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Probabilistic estimation of voltage sags using erroneous measurement information

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ABSTRACT

Estimating voltage sag performance is important for distribution network operators who are keen to reduce costly interruptions, plan network investment and reduce operational expenditure. This paper proposes a robust method to locate faults and estimate the magnitude of voltage sags using information from a limited set of arbitrarily accurate monitoring devices. The developed method uses statistical analysis and impedance based fault location equations to find the most likely fault location and sag magnitude at non-monitored busbars. The method robustly handles measurement errors, and helps to eliminate some of the sensitivity present in existing impedance based fault location algorithms. The method is also shown to be effective at eliminating multiple fault location solutions caused by multiple overlapping impedance paths by synthesizing information from all monitors installed in a network. The method is validated and shown to be effective on a generic section of the UK's distribution network.

1. Introduction

Voltage sags represent the most significant component of power quality (PQ) problems in distribution networks [1] both in terms of gross numbers of events and the high associated costs to end users [2–4]. An EU study estimated that voltage sags and short interruptions contributed to an annual cost of €86bn [5] and in 2008/2009, voltage sags (and faults) caused an average of 0.73 interruptions per customer and contributed to an average of 76 customer minutes lost (CMLs) over the course of a one year period. These interruptions cause different impacts to different customers. For example, a momentary interruption for a large customer is estimated to cost £216k, whereas a 4 h interruption on a residential customer is estimated to cost only £4.78 [6].

Voltage sag performance estimation concerns both localizing the source of a voltage sag (most often a fault) and estimating the voltage sag magnitude in order to subsequently assess the impact on customers. DNOs are placing increasing emphasis on power quality monitoring to obtain greater visibility of power quality events, such as voltage sags, [7] beyond monitoring a limited group of large important customers. Through network wide monitoring, the level of power quality within a network can be quantified in terms of both events and costs and important current problems can be identified. Monitoring allows a DNO to perform reliability benchmarking, monitor power quality contracts and plan predictive maintenance [8]. Significant efforts in surveying power quality are also evidenced in the Benchmarking Report on the Quality of Electricity Supply of the Council of European Energy Regulators (CEER) [9]. A network operator's monitoring investment decision is also driven by other factors such as new initiatives like the Smart Grid, changes in the regulatory environment, concerns about customer retention and new competition within the utility sector. The Electric Power Research Institute (EPRI) lists forecasting and short circuit analysis as the two main reasons for monitoring alongside permanent power quality monitoring [8] in future power networks.

Finding the source of a voltage sag is closely related to the task of fault localization. This topic has been covered in existing research, recently in [10–14]. Fault localization in modern distribution networks is complicated in practice because information is only available from a limited number of variably accurate monitors. One of the most notable works which deals with measurement error is [13]. In [13] the authors developed a technique capable of locating faults using measurements taken from any two locations in the power network by utilizing an optimal estimation procedure based on the method of least squares. However, [13] does not consider how information from multiple monitoring devices could be combined to yield a distribution (rather than a point estimate) for the most likely fault location and does not consider situations where the number of monitors is fewer than required to obtain a single unique fault location estimate.

Estimating a fault-induced voltage sag's magnitude can be accomplished after the fault location has been identified. This two step procedure was implemented in [14]. Like [13], the approach

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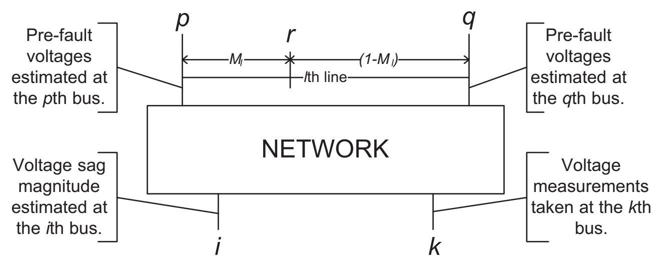

Fig. 1. A representation of the estimated and monitored buses required to perform fault location and voltage sag profile estimation.

taken in [14] yields a single estimate for an output parameter, in this case voltage sag magnitude. An alternative to voltage magnitude estimation is to simulate a short circuit fault at the fault location identified [15,16].

The method developed in this paper adds to the research developed in [11,13] and has several advantages over existing techniques. It firstly allows power system operators to formulate a robust statistical estimate for both the fault location and voltage sag profile whilst taking into account the errors of monitoring devices within the network. Secondly, the method is independent of the accuracy of the monitoring device, so operators can utilize measurements from any monitoring device available in their network, including relays, power quality meters, disturbance recorders, phasor measurement devices (PMUs) or revenue meters. Lastly, the method synthesizes a fault location using all available information from an arbitrary positive number of devices. By using information from all available monitors, both the fault location and voltage profile estimate are more accurate than the single or double ended approaches presented in [11]. It also overcomes some issues caused by multiple impedance paths by reducing the number of fault locations to those that are the most feasible.

