SS}{}^1$ are presented in (1).

Thr_{LF} threshold of the ratio $I_{sag}{}^1 / I_{SS}{}^1$ in transformer saturation event.

The implemented algorithm performs a previous classification of the causes of the voltage sags and using the decision rules presented in (1), (2), (3) and (4), determines the relative location of the voltage sags. Some limitations found in the algorithm are the classification incorrect of some classes of voltage sags, such as voltage sags caused by network faults with fault impedance, network faults in isolated electrical systems, transformer energization with load, network faults which cause harmonic contents on the electrical system, transformer saturation, among others.

B. Relative Location of Voltage Sags Source Based on the Sequence Current Magnitude

The proposed methodology in this article focuses on the use of positive sequence current (RPSC), calculated before and during the voltage sag [5]. The formulation consists in establishing the expressions for the positive sequence currents and their respective decision rules for determining the relative location of the source of voltage sags. The rules are shown in (5).

$$|I_{Down}| > |I_{SS}| > |I_{Up}|$$
$$Downstream \quad if \quad \frac{|I_{Down}|}{|I_{SS}|} > 1 \tag{5}$$
$$Upstream\ if \quad \frac{|I_{Up}|}{|I_{SS}|} < 1$$

Where,

$|I_{Down}|$, $|I_{Up}|$ currents downstream and upstream respectively measured at the PQM.

$|I_{SS}|$ current of non-faulted steady state.

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 meters in the electrical system.

The purpose of this paper is to provide solutions for electrical distribution systems in which only implement voltage power quality monitors or else only collect records voltage electromagnetic events presented in the network. Currently there are electrical distribution systems with a limited metering infrastructure, generally focus to voltage records only. The proposal is striking for implementing of fault localization systems through the installation of power quality monitors, measuring only voltage and distributed strategically in the electrical distribution system.

III. Proposed Algorithm

The positive sequence currents are important for the analysis of asymmetric faults in power systems because it is present in all types of network faults [5]. Therefore, this variable is important for a detailed analysis of the relative location of voltage sags in the electrical distribution system.

Similar to the work presented in [5], for purposes of this work, only the positive sequence voltage is chosen as a variable that could determine the relative location of voltage sags.

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

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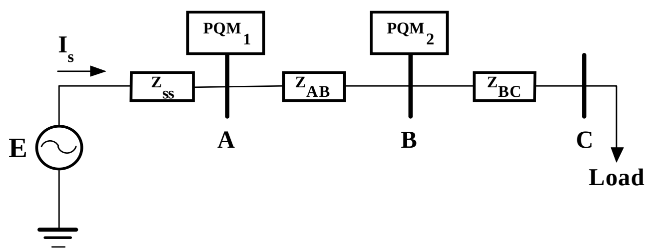

Figure 1. One-line diagram of a radial distribution systems

Figure 2 shows the positive sequence network of the system presented in Figure 1. An upstream network fault of monitors is presented. By analyzing the type of network faults, according to [6], if it is symmetrical fault then the positive sequence network is presented only. 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.

According to (6), if the network fault is originated upstream of PQM_1, 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 is deviated 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 PQM_1 and PQM_2, it is expected that the voltage drop of positive sequence $V_{A\text{-}B}$ is increased. Figure 3 shows a network fault that it was originated downstream of power quality monitors.

$$\begin{aligned} I^1_{AB_{Fault}} &\ll I^1_{AB_{Pre-fault}} \\ V^1_{AB_{Fault}} &\ll V^1_{AB_{Pre-fault}} \end{aligned} \qquad (6)$$

Where:

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

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

$V^1_{AB_{Fault}}$ 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 recorded voltages differ greatly respecting to the steady state, so that the voltage difference will be significant when compared to the steady state voltage of the system. Therefore it is decided implement the methodology with a minimum of two voltage power quality monitors to determinate the relative location of voltage sags.

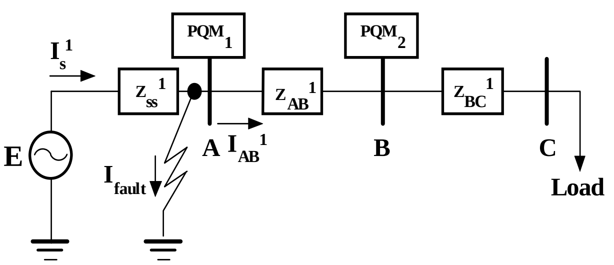

Figure 2. Electrical fault upstream of power quality monitors

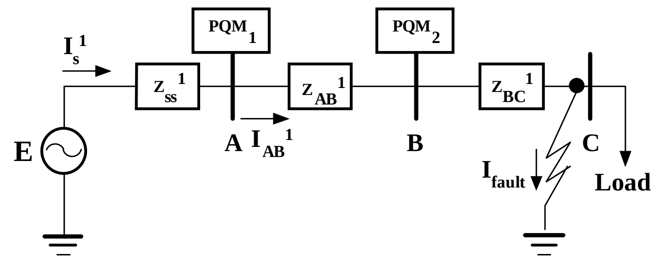

Figure 3. Electrical fault downstream of power quality monitors

Analyzing the behavior of the variables in the circuit shown in the Figure 3, the rules are presented in (7).

