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Review of Voltage Sag Source Identification Methods for Power Quality Diagnosis

***Abstract**. Voltage sag is considered as one of the most common power quality problems causing sensitive equipment to malfunction and many industrial process interruptions. Complains about the economic loss and equipment damage from industrial customers has stimulated the investigation on the voltage sag source location. As a result, many efforts have been made to know the location of voltage sags by utilizing various concepts. Generally, there are two broad categories of methods to locate voltage sags source, namely, single and multi-monitor based methods. Therefore, the purpose of this paper is to present a comprehensive review of articles that involves various methods to identify the location of voltage sag source. Accordingly, the concepts, advantages and disadvantages of these methods are discussed and tabulated for review. Although this paper does not exhibit a numerical performance comparison, most of the research publications under the subject of voltage sag source location methods have been sorted and appended for a rapid reference.*

***Streszczenie.** Zapady napięcia są jednym z ważniejszych parametrów opisjących jakość energii. Mogą one powodować uszkodzenia urządeń i zakłócenia procesów przemysłowych. Artykuł omawia metody lokalizacji źródeł zapadów napięcia. Zaprezentowano przegląd publikacji opisujących ten problem uwypuklając zalety i wady każdej z metod. (**Przegląd metod identyfikacji źródła zapadów napięcia**)*

Keywords: Power Quality, Voltage Sag Location, Upstream/Downstream, Single Monitor, Multi-Monitor.

Słowa kluczowe: jakość energii, zapady napięcia

Introduction

According to IEEE Standard 1159-1995, voltage sag is defined as a decrease in root mean square (RMS) voltage or current at the power frequency for durations from 0.5 cycles to 1 minute. IEC defines voltage sag as a sudden reduction of voltage at a point in the electrical system, followed by a voltage recovery after a short period of time, from half a cycle to a few seconds [1]. Voltage sag may be caused by switching operations associated with temporary disconnection of supply, the flow of heavy current associated with starting of large motor loads or the flow of fault currents. These events may originate from customers' systems or from the public electricity supply network. Fig. 1 shows typical voltage sag that is associated with a single line-to ground (LG) fault.

A fault on a parallel feeder circuit may result in voltage sag at the substation bus that affects all the other feeders until the fault is cleared. Typical fault clearing times usually range from 3 to 30 cycles, depending on the fault current magnitude and the type of over current detection and interruption [2]. Voltage sag duration usually depends on the fault clearing time. Voltage sag is said to occur when the voltage is below its voltage threshold value of 0.9 p.u. It was reported that voltage sag magnitude of 85% to 90% of nominal voltage with duration as short as 16 ms has triggered immediate outage of critical industrial processes [1].

Complains about the economic loss and equipment damage from industrial customers has stimulated the investigation on the voltage sag source location so that penalties can be imposed to the responsible party causing interruptions [2]. Thus, location of voltage sag source has become increasingly important as the first step to diagnose the problem in a power system. By having the exact location, trouble-shooting, diagnosis and mitigation can be applied to the network to improve the PQ performance of electric supply to domestic and industrial customers [3].

Generally, there are two broad categories of methods to locate voltage sags source, namely, single and multi-monitor based methods. In case of single monitor method, the relative location of voltage sag source is correlated to the data analyzed at the monitor. The monitor can determine whether the origin of voltage sag source is upstream or downstream from the monitoring point [4-20].

