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Voltage Sag Source Location Based on Voltage Measurements Only

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***Summary*: This paper introduces an alternative method for voltage sag source location based on voltage information only. The source is located considering the sag magnitude at the primary and secondary side of a transformer. A comprehensive review of previously proposed methods based on voltage and current measurements is presented. The performance of the proposed method is compared with the previous ones using PSCAD/EMTDC on a model of a regional network including transmission and sub-transmission levels. Moreover, the sag magnitude method is applied on a set of measurements taken from the regional network during a one year sag survey. The results show the good performance of the new method and its unique applicability in cases where only voltages are recorded, such as the sag survey presented.**

Key words:
power quality,
voltage sags (dips),
source location

1. INTRODUCTION

Voltage sags cause several problems on end-users' equipments. These problems have been quantified and for instance, sensitive industrial load malfunction costs billions of dollars every year [1]. The most severe voltage sags are caused by faults in the power system. Unfortunately the sags are not confined nearby the fault location; they propagate through the system affecting loads connected far away from the sag source [2]. Therefore, the accountability for the generation of disturbances on the system must be assessed and the sag sources must be analyzed and located.

One of the first works aiming to locate the source of voltage sags defined the concepts of "disturbance power and disturbance energy". This concept was applied to locate the source of disturbances caused by capacitor switching and faults in the network [3].

Later, a second work introduced the concept of "slope of the system trajectory" to locate the source of voltage sags [4]. This method was generalized to a new approach using the sign of an estimated resistance to locate the source of voltage sags [5].

Meanwhile, another approach using the variation of the real current component was introduced. This method uses the real part of the complex current to locate the sag source [6].

Another method was motivated by the increasing use of digital relays and their applicability for power quality analysis. The distance relay algorithms can be used for the location of the voltage sag source based on the magnitude and angle of the measured impedance before and during a fault [7].

These methods have been tested for symmetrical and asymmetrical faults and most of them have not been very accurate especially for asymmetrical faults [8].

Moreover, the previous methods need both the current and the voltage measurements to locate the source of the sag. However, during several voltage sag surveys, it has been observed that it is a common practice to register and save voltage information only. Therefore, a method to locate the sag source based on the voltage sag magnitude obtained at two voltage levels of a substation is proposed. This method is the only one capable to locate a sag source when the current measurement is not available. The method shows a remarkable accuracy for the location of the source of sags observed at transmission networks.

2. REVIEW ON SOURCE LOCATION BASED ON VOLTAGE AND CURRENT MEASUREMENTS

The location of the sag source as observed from a monitored bus is defined as upstream or downstream, using the steady state power flow direction as reference. Upstream is the region against the flow of power and downstream is the region following the flow of power, as shown in Figure 1.

One of the first published methods aiming to locate the source of the disturbances is based on the disturbance power (DP) and the disturbance energy (DE). DP is the difference between the power delivered during the voltage sag and the steady-state power. The DE is calculated by the integral of the disturbance power during the voltage sag. The final sign of the DE indicates the location of the sag source. If the final DE is positive the sag source is located downstream. If the final DE is negative the source of the sag is located upstream. If the sign of the initial peak of the DP coincides

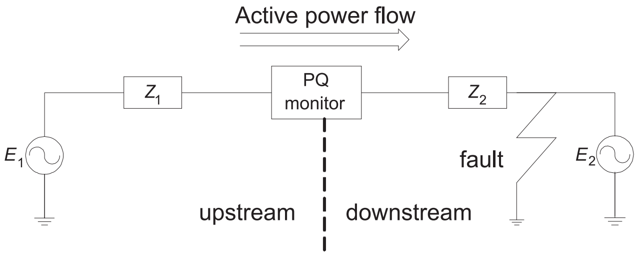

Fig. 1. Basic circuit to describe the localization of the sag source

with the sign of the final DE, a high degree of confidence is expected [3].