$$\begin{aligned} I^1_{AB_{Fault}} &\gg I^1_{AB_{Pre-fault}} \\ V^1_{AB_{Fault}} &\gg V^1_{AB_{Pre-fault}} \end{aligned} \qquad (7)$$

When the fault occurs between the two monitors as illustrated in Figure 4, the V_{AX}^{1} voltage of positive sequence is increased compared to the pre-fault voltage of positive sequence due to the flow of the fault current of positive sequence (I_{AX}^{1}) by this branch. This generates an increase in voltage of positive sequence V_{AB}^{1} during the network fault compared with the prefault voltage V_{AB}^{1}, although it is clear that the ratio is lower compared to the case where the network fault is present downstream PQM_2.

Initially using the proposed rule in (7), it is possible to estimate that the network fault is located downstream of PQM_1 and PQM_2, correct result only for PQM_1. As a solution to this imprecision is used a third power quality monitor PQM_3 as a mechanism to estimate the correct relative location of the network fault. Applying the rule formulated in (6) to the voltage between the monitors PQM_2 and PQM_3, it is concluded that the network fault is located upstream of PQM_2 and downstream of PQM_1, which is the same as between the two monitors.

The descriptors and rules presented in (6) and (7) are the basic formulation for determining the relative location of voltage sags based on voltage measurements only. The methodology consists of the strategic location of power quality monitors for to register voltage only. These monitors should to make possible a coordinated monitoring of the voltage sags present in the network and thus apply the algo-

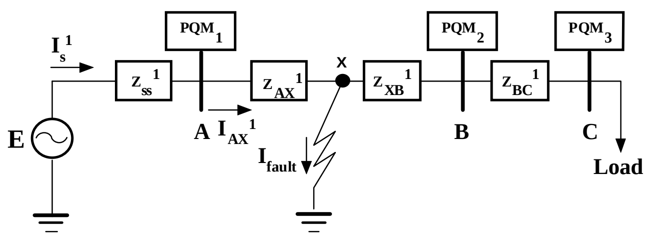

Figure 4. Fault between two power quality monitors

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

rithm proposed in this work, Figure 5. The level of accuracy is improved with the availability of a large number of voltage power quality monitors in the distribution system. According to Figure 5, 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.

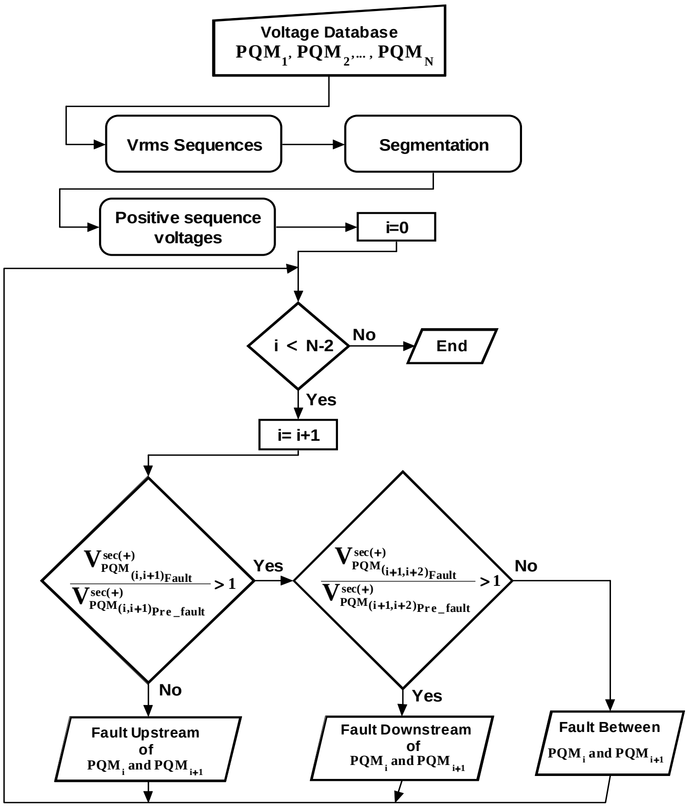

Figure 5. Proposed Algorithm

The proposed algorithm has several steps:

- A step for loading the voltage records from the database with the electromagnetic events recorded. These records are correlated, so that the same voltage sag is recorded by all the monitors with their respective tags.
- Step for calculating *RMS* sequences of the voltage sags recorded.
- Segmentation of the voltage sags, in order to determine the segments of the signals corresponding to the fault and prefault states.
- Calculation of the positive sequence voltages of the signals recorded.
- Feature extraction and evaluation of the decision rules of the algorithm.
- Diagnosis of the relative location of the source of the voltage sags.