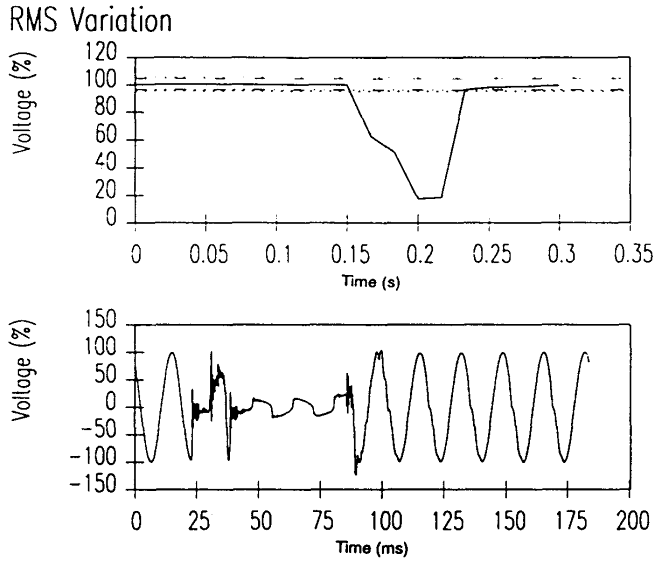

Fig.1. Instantaneous voltage sag caused by a LG fault

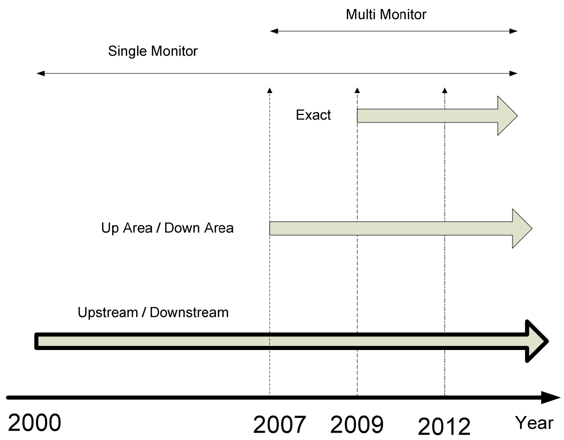

Fig. 2. Voltage sag location using single and multi-monitor methods.

The multi-monitor methods use more than one PQ monitor in the network to locate the voltage sag source. Data collected from multi PQ monitor in a power network are stored and processed to determine the sag source location [21-33]. Fig. 2 shows the current voltage sag location methods using single and multi-monitor methods.

The main objective of this paper is to provide a comprehensive review of voltage sag source identification methods in a power system. Accordingly, the concepts as well as the advantages and disadvantages of these methods are discussed and tabulated for an all-exclusive review.

Single Monitor Based Voltage Sag Source Identification Methods

The concept of sag source detection is shown in Fig. 3, in which a PQM is installed at point M in the network [15]. When voltage sag occurs in the network, the PQM will detect and record the disturbance depending upon its voltage threshold setting. The source of sag can appear at upstream or downstream locations of measurement point, M. Upstream side can be defined as the side that supplies the power into the monitoring point at steady state conditions, where the downstream side is the side that the power leaves from the monitoring point. Based on this concept, several methods have been reported to predict the location of occurred voltage sag in the system. An overview of the existing methods to locate voltage sag using a single measurement device are based on the use the disturbance power and energy, slope of system trajectory and resistance sign, real current component, distance relay, voltage magnitude, instantaneous voltage and current vectors, S-transform disturbance power, wavelet multi- resolution, dq-component and superimposed quantities and negative sequence.

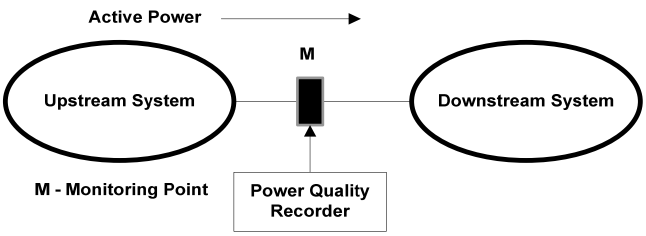

Fig.3. Concept of single monitor based method to locate voltage sag

Disturbance power and energy (DPE) based method

This method is based on the DP and DE indices in which the DP index is applied to calculate the difference between the delivered steady-state power during the occurrence of voltage sag, and the DE index is applied to calculated the integral of the disturbance power during the voltage sag, as follows [17]:

(1) $$DP(t) = P(t)_f - P(t)_{ss}$$

(2) $$DE(t) = \int_0^t DP(u)du$$

where and are the delivered instantaneous power during the fault and normal steady-state conditions, respectively.

The sign of the DE index indicates the location of the sag source such that if the sign is positive, the sag source is located downstream, otherwise, the sag source is located upstream. Moreover, if the sign of the initial peak of the DP coincides with the sign of the final DE, a high degree of confidence is expected. The accuracy of the DPE method depends on the confidence degree of both DP and DE indices, and the degree of confidence reduces if the signs of DE and DP do not match [19]. An alternative method based on the variation of reactive power in addition to disturbance power and energy calculation are considered in [35, 16]. In this method, a fault is considered downstream when the reactive power is negative and otherwise the fault is upstream. In other words, a positive deflection of reactive power during the disturbance ($Q/P > 0$) can specify a downstream fault, while an upstream fault is indicated by a negative deflection. However, when the monitor is placed at the faulty bus, this method is not able to accurately locate voltage sag.