The method of the slope of the system trajectory (SST) is explained in terms of the relation between the measured voltage and current. The SST is obtained by linear fitting on a set of values $(I, |V\cos(\theta)|)$ during the voltage sag. A positive slope indicates an upstream fault location whereas a negative slope means a downstream fault. If the power flow is inverted during the sag the fault is located upstream [4].

A second method developed by the same researchers also proposes to use the sign of the resistance to classify the source of the sag. This method proposes to use the positive-sequence voltage and current. A resistance is estimated using two matrix equations described in [5]. If the resistances estimated by both equations have the same sign the test is conclusive. A positive sign means that the fault is upstream whereas a negative sign indicates a downstream fault.

The method of real current component (RCC) is based on the analysis of the variation of the real part of the complex current $(I\cos(\theta))$. The method establishes that if $I\cos(\theta)>0$ at the beginning of the sag then the fault is located downstream. On the other hand, if $I\cos(\theta)<0$ at the beginning of the fault then the fault is upstream [6].

The approach of using a distance relay algorithm (DR) analyzes the impedance seen during the event. The impedance is estimated using the voltage and current phasors at the monitored location. Therefore, this method proposes the following rule for the sag source detection: if $|Z_{SAG}|<|Z_{PRE\text{-}SAG}|$ and $angle(Z_{SAG})>0$ then the sag source is located downstream, otherwise the sag source is located upstream [7].

The several methods using voltage and current values have been tested to locate the voltage sag source in a transmission network [8]. In general the performance of the methods is much more accurate for symmetrical faults, where accurate results were obtained in 87% of the cases. On the other hand, for asymmetrical faults accurate results were obtained in 65% of the cases. This fact and the need for a method based on voltage measurements motivated the proposal of a new voltage-based method.

3. SOURCE LOCATION BASED ON VOLTAGES ONLY

A method based on the analysis of the voltage sag magnitude and phase-angle jump was proposed to classify the source at the connection point of sensitive customers [9]. For a typical industrial installation the sags generated in the utility grid and the sags generated inside the industrial grid will follow different phase-angle jump *vs*. sag magnitude relation. Unfortunately, this method is not suitable for classifying sags at the interconnection point of two utilities at transmission levels because it is not expected to observe such a phase-angle jump *vs*. magnitude characteristic when there are transmission networks at both sides of the monitoring point.

An alternative simple approach to locate the sag source based on voltages sag magnitude at both sides of the transformer that interconnects two grids, as shown in Figure 2, is now proposed.

The idea is to compare the voltage sag magnitudes in per unit with respect to pre-fault voltages at both sides of the transformer:

$$V_1 = \frac{V_{1-sag}}{V_{1-prefault}} \tag{1}$$

$$V_2 = \frac{V_{2-sag}}{V_{2-prefault}} \tag{2}$$

where $V_{i\text{-}sag}$ is the during sag voltage in kV and $V_{i\text{-}prefault}$ is the pre-fault voltage in kV.

The voltage drop at each side of the transformer is given by:

$$\Delta V_1 = Z_1 I_{fault} \tag{3}$$

$$\Delta V_2 = \left(Z_1 + Z_{TRAFO}\right) I_{fault} \tag{4}$$

where Z_{TRAFO} is the transformer impedance and I_{fault} is the fault current.

The voltage drop is higher on the side where the fault is located. Therefore, if $\Delta V_2 > \Delta V_1$ ($V_1 > V_2$) the fault is downstream, otherwise the fault is upstream. If the downstream system does not include generation units, V_1 and V_2 are expected to be equal during upstream faults.

This method is intended to locate sag source at the interconnection point of transmission utilities. At this level the influence of loads is not so evident. And the effect of constant power loads may not affect the performance of the method because other loads such as induction machines will supply the extra current demanded by the constant power loads during short sags.

Another concern is when unbalanced voltage sags propagate through a delta/star transformer. The relation of the voltage sag magnitudes at both sides of the transformers will depend on the sag type [10].