IV. Testing

A. Simulation

IEEE 34 Node Test Feeder [7] 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). The one-line diagram of test feeder is presented in the Figure 6. Five voltage power quality monitors are installed and the synthetic voltage sags are simulated and recorded.

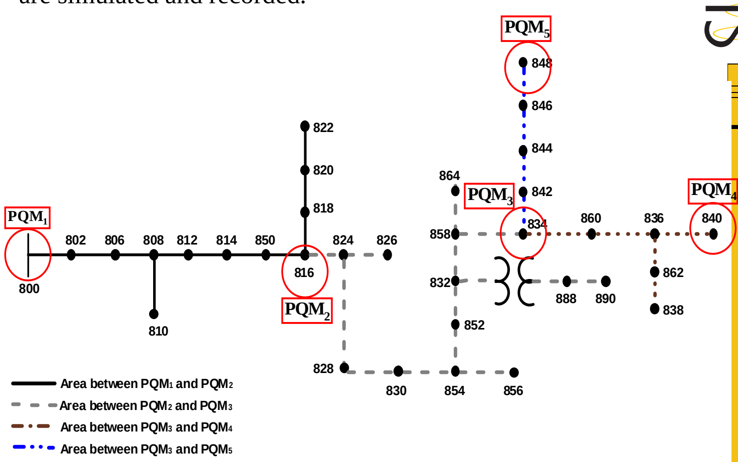

Figure 6. Distribution system for simulating voltage sags in ATP-EMPT

In the electrical system, some areas are defined according to the strategic location of the power quality monitors. These areas determine the relative location of voltage sags respect at power quality monitors, as a shown in Figure 6. 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 PQM_1 and PQM_2. Table I shows the summary of the simulated network faults according to areas and the fault type.

Table I. Simulated Voltage Sags in ATP-EMPT

Area	Network Fault Type		Number of voltage sags
Area PQM_1-PQM_2	SGL	Zero fault impedance	8
		Non-zero fault impedance	5
	LLF	Zero fault impedance	6
		Non-zero fault impedance	5
	DLG	Zero fault impedance	6
		Non-zero fault impedance	5
	TLF		6
Area PQM_2-PQM_3	SGL	Zero fault impedance	8
		Non-zero fault impedance	8
	LLF	Zero fault impedance	9
		Non-zero fault impedance	8
	DLG	Zero fault impedance	8
		Non-zero fault impedance	8
	TLF		9

Area	Network Fault Type		Number of voltage sags
Area PQM_3-PQM_4	SGL	Zero fault impedance	3
		Non-zero fault impedance	3
	LLF	Zero fault impedance	3
		Non-zero fault impedance	2
	DLG	Zero fault impedance	3
		Non-zero fault impedance	2
	TLF		3
Area PQM_3-PQM_5	SGL	Zero fault impedance	4
		Non-zero fault impedance	3
	LLF	Zero fault impedance	4
		Non-zero fault impedance	3
	DLG	Zero fault impedance	4
		Non-zero fault impedance	3
	TLF		4
Total			**143**

B. *Results of the algorithm*

The algorithm is applied to all the 143 voltage sags. Table II presents in detail some of the results of the applied descriptors for the purpose of analyzing the algorithm performance. The values taken by the descriptors are presented and the decision rules are analyzed.