In 2007, Kong et al. applied the instantaneous power theory, which can be further decomposed into instantaneous active and reactive powers based on Hilbert transform [36], to locate the source of voltage sags. Here, if the calculated instantaneous active and reactive powers are negative, then the voltage sag source is located downstream otherwise the voltage sag source is at upstream point [12]. The accuracy of this method is influenced by the inception angle of faults and fault impedance.

Slope of system trajectory (SST) and resistance sign (RS) based methods

The SST method is based on the relation between the voltage and current during a fault [14]. First, voltage and current are plotted during the occurrence of disturbance, and then the least-squares method is applied to fit the points with a linear line. The sign of the line slope indicates the direction of the disturbance fault. If the fault occurs in downstream side,

(3) $$|V\cos\theta| = -RI + E_1\cos\theta_1$$

and for upstream faults,

(4) $$|V\cos\theta| = +RI + E_1\cos\theta_1$$

where *V* and *I* are the measured RMS voltage and current by the PQ monitor, E_1 is the voltage source , R is the real part of Z_1 which is impedance between source and monitor, θ is the phase difference between V and I and θ_1 is the phase difference between E_1 and I, respectively [13]. The SST method uses a line fitting technique to plot the gradient in which the results are based on the accuracy of this line-fitting. The method has not been extensively tested for asymmetrical faults and therefore, the results may not be accurate in these situations.

The same researchers in [13], proposed a method for locating voltage sag using the sign of resistance [19]. In this method, the first step is to extract and analyze the fundamental-frequency positive-sequence voltage and current. Using equation (5), if the real value sign of impedance is positive, it indicates an upstream fault, while a negative sign indicates a downstream event.

(5) $$Z_e = \frac{\Delta V}{\Delta I} = \frac{V_f - V_{ss}}{I_f - I_{ss}}$$

where (V_{ss}, I_{ss}) and (V_f, I_f) are pairs of pre-sag and during-sag fundamental-frequency positive sequence voltage and current, respectively. This method is less reliable due to the assumption of linear loads. However, in a practical system there are always non-linear loads such as variable frequency drives and induction motors. For nonlinear loads, the method has to be improved to take into account transient characteristics of the load.

Real Current Component (RCC) based Method

The RCC method is based on the directional relay concept which uses the power factor angle to locate the disturbing source [7]. In this method, the current magnitude and the phase angle of voltage and current is measured at the point of measurement, and then the current magnitude is multiplied by the cosine of the power factor angle. If the obtained value is positive at the beginning of the sag, then the fault is located downstream as,

$$I\cos\theta > 0 \quad (6)$$

Otherwise it is upstream as [7],

$$I\cos\theta < 0 \quad (7)$$

The above mentioned method is further developed using the Current Component Index (CCI) algorithm [6]. The CCI calculated using,

$$\frac{I\cos\Phi_f}{I\cos\Phi_{bf}} > 1 \rightarrow \begin{cases} CCI_f > CCI_{bf} \rightarrow Upstream \\ CCI_f < CCI_{bf} \rightarrow Downstream \end{cases} \quad (8)$$

where $I\cos\Phi_{bf} \equiv CCI_{bf}$ and $I\cos\Phi_f \equiv CCI_f$ is the current component index before and during fault respectively. Here, if the CCI magnitude during sag is higher than the pre-sag CCI magnitude, the location of the voltage sag is upstream, otherwise it is downstream.

Distance Relay (DR) based Method

DR method locates the source of voltage sag by using the computed seen impedance from the measured voltage and current phasors at the monitoring location as [17].

$$Z_{seen} = \frac{V}{I} = Z_1 + \Delta Z \quad (9)$$

where Z_1 is the positive-sequence impedance up to the disturbance location, ΔZ is a function of fault impedance and its load characteristics, V and I are the measured voltage and current phasors, respectively. If the obtained impedance magnitude during a fault is greater than the pre-fault impedance and the impedance angle during a fault is greater than zero, then the sag source is located downstream, otherwise the sag source is located upstream [17]. However, if a fault occurs between the source and distance relay, there will be no change in impedance magnitude and resultantly this method cannot identify the correct location of voltage sag. In addition, in the absence of distance relays, the method cannot be applied.