4. SIMULATIONS

4.1. The power system

The method to locate the sag source is tested using a model of a regional network including transmission and

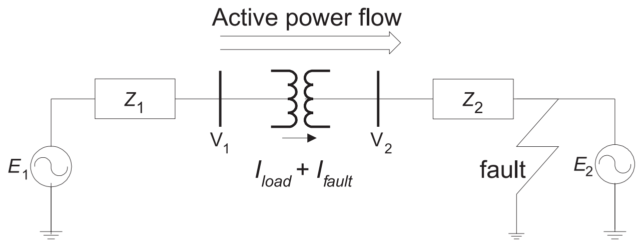

Fig. 2. Basic circuit to describe the method for sag source location using sag magnitude

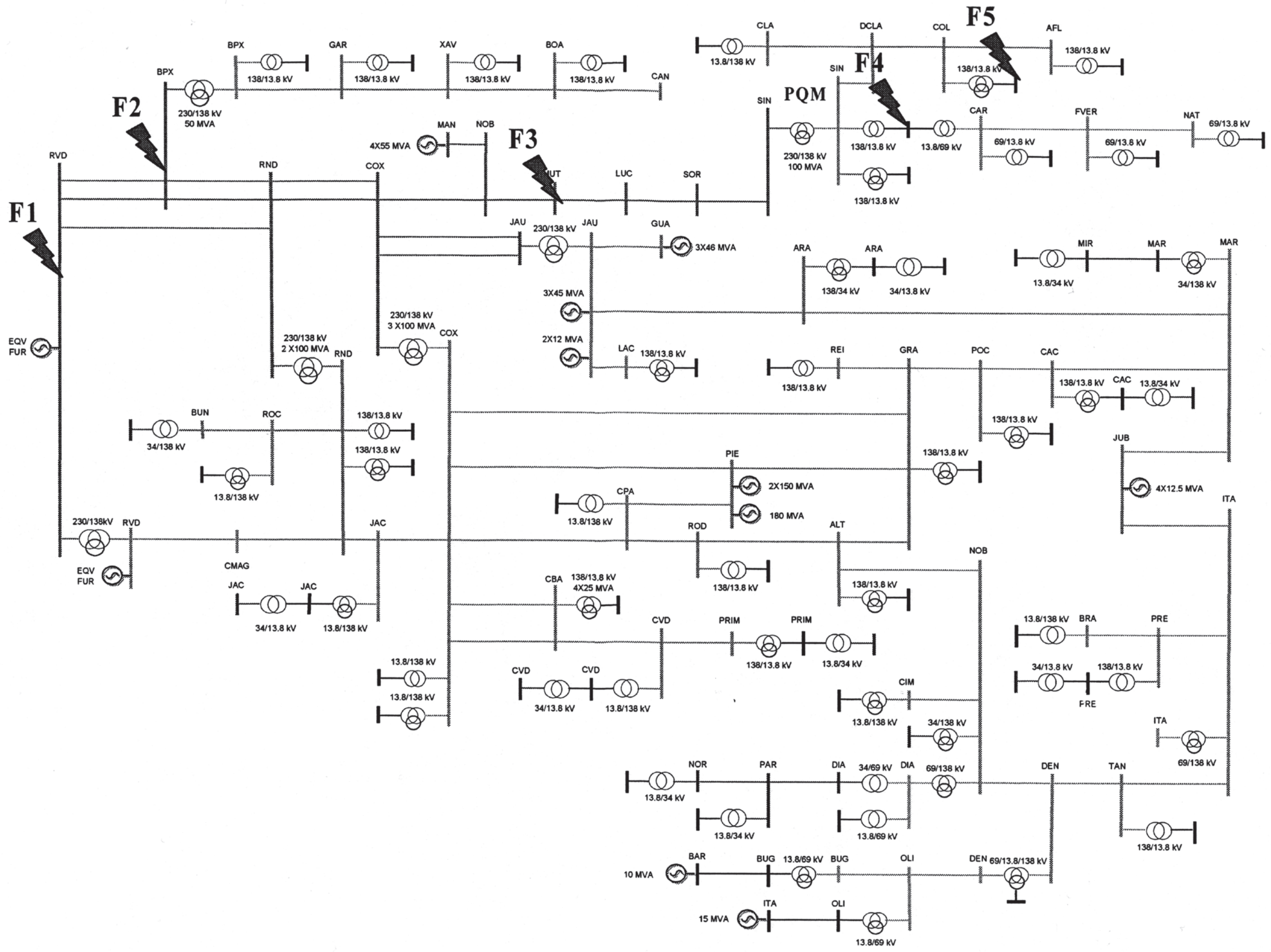

Fig. 3. Power system single-line diagram, fault locations and the two monitored buses at the SIN substation are indicated

sub-transmission levels, as well as meshed and radial system configurations. The network contains 67 power lines (69, 138, and 230 kV) with a total length of 6619 km. There are 93 substations with an installed transformer capacity of 2076 MVA. The generation capacity is larger than the present demand. The excess of generated power is exported to other regional grids through the RVD substation. A schematic network diagram is shown in Figure 3.

The simulation is performed using the PSCAD/EMTDC program. The instantaneous phase-to-ground voltages obtained from the simulation are processed using MatLab in order to get the rms voltages. As a result the rms voltage during time is obtained, as shown in Figure 4. The voltage sag magnitude is defined as the lowest steady state rms voltage during the fault. When each phase experiences different magnitudes the lowest magnitude of the three phases is used to characterize the three-phase sag.

A substation that interconnects two utilities is chosen for PQ-monitoring (PQM). The 230 kV and the 138 kV grids are operated by two different utilities. Therefore, it is relevant to locate the source of the sag taking into account the boundaries between the two utilities.