Table II. Results of Descriptors for some Network Faults

Fault Node	N808 SLG	N820 SGL	N828 DLG	N844 TLF	N836 LLF
$V^{sec(+)}_{PQM(1\_2)pre\_fault}$	992,65	992,65	992,65	993,80	992,74
$V^{sec(+)}_{PQM(1\_2)fault}$	4016,5	2699,3	8316,7	7357,3	4118,7
$V^{sec(+)}_{PQM(2\_3)pre\_fault}$	823,04	823,04	823,04	824,02	823,13
$V^{sec(+)}_{PQM(2\_3)fault}$	670,31	741,18	1350,8	7507,1	4146,4
$V^{sec(+)}_{PQM(3\_4)pre\_fault}$	9,2754	9,2754	9,2754	9,274	9,57
$V^{sec(+)}_{PQM(3\_4)fault}$	7,6054	8.37	3,063	0,105	225,33
$V^{sec(+)}_{PQM(3\_5)pre\_fault}$	19,52	19,52	19,52	19,72	19,69
$V^{sec(+)}_{PQM(3\_5)fault}$	14,81	17.04	7,424	153,03	10,60
$\frac{V^{sec(+)}_{PQM1\_2Fault}}{V^{sec(+)}_{PQM1\_2Pre\_fault}}$	4,0462	2,71	8,3783	7,4031	4,1488
$\frac{V^{sec(+)}_{PQM2\_3Fault}}{V^{sec(+)}_{PQM2\_3Pre\_fault}}$	0,8144	0,9	1,6412	9,1103	5,0374
$\frac{V^{sec(+)}_{PQM3\_4Fault}}{V^{sec(+)}_{PQM3\_4Pre\_fault}}$	0,8200	0,90	0,3302	0,0114	23,546
$\frac{V^{sec(+)}_{PQM3\_5Fault}}{V^{sec(+)}_{PQM3\_5Pre\_fault}}$	0,7586	0,87	0,3803	7,7604	0,538

According the results of the Table II and the decision rules of the algorithm, results in the relative location are shown in Table III. The results estimate correctly the relative location of network fault as can corroborate the location previously identified.

Table III. Results of Relative Location

Network Fault	Relative Location
N808 SLG	Fault between PQM_1 and PQM_2
	Fault upstream PQM_2 and PQM_3
	Fault upstream PQM_3 and PQM_4
	Fault upstream PQM_3 and PQM_5
N820 SGL	Fault between PQM_1 and PQM_2
	Fault upstream PQM_2 and PQM_3
	Fault upstream PQM_3 and PQM_4
	Fault upstream PQM_3 and PQM_5
N828 DLG	Fault downstream PQM_1 and PQM_2
	Fault between PQM_2 and PQM_3
	Fault upstream PQM_3 and PQM_4
	Fault upstream PQM_3 and PQM_5
N844 TLF	Fault downstream PQM_1 and PQM_2
	Fault downstream PQM_2 and PQM_3
	Fault upstream PQM_3 and PQM_4
	Fault between PQM_3 and PQM_5
N836LLF	Fault downstream PQM_1 and PQM_2
	Fault downstream PQM_2 and PQM_3
	Fault between PQM_3 and PQM_4
	Fault upstream PQM_3 and PQM_5

The results presented in the Table III are easily validated considering the diagram of Figure 6 and the nodes on which performed the network faults.

Table IV presents the overall performance of the algorithm. The confusion matrix validates the effectiveness of the algorithm in identifying of the relative location of voltage sags caused by network faults. The results show that the algorithm is efficient by 97, 9 % in the relative location of network faults and an error percentage of 0,7 % in the estimation of the same faults.

Table IV. CONFUSION MATRIX WITH THE RESULTS OBTAINED OF TEST CASE

Relative Location	Area between PQM_1 and PQM_2	Area between PQM_2 and PQM_3	Area between PQM_3 and PQM_4	Area between PQM_3 and PQM_5	***TOTAL***
True Positives (TP)	*41*	*58*	*19*	*22*	*140*
False negatives (FN)	*0*	*0*	*0*	*3*	*3*
False positives (FP)	*0*	*3*	*0*	*0*	*3*
True negatives (TN)	*102*	*82*	*124*	*118*	*426*
True Positive Rate (TPR)	*1*	*1*	*1*	*0,88*	***0,979***
False Positive Rate (FPR)	*0*	*0,0352*	*0*	*0*	***0,007***

For cases in which the estimate of the relative location was not correct, it is found that the reason is because network faults that occur at the boundaries of two consecutive areas generate positive sequence voltages not too high in the faulted feeder.

Thus, the algorithm locates the fault in the area precedent to failed area. Justly, the three voltage sags with incorrect estimation correspond to faults on the node 842, 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. According to the proposed algorithm, the network fault would not be located in the area bounded by these two power quality monitors.

V. Conclusions

Some important conclusions of this work:

The main advantage of this method is based on voltage measurements only for the relative location of voltage sags, considering that in many cases the current measurements are not available in the electrical distribution systems.

The implementation of this method 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.

The algorithm proposed is useful for automatically locating electrical faults in distribution systems using it as a computational tool. It has possible automatically analyzed an extensive database with records of voltage sags obtaining accurate results.

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.

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

VI. Acknowledgements

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