Voltage Magnitude (VM) based Method

Another approach for detecting the sag source location is by comparing the measured pre and post-fault voltages sag magnitude at both sides of a transformer [34]. Assuming V_1 and V_2 are the voltages sag magnitude at both sides of the transformer as,

$$V_1 = \frac{V_{1-sag}}{V_{1-prefault}} \quad (10)$$

and

$$V_2 = \frac{V_{2-sag}}{V_{2-prefault}} \quad (11)$$

where V_{1-sag} and V_{2-sag} are the magnitudes of voltage sag, $V_{1-prefault}$ and $V_{2-prefault}$ are the pre-fault voltage magnitudes. The equations for the voltage drop at each side of the transformer are derived as,

$$\Delta V_1 = Z_1 I_{fault} \quad (12)$$

and

$$\Delta V_2 = (Z_1 + Z_T) I_{fault} \quad (13)$$

where Z_T is the transformer impedance and I_{fault} is the fault current. In this method, to locate the sag source, the values of voltage drop are compared. The voltage drop will be higher at the side where the fault occurs. Thus, if $\Delta V_1 > \Delta V_2 (V_2 > V_1)$, it is an upstream fault or else, the fault is downstream [34].

Instantaneous Voltage and Current Vectors (IVCV) based Method

The IVCV uses the instantaneous voltage and current vectors. This method is considered as generalized versions of other methods like the known current-based method, which are based either on voltage–current characteristic or on an active current component, using the vector-space approach. For the generalization of voltage-current method, instead of using voltage and current phasor length and phase angle, the norm of the active-current vector is used [35]. The results show that this method is suitable for locating source of symmetrical and asymmetrical voltage sags [36].

S - Transform Disturbance Power (STDP) based Method

This method is based on the S-transform [37,38], and an index named as the STDP is developed [39]. The S-transform produces a time–frequency representation of a time series signal by uniquely combining a frequency-dependent resolution that simultaneously localizes the real and imaginary spectra. The S-transform equation is described by,

$$s(\tau, f) = \frac{|f|}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} x(t) e^{\frac{-(t-\tau)^2 f^2}{2}} e^{-i2\pi ft} dt \quad (14)$$

The S-transform distinguishes itself from the many time–frequency representations by combining progressive resolution with absolutely referenced phase information. Similar criteria for determining the origin of voltage sags used by the DP method is adopted by the STDP method. The STDP is then expressed as:

$$STDP = [(V_{STR} * I_{STR}) + (V_{STS} * I_{STS}) + (V_{STT} * I_{STT})] \quad (15)$$

$$V_{STR} = \frac{|f|}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} v_R(t) e^{\frac{-(t-\tau)^2}{2}} e^{-i2\pi ft} dt \ ,$$

$$I_{STR} = \frac{|f|}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} i_R(t) e^{\frac{-(t-\tau)^2}{2}} e^{-i2\pi ft} dt$$

where V_{STR} and I_{STR} are the S-matrix of size m*n for voltage and current signal v_R and i_R respectively. Also, ST voltage and current for phases of S and T (values of V_{STS}, I_{STS}, V_{STT} and I_{STT}) can be obtained by using similar procedure independently. If the value of STDP>0, then the sag source is said to be a downstream, otherwise if the STDP<0, then the sag source is said to be upstream.

Wavelet Multi- resolution (WMR) based Method

This method is based on the concept of multi- resolution [40] and it considers the energy flow in monitoring points during sag time. In this method, the three-phase instantaneous power changes during sag is first calculated, and then the energy change of power signal is calculated using the wavelet multi resolution analysis to determine the sag source location. According to Parseval theorem, the original signal energy can be obtained by summing the sub-band energy in the scales which can be calculated by high-frequency, low-frequency coefficients in each decomposition scale as follows [41,42].

$$\int |f(t)|^2 dt = \sum |C_j(t)|^2 + \sum_j \sum_k |d_j(k)|^2 \qquad (16)$$

If E and E_0 are the signal energy during sag and steady state, respectively, then $\Delta E = E - E_0$, is the change between E and E_0. When E decreases in the initial time of sag and ΔE is negative during sag, the sag source is behind the monitoring point, and vice versa it is before the monitoring point [20].