The faults are simulated at both utility networks, in upstream and downstream locations referred to the monitored buses. The simulated fault locations are named in Table 1.

At each fault location 4 types of faults are simulated (LLLG, LL, LLG, and LG). At the monitored bus the active power always flows from the 230 kV to the 138 kV bus due to the lack of generation units at the downstream network.

Table 1. Fault location used for simulations

F1	F2	F3	F4	F5
RVD 230	BPX 138	MUT 230	SIN 13.8	AFL 138
US	US	US	DS	DS

Note: US: upstream, DS: downstream.

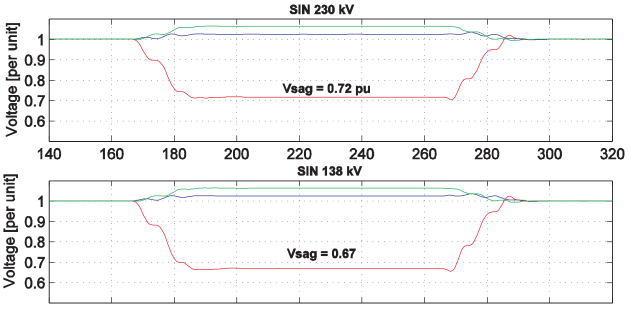

Fig. 4. rms voltage vs. time at the 230 and 138 kV buses measured at SIN substation for a LG fault at F3

4.2. Results

The results for the simulations are organized in Table 2 –5, one for each type of fault (LLLG, LL, LLG, LG). The first row of the table indicates the fault position as shown in Figure 3; the second and the third rows show the sag magnitude at the 230 kV and 138 kV buses; and the fourth row shows the location assessed by the test.

The location decision is based on the sag magnitude at 230 kV and 138 kV buses. Considering that the power flow is from the 230 kV to the 138 kV bus, when the sag magnitude is lower at 138 kV than at 230 kV the source of the sag is located downstream, otherwise the source is located upstream.

There are two fault positions (F4 and F5) that are located downstream. The results obtained for each type of fault confirm the fault location. For instance, for a LLLG fault at F4 the sag magnitude at 230 kV bus is 0.78 per unit whereas the sag magnitude at the 138 kV bus is 0.73 per unit, as shown in Table 2. The difference on the sag magnitude is due to the additional voltage drop over the power transformer caused by the fault current.