2. Impedance based fault localization and sag magnitude estimation

Impedance based fault location algorithms [11] utilize the impedance of the network and the observed voltage drop to arrive at an estimated fault location. Impedance based methods may be transient, or steady state, and typically use measurements from monitors at one or both ends of a line. This research advances the steady state single monitor impedance based algorithms developed in [11]. The algorithm presented in this paper extends the approach described in [11], enabling one, two or any number measurements taken anywhere in a network to be synthesized into a single fault location estimate.

The equations developed in [11] calculate the fault location using measured data from one or two monitoring devices. The equations require pre-fault voltage measurements at the monitored bus and at the ends of the faulted line, as well as during-fault voltage measurements at the monitored busbar. The equations are also independent of fault impedance, if the fault impedance is assumed to be entirely resistive [11].

2.1. Fault localization equations

The aim of the fault localization equations can be illustrated through Fig. 1. The objective of the equations is to locate a fault at position r along the lth line between buses p and q and then subsequently perform voltage sag profile estimation at a non-monitored bus i with measurements taken at the kth busbar.

Assuming the network's impedance parameters can be derived accurately, the accuracy of the fault location equations will depend upon the values of the measured pre-fault voltages at the kth busbar and the estimated pre-fault voltage at the ends of the lth line. The accuracy of the measurement at the kth busbar is dependent on the installed monitor's accuracy, and this may vary depending on the device that is installed. Unless there happens to be a monitor at either the pth or the qth busbar, these voltages must be estimated through distribution system state estimation (DSSE) [17]. The accuracy of the DSSE voltage estimates will directly depend on the accuracy of the pseudo-measurements used to estimate the load throughout the network.

2.1.1. Single line to ground (SLG) faults

The fault location equation for a SLG fault is shown in Eq. (1).

$$M_l = \frac{B_k^{(2)} - G_k B_k^{(0)}}{G_k C_k^{(0)} - C_k^{(2)}} \tag{1}$$

where $B_k^{(i)}$ and $C_k^{(i)}$ are network dependent parameters and are derived from elements in the $\boldsymbol{Z_{bus}}$ impedance matrix, G_k is the ratio of the negative sequence voltage to the zero sequence voltage $(E_k^{(2)}/E_k^{(0)})$ as measured at bus k and M_l is the distance in per unit along the faulted line l [11]. Note that the derivation of $B_k^{(i)}$ and $C_k^{(i)}$ are not shown here for brevity, but this is covered in detail (using the same notation) in [11].

For SLG faults, M_l can be solved independently of fault impedance and pre-fault voltage estimates. The accuracy of M_l is dependent only on the accuracy of during-fault measurements at the monitored bus k ($E_k^{(2)}$ and$E_k^{(0)}$).

Similar single monitor fault location equations can be derived for line to line, double line to ground, and three phase symmetrical faults. Full sets of equations can be found in [11].

2.1.2. Calculating voltage sag depth

The calculated values of the fault location M_l can be used to determine the during-fault voltage drops at the ith unmonitored busbar. The during-fault voltage drops at bus i can be considered as functions of the fault location and the measured voltage at bus k only. These during-fault voltage drops in the sequence domain are expressed in Eqs. (2)–(4):

$$E_i^{(0)(k)} = \frac{Z_{ir}^{(0)} E_k^{(0)}}{Z_{kr}^{(0)}} = E_k^{(0)} \frac{B_i^{(2)} + C_i^{(2)} M_l}{B_k^{(2)} + C_k^{(2)} M_l} \tag{2}$$

$$\begin{aligned} E_i^{(1)(k)} - E_i^{(1)0} &= -\frac{Z_{ir}^{(2)}(E_k^{(1)0} - E_k^{(1)})}{Z_{kr}^{(1)}} \\ &= (E_k^{(1)0} - E_k^{(1)}) \frac{B_i^{(1)} + C_i^{(1)} M_l}{B_k^{(1)} + C_k^{(1)} M_l} \end{aligned} \tag{3}$$

$$E_i^{(2)(k)} = \frac{Z_{ir}^{(2)} E_k^{(2)}}{Z_{kr}^{(2)}} = E_k^{(2)} \frac{B_i^{(2)} + C_i^{(2)} M_l}{B_k^{(2)} + C_k^{(2)} M_l} \tag{4}$$

Note that the superscript (k) denotes that $E_i^{(s)(k)}$ the voltage at bus i is calculated from measurements taken at the kth monitor (where s denotes the sequence). $E_i^{(s)0}$ is the pre-fault voltage as measured at the kth (monitored) busbar. Eqs. (2)–(4) are independent of pre-fault voltage estimates and fault impedance. However, M_l may be dependent on pre-fault voltage estimates and fault impedance, subject to the fault type.