DQ Component (DQC) based Method

This method is based on impedance measurement in the dqo coordinate system. Initially, the three-phase voltage and current measured at the monitoring point are transformed using the orthogonal Park's transformation [43]. Then, according to the change in the waveforms, the voltage sag source location is determined [44]. Assuming the voltage and current vectors of a three-phase system as *u(t)* and *i(t),* respectively, the instantaneous impedance is computed in the dqo coordinate system and is expressed as:

$$Z(t) = \frac{\|u(t)\|^2}{p(t)} = \frac{u_d^2(t) + u_q^2(t) + u_0^2}{u_d(t)i_d(t) + u_q(t)i_q(t) + u_0(t)i_0(t)} \qquad (17)$$

Accordingly, if this impedance is decreased, the sag source is on the downstream side, else it is on the upstream.

Superimposed Quantities and Negative Sequence (SQNS) based Method

Voltage sag location identification based on the negative sequence and superimposed quantities concept is proposed in [27]. The superimposed quantities concept uses the superposition principle to determine the voltages and currents of the faulted circuit [45]. The voltage and current during fault are,

$$V = V_{pre-fault} + \Delta V, I = I_{pre-fault} + \Delta I \qquad (18)$$

where $V_{pre-fault}$ and $I_{pre-fault}$ are pre-fault voltage and current, respectively.

The ΔV and ΔI are the differences of voltage and current during a fault. This concept is also used in directional relays. The algorithm to find the direction in directional relays is calculated from the incremental impedance. In this method, if a fault is in the forward direction, the impedance will give a negative sign and magnitude, and the source impedance is behind the monitoring point .

However, if a fault is in the backward direction, the impedance will give positive sign and magnitude is the summation of remote source and line impedance.

This method can identify faults inside the utility area or customer area where the impedance has either positive or negative sign, respectively [27].

Other single monitor based methods

A method based on the analysis of voltage sag magnitude and phase-angle jump has been developed to determine whether the voltage sag origin is upstream or downstream from the single measuring point [5]. 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 voltage sag magnitude characteristic when there are transmission networks at both sides of the monitoring point. So, an alternative simple approach to locate the sag source based on voltages sag magnitude at both sides of the transformer that interconnects two grids is proposed in [34].

Two approaches for voltage sag source location based on a statistical model of the waveforms using multi way principal component analysis (MPCA) [9,10] have been developed as a dimension reduction tool and simple features extracted from the RMS waveforms [4]. MPCA has a pre-processing step known as unfolding which is required to convert a three dimensional data matrix to a large two dimensional matrix.

Limitations of single monitor based voltage sag source identification methods

Various voltage sag source location methods which are based on using single monitors have been discussed in the previous section 2. A review of the single monitor based voltage sag source location methods showed that the methods have some limitations described as follows:

i. The method only indicates the relative location of sag source from the monitoring point and not the exact location of sag.

ii. The method is suitable only for identifying sag source in radial distribution networks but not for transmission networks in which the accuracy of sag source identification is very poor.

iii. Most of the single monitor based methods can accurately identify source of voltage sags caused by symmetrical faults and not for unsymmetrical faults.

Considering the limitations of the single monitor based voltage sag source identification methods, a multi monitor based method is considered in this paper.

Multi Monitor Based Voltage Sag Source Identification Methods

All the methods discussed previously indicate that the sag source is located either in downstream or upstream direction from the monitoring point by using a single monitor. However, with the existing transmission network, many PQ monitors are required to be installed at every common connection point to figure out an exact sag source location. Thus, single monitor method cannot be applied for transmission networks. In the multi PQ monitor method, more than one PQ monitor are installed in the network to locate the voltage sag source. The data collected from each PQ monitor in a transmission network will be stored inside the database. After processing data from the multi PQ monitor, one can determine the sag source location. The multi PQM methods are based on the direction and event cause, the topological locating algorithm, branch current deviation, coefficient matrix and multivariable regression.