Table 2. Source location for symmetrical faults

Fault	Vsag 230 kV	Vsag 138kV	Location
F1	0.93	0.93	US
F2	0.92	0.92	US
F3	0.01	0.01	US
F4	0.78	0.73	DS
F5	0.66	0.57	DS

Note: US: upstream, DS: downstream

Table 3. Source location for LL faults

Fault	Vsag 230 kV	Vsag 138kV	Location
F1	0.93	0.93	US
F2	0.92	0.92	US
F3	0.50	0.50	US
F4	0.81	0.77	DS
F5	0.74	0.69	DS

Note: US: upstream, DS: downstream

Table 4. Source location for LLG faults

Fault	Vsag 230 kV	Vsag 138kV	Location
F1	0.94	0.94	US
F2	0.93	0.93	US
F3	0.07	0.07	US
F4	0.74	0.69	DS
F5	0.67	0.60	DS

Note: US: upstream, DS: downstream

Table 5. Source for LG faults

Fault	Vsag 230 kV	Vsag 138kV	Location
F1	0.98	0.98	US
F2	0.97	0.97	US
F3	0.11	0.11	US
F4	0.72	0.67	DS
F5	0.72	0.67	DS

Note: US: upstream, DS: downstream

On the other hand, for the faults at F1, F2, and F3, that are located upstream, the sag magnitude at each side of the transformer is the same. However, for upstream faults it may occur that the sag magnitude is lower at 230 kV bus than at 138 kV bus, when there is a contribution to the fault current from some loads or co-generation units installed at a downstream location.

5. MEASUREMENTS

Voltage sags have been measured during a one year period in several buses of the system shown in Figure 3 Among the monitored buses are the two buses used during the simulations. During this sag survey only voltage information was registered. Fortunately also the fault location has been obtained for events at the 230 kV and 138 kV lines. Therefore, it is possible to evaluate the proposed methodology to locate the sag source.

Table 6 shows the voltage sag magnitude registered at both buses in the substation during the identified faults. Not all the measured sags are used because to test the method

Table 6. Measurement results

Fault type	Fault location	Relative Location	Vsag 230kV	Vsag 138kV
LL	COL/ALF	DS	0.67	0.60
LG	COX/JAU	US	0.65	0.66
LG	NOB/DEN	US	0.97	0.97
LG	COL/ALF	DS	0.71	0.63
LG	COX/JAU	US	0.90	0.89
LG	BPX/RND	US	0.92	0.92
LG	JAC/COX	US	0.90	0.90
LG	COX/JAU	US	0.88	0.88
LG	COL/ALF	DS	0.68	0.63
LL	CBA/CVD	US	0.87	0.86
LLL	CMAG/RND	US	0.94	0.93
LLL	JUB/MAR	US	0.96	0.95
LLL	DEN/TAN	US	0.96	0.96
LLG	JAC/COX	US	0.90	0.89
LG	GRA/POC	US	0.93	0.93
LG	JUB/MAR	US	0.97	0.97
LG	DCLA/COL	DS	0.58	0.46
LG	JUB/MAR	US	0.97	0.97
LG	NOB/DEN	US	0.97	0.97
LG	RVD/RND	US	0.93	0.92
LLG	DCLA/COL	DS	0.50	0.37
LLL	PRE/ITA	US	0.92	0.92
LL	ITA/JUB	US	0.93	0.93
LLL	NOB/MUT	US	0.00	0.00
LL	JUB/MAR	US	0.93	0.93
LLL	DCLA/COL	DS	0.38	0.23
LL	DEN/TAN	US	0.96	0.96
LL	DEN/TAN	US	0.96	0.96
LLG	MAR/CAC	US	0.97	0.96
LL	JAC/COX	US	0.89	0.90

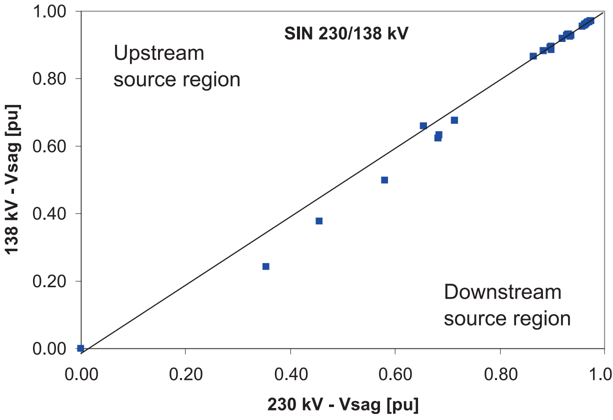

Fig. 5. Voltage sag magnitudes measured at 230 and 138 kV buses

the fault location must be previously known. Therefore, only fault that happened at the 230 kV and 138 kV networks are identified and used for the method validation.

The downstream events are highlighted with gray. In all the downstream cases the sag magnitude is lower at the 138 kV bus. There are some events where the sag magnitude is slightly lower (0.01 per unit) at the 138 kV bus, but these events were upstream. To ensure the reliability of the test the difference between the sag magnitudes must exceed a certain threshold.

The voltage sag magnitudes obtained from the measurements can be shown in a way that the location decision is seen graphically. Figure 5 shows the plot of 138 kV sag magnitudes *vs.* 230 kV sag magnitudes. The line divides the plot in two zones. The events represented above or on the line correspond to the ones whose source is located upstream. The events represented below the line are the sags whose source is located downstream.

When there is co-generation or great penetration of induction machines at the downstream location it is expected to find events above the boundary line. That is not the case of the measured network.

Now that the correlation between sag magnitudes and source location has been shown for the interconnection substation, the source of the next registered events can be accurately located.

Influence of transformers and loads

6. TRANSFORMER WINDING CONNECTION

The proposed method for source location can be straightforwardly applied when the transformer at the substation has star/star winding connections. This is a typical transformer at the interconnection of two transmission utilities in the Brazilian network, where the measurements have been taken.

However, a more general approach could be to include other types of transformer connections. Here the sag propagation through a delta/star transformer is analyzed. This type of transformer swaps the sag type.

Considering the characterization of unbalanced three-phase voltage sags [2], a set of equations describing the relation between sag magnitudes for delta and star connected PQ-monitors was proposed [10]. The relation between these sag magnitudes is plotted in Figure 6.

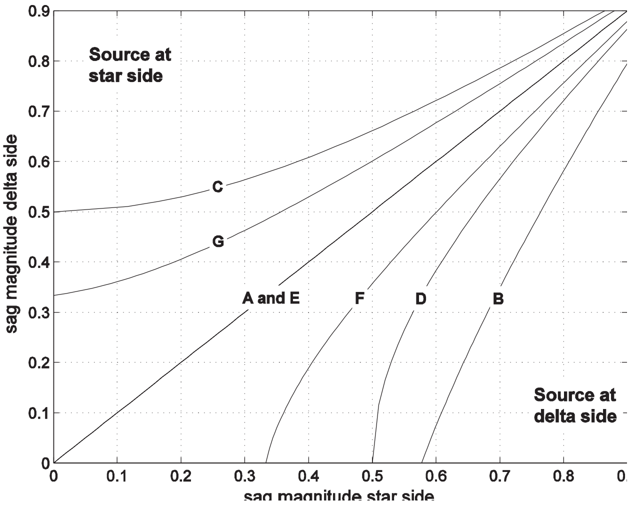

Fig. 6. Sag magnitude relation at both sides of a transformer with delta/star windings connection

Therefore, the generalization of the proposed method includes an additional step. In order to locate the sag source it is necessary to classify the sag according to the ABC classification [2]. Then, if the event is under the reference curve the source location is at the delta side of the transformer, otherwise it is at the star side.