Direction and Event Cause (DEC) based Method

The DEC method identifies the direction of voltage sag source by considering the cause of event [25]. If a monitor is installed in a power system, the monitor can determine whether the event is coming from up or down area. Down area is defined as the area to which power flows from the monitoring point while up area is the other area which is not included in down area. After classifying three main causes of voltage sag, namely line fault, starting of an induction motor and the transformer saturation, the ratio of the current magnitude, the ratio of active power deviation and the current ratio with an adapted threshold are derived to determine the relative sag source location [25].

(19)
$$\frac{I_{sag}^{1}}{I_{ss}^{1}} \geq Thr_{LF} \rightarrow Downarea$$
$$\frac{I_{sag}^{1}}{I_{ss}^{1}} \leq Thr_{LF} \rightarrow Uparea$$

(20)
$$\frac{P_{post}-P_{pre}}{P_{pre}} \geq Thr_{LF} \rightarrow Downarea$$
$$\frac{P_{post}-P_{pro}}{P_{pro}} \leq Thr_{LF} \rightarrow Uparea$$

(21)
$$\frac{\Delta I_2}{\sum_{h=2}^{7}\Delta I_h} \geq Thr_{H} \rightarrow TranformerSaturate$$
$$\frac{\Delta I_2}{\sum_{h=2}^{7}\Delta I_h} \leq Thr_{H} \rightarrow TranformerSaturate$$

where $I_{ss}^1, I_{sag}^1 and\ Thr_{LF}$ are fundamental frequency component of current before, during line fault and threshold of the ratio I_{sag}^1 / I_{ss}^1, respectively. Also, P_{pre}, P_{post} and Thr_{LF} are the steady state active power-before, after induction motor starting and threshold of the ratio $(P_{post}-P_{pre})/P_{pre}$, respectively. The final index, $h, \Delta I_h and\ Thr_H$ are order of harmonic contents, change of harmonic current whose order is *h* and threshold of the ratio $\Delta I_2 / \sum_{h=2}^{7} I_n$, respectively. In [32], this method is tested on a practical Korean power system and on IEEE 13bus system [26]. This method is tested only on radial networks in which the number of PQ monitors used is considered many.

Topological Locating Algorithm (TLA) based Method

The TLA method is based on topological location of PQ event source [23]. The suggested algorithm used up/down area concept, the graph theory, monitor location and relative location of the PQ event to establish the coverage matrix and direction matrix. Then, multiplication of coverage matrix and direction matrix gives the candidate matrix.

(22)
$$M_c = \frac{1}{M} M_{co}.M_D$$

Where M_C, M_{co} and Md are the candidate matrix (L×1), coverage matrix (L×M) and direction matrix (M×1) respectively. Also, M and L are the total number of monitor and total number of component.

The suspicious area for the event source has been determined from the candidate matrix. Also, component locating, which utilizes event cause and related equipment, has reduced the suspicious area. In this method, the fault distance is calculated to identify the event location accurately [23]. The results in [23] and [24] show that this method is suitable for identifying voltage sag source in radial power networks and the number of PQ monitors increase with network buses.

Branch Current Deviation (BCD) based Method

The branch current deviation (BCD) method identifies the voltage sag source location using limited available voltage measurement devices installed in a large transmission network [21]. The first step in the BCD method is to determine the location of PQM to be installed so that the voltage sag source location can be tracked by prioritizing the calculated branch current deviations before and after a disturbance at each meter location. The location for PQM installation can be determined by Equation (23). This equation represents the sensitivity of the system fault current change corresponding to the faulted voltage at bus k. By arranging the values of (23) for all buses in descending order, the faulted bus with a maximum value is given the top priority for the placement of PQM.

(23)
$$\frac{\partial f}{\partial V_f^k} = \sum_{\substack{i=1\\ i\neq j}}^{m}\sum_{\substack{j=1\\ j\neq i}}^{m} \frac{(z_{ik}-z_{jk})/(z_{kk}+z_f^k)}{z_{b,ij}}, k=1,2,...,m$$

where, Z_{ik} is the transfer impedance between bus i and bus k, Z_{bus} is the network impedance matrix, Z_{jk} is the transfer impedance between bus j and bus k, Z_{kk} is the Thevenin impedance at bus k, Z_f^k is the fault impedance, $Z_{b,ij}$ is the branch impedance between bus i and bus j, m is the number of buses in a power system and n is the number of branches in a power system. The change in current is then measured from time to time by using,

(24)
$$BCD_i = \frac{I_f - I_s}{I_s}$$

where I_s and I_f are current before and during fault occurrence, respectively.