6.2. Load Influence

The load behavior during the voltage sag may affect the performance of the method. The initial hypothesis that only a downstream fault produces an increase of the current flowing through the transformer may fail when the load is mainly constant power and the time response of the load is in the order of milliseconds. In such a situation the reduction of the voltage during a sag also increases the load current.

The proposed method for sag source location is intended to be used at the connection substation of two transmission utilities, where the load cannot be considered as constant power but as composite load (5):

$$S = P_0\left(\frac{V}{V_0}\right)^{\alpha} + Q_0\left(\frac{V}{V_0}\right)^{\beta} \qquad (5)$$

where P_0 and Q_0 are the active and reactive power at nominal voltage and V_0 is the nominal voltage; α and β are empirics coefficients that show the load voltage dependence.

It has been shown that during a voltage sag the behavior of such a composite load is close to a constant impedance model. Considering different periods of the year (winter, summer) and bus characteristics (residential loads, industrial loads) the values of α varies from 1.5 (industrial area during summer) to 2.5 (residential area during winter) [11]. The β values are greater than 4.0 for all scenarios. Therefore the proposed method should not fail as a consequence of load behavior when it is applied at transmission and subtransmission levels.

7. CONCLUSIONS

The voltage sag magnitude, estimated in terms of the pre-fault voltage, at both sides of a power transformer is used to find the relative location of the sag source. The method was successfully applied to simulated voltage sags on a model of a regional network comprising both the transmission and the distribution levels.

The method was applied at a substation where the power transformer winding connections were star/star grounded at both sides. The generalization of the method for other types of transformers is explained as well. The applicability of the method considering the behavior of loads is also analyzed in the paper.

Voltage sag measurements taken during a sag survey on the real network confirmed the applicability and accuracy of the proposed method.

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REFERENCES

1. McGranaghan M., and Roettger B.: *Economic evaluation of power quality.* IEEE Power Engineering Review, 2002, 22, 2, pp 8–12.
2. Bollen M.H.J.: *Understanding Power Quality Problems – Voltage Sags and Interruptions.* New York: IEEE Press, 1999.
3. Parsons A.C., Grady W.M., Powers E.J., and Soward J.C.: *A direction finder for power quality disturbances based upon disturbance power and energy.* IEEE Transactions on Power Delivery, 2000, 15, pp. 1081–6.
4. Li C., Tayjasanant T., Xu W., and Liu X.: *Method for voltage-sag-source detection by investigating slope of the system trajectory.* IEE Proceedings - Generation, Transmission and Distribution, 2003, 150, pp. 367–72.
5. Tayjasanant T., Li C., and Xu W.: *A resistance sign-based method for voltage sag source detection.* IEEE Transactions on Power Delivery, 2005, vol. 20, pp. 2544–51.
6. Hamzah N., Mohamed A., and Hussain A.: *A new approach to locate the voltage sag source using real current component.* Electric Power Systems Research, 2004, vol. 72, pp. 113–23.
7. Pradhan A.K. and Routray A.: *Applying distance relay for voltage sag source detection.* IEEE Transactions on Power Delivery, 2005, vol. 20, pp. 529–31.
8. Leborgne R.C., Karlsson D., Daalder J.: *Voltage sag source location methods performance under symmetrical and asymmetrical fault conditions.* In Proc. IEEE PES Transmission and Distribution Conference and Exposition Latin America, 2006, Caracas, Venezuela.
9. Gomez J., Morcos M., Tourn D., and Felici M.: *A novel methodology to locate originating points of voltage sags in electric power systems.* In Proc. 18th CIRED, Turin, 2005.
10. Leborgne R.C., Olguin G., Bollen M.H.J.: *The Influence of PQ-Monitor Connection on Voltage Dip Measurements.* In Proc. 4th Mediterranean IEE Conference on Power Generation, Transmission, Distribution and Energy Conversion, Cyprus, 2004.
11. Karlsson D.: *Voltage stability simulations using detailed models based on field measurements.* Ph.D. thesis, School of Electrical and Computer Eng., Chalmers University of Tech., Gothenburg, Sweden, 1992.

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