When a fault occurs, the branch currents that are connected to the faulted bus will significantly increase in value and the large deviations in currents are then detected. The location of voltage sag source can be determined by prioritizing the calculated branch current deviations before and after a disturbance at each meter location. The method has been improved by using the voltage disturbance energy index and phase angle variation index [22]. It is shown that the improved method can accurately track the path or a confined area where the PQ monitors are most likely located. It has been verified that the method is suitable for radial and meshed power networks.

Coefficient Matrix (CM) based Method

The CM method uses the system coefficient matrix and voltage measurements matrix to estimate all the unmonitored bus voltages [32,46]. The results show that the study is tested on steady state condition. In this method, the bus voltage magnitudes from load flow represent the steady state bus voltage and the bus voltages after load switching represent the voltage sag. A voltage deviation index is used to identify the voltage sag source bus based on the largest voltage deviation from its steady state voltage.

(25)
$$V\% = \frac{(V_{ss}-V_{sag})}{V_{ss}} \times 100$$

(26) $$V_{sag,k} = \max\left|V_{\%1}, V_{\%2}, V_{\%3}, ...V_{\%n}\right|$$

where V_{ss} is the steady state bus voltage and V_{sag} is the minimum voltage sag value.

The voltage sag source bus can be referred to as the bus with maximum of $V_{\%}$ of all buses as given by (25). It is suggested that if the number, placement of PQ monitors and the system coefficient matrix are definite, the method can estimate the unmonitored bus voltages. This method has several limitations, in which, the method did not consider voltage sag caused by LG, LLG, LLL faults and induction motor starting. In addition, the number and placement of PQ monitors have to be first specified and the voltage deviation index is not able to identify location of voltage sag. So, the limitations of the existing multiple monitor based voltage sag source identification methods are described as follows:

i. Most of the methods are developed for identifying source of voltage sags in transmission networks and not for distribution networks.
ii. The sag source location is in terms of areas or zones and not a precise location such as the bus location.
iii. The method requires detailed system information such as impedance and other system data.
iv. The accuracy of the sag source location is dependent on the number of installed monitors.

overcome the limitations of the existing the multiple monitor based voltage sag source identification methods, a new sag source identification method is proposed which can be applied for both distribution and transmission networks and also locating exact sag source location.

Multivariable Regression (MVR) based Method

A relatively new sag source location method has been developed based on the MVR model and voltage deviation (*VD*) and standard deviation (*SD*) indices [28]. The method uses the recorded data available in a substation or via simulation of test system to obtain relationship between all of the buses in a system. The method then determines the best number and placement of PQ monitors based on the correlation coefficient, the CP statistic and the Rp indices [31]. After assessment of monitor placement, if a fault occurs in each bus, the MVR model estimates all the unmonitored bus voltages by using the *VD* and *SD* indices, and hence identifies the voltage sag source exact location [29,30].

$$B = (X'X)^{-1}X'Y \quad , \widetilde{V} = B_0 + \sum_{j=1}^{k} B_j V_{ij}, i = 1,...,n$$

$$E = V - \widetilde{V}$$

(27) $$VD = \Delta V = (V_{ss} - V_{sag})/V_{sag}$$

(28) $$SD = \sqrt{\frac{\sum_{i=1}^{n}(V_i - \overline{V})^2}{n-1}}$$

where B, X, Y, E,V and $\widetilde{V}$ are the regression coefficient, independent variables, dependent variable, error, the observed and estimated voltage respectively.

The MVR method is found to be suitable for locating voltage sag source in both distribution and transmission networks.

Conclusion

This paper presents a review of voltage sag source location methods in power systems. The methods are categorized as single and multi-monitor methods for identifying the voltage sag source location. A description on all the single and multi monitor methods are presented. A comparison is then made on the single and multi-monitor methods so as to evaluate the advantages and disadvantages of the methods. The results show that the single monitor methods are not suitable for identifying voltage sag location in large sized radial and transmission networks due to the increased number PQ monitors. The MVR method is considered to be superior to the other multi-monitor methods because it can identify exact location of voltage sag source with suitable number of PQMs.

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