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Non-linear representation of voltage sag profiles for fault location in distribution networks

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ABSTRACT

Fault location for distribution networks with multiple laterals would requires additional information such as from fault indicators and protective devices. As SCADA systems to provide such information are limited in 11 kV or lower voltage distribution networks, effective fault location method that only use information from a measurement at primary substation is needed. This paper presents the application of calculated non-linear voltage sag profiles and voltage sag measurement at primary substation to locate a fault in distribution networks. The proposed method firstly identifies the faulted section. From the indentified section, fault distance is calculated. The method has been tested under different fault scenarios that include various fault resistance, loading variation and data measurement errors. The results indicate the possibility of using this method to support automatic fault management system.

1. Introduction

The deregulation and privatization of power industry demand power utilities to deliver uninterrupted and high quality of power supply. Power supply is however often interrupted by faults that lead to Customer Minutes Lost (CML). According to a report by Office of Gas and Electricity Markets (OFGEM) in UK [1], over 75% of CML were caused by faults in distribution networks. This occurs since most of distribution networks in UK operate in radial configuration and only protected by a circuit-breaker at the primary substation. Moreover, most of the networks, in particular 11 kV or lower voltage systems are not supported by SCADA system to provide sufficient information for effective faults location. Hence, a fault location method that relies on minimum information is needed.

Fault location methods can be classified into travelling-wave technique, knowledge-based technique and impedance-based technique. Different requirements are needed in order to use these techniques effectively. Travelling-wave technique requires accurate monitoring equipment at one end or two end of a line to measure travelling time of voltage or current reflection waveform from the fault location to the measurement point to calculate fault distance [2,3]. The technique however has difficulty to locate a fault if multiple laterals exist between the fault location and the measurement points due to multiple reflections. Impedance-based technique uses voltage/current measured at a monitored node to locate a fault using mathematical equations [4–8]. Since fault at different locations could produce the same voltage/current value at the monitored node, multiple fault location usually produced in a network with multiple laterals. Additional information such as from fault indicators or protective devices was commonly used to find the most likely fault location [7,8]. Knowledge-based technique uses learning algorithm such as expert system, artificial neural network and fuzzy logic to locate a fault [9,10]. The main requirement to use the technique is to provide suitable and sufficient data for training or for developing logical set of rules in the algorithm.

Recently, data matching technique also has been proposed for fault location. The technique works by matching the measurement data with a list of data from fault calculation. The match will lead to the possible fault location. Different types of data were reported to be used. In [11], a reactance value from a distance relay was matched with simulated one to locate a fault. Voltage sag measurement also was reported to be used [12–15]. In [12], voltage sag waveform from measurement is matched with the simulated one using genetic algorithm. In [13], voltage sag measured from different locations is matched with the simulated vulnerable voltage sag's contours to locate a fault in a transmission line system. Data matching technique using voltage sag measurement was also reported in our previous papers [14,15]. In [14], voltage sag pattern characteristic was used to locate a faulted section in distribution networks. Latter, the method was improved by determining the fault distance [15]. However, it was found that the selection

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condition of a faulted section that based on the assumption of linear voltage sag variation between two adjacent nodes could lead to wrong selection of a faulted section. This is due to the fact that voltage sag variation could be also a non-linear type as described in [16].

The main idea of this paper is to propose a fault location method by using only a voltage sag data, measured at the primary substation. Different from other methods, a non-linear voltage sag profile is used in the proposed method to locate a fault in distribution network. Furthermore, the method also addressed the problem of obtaining multiple fault locations due to equal electrical equivalent impedance at different locations through ranking reasoning. The proposed method will rank the possible faulted locations according to the most likely location. For a distribution network that does not have fault indicators, historical fault events, or protection equipment to prune down the most likely location, the proposed method can be an alternative method. The method has been tested using a non-homogenous distribution network with multiphase laterals. The common accuracy tests including fault resistance, different fault locations, loading variation and measurement error as in other methods [4–8] have been considered in evaluating the performance of the proposed method. Besides these common tests, the method also has been evaluated for a network that connected with distributed generation.

2. Basic idea of the proposed method

2.1. Non-linear voltage sag profile formulation

For any type of fault, the voltage sag profile of a line section (as seen at the monitored node) can be presented in term of voltage phasor as a function of fault distance:

$$V_{1,i}(d) = V_{1,i}(d)\angle\phi_{1,i}(d) \tag{1}$$

where d is the fault distance from node i, $V_{1,i}(d)$ and $\phi_{1,i}(d)$ are the voltage magnitude and phase angle respectively as a function of fault distance for section i (as seen at monitored node 1). Section i can be any line section in a network. Based on the non-linearity variation of voltage magnitude/phase angle over fault distance [13], these functions are assumed in the form of a quadratic equation:

$$V_{1,i}(d) = a_0 + a_1 d + a_2 d^2 \tag{2}$$

$$\phi_{1,i}(d) = b_0 + b_1 d + b_2 d^2 \tag{3}$$

where a_0, a_1, a_2 and b_0, b_1, b_2 are coefficients of the voltage magnitude and phase angle profile respectively.

The voltage sag profiles of a line section can be established by using a set of voltage sags data from fault simulation. To describe the generating process of these data, a line section i with the length of l_{SR} in Fig. 1 is considered.

To produce voltage sag data, fault is simulated at location d_1, d_2, d_3, d_4 and d_5. For each fault location, the voltage sag at the monitored node is taken. Only the lowest voltage magnitude and its corresponding phase angle are considered to establish the voltage sag profiles. In this process, different value of fault resistance can also be considered.

Supposedly, the obtained voltage sags for fault at d_1, d_2, d_3, d_4 and d_5 are (V_1, ϕ_1), (V_2, ϕ_2), (V_3, ϕ_3), (V_4, ϕ_4) and (V_5, ϕ_5) respectively. By using curve fitting technique, these voltage sags are used to find the coefficients of voltage sag profiles in (2) and (3). The solution of the coefficients in (2) and (3) is given in (4) and (5) respectively:

$$\begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \sum_{k=1}^{n} 1 & \sum_{k=1}^{n} d_k & \sum_{k=1}^{n} d_k^2 \\ \sum_{k=1}^{n} d_k & \sum_{k=1}^{n} d_k^2 & \sum_{k=1}^{n} d_k^3 \\ \sum_{k=1}^{n} d_k^2 & \sum_{k=1}^{n} d_k^3 & \sum_{k=1}^{n} d_k^4 \end{bmatrix} \begin{bmatrix} \sum_{k=1}^{n} V_k \\ \sum_{k=1}^{n} d_k V_k \\ \sum_{k=1}^{n} d_k^2 V_k \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} \sum_{k=1}^{n} 1 & \sum_{k=1}^{n} d_k & \sum_{k=1}^{n} d_k^2 \\ \sum_{k=1}^{n} d_k & \sum_{k=1}^{n} d_k^2 & \sum_{k=1}^{n} d_k^3 \\ \sum_{k=1}^{n} d_k^2 & \sum_{k=1}^{n} d_k^3 & \sum_{k=1}^{n} d_k^4 \end{bmatrix} \begin{bmatrix} \sum_{k=1}^{n} \phi_k \\ \sum_{k=1}^{n} d_k \phi_k \\ \sum_{k=1}^{n} d_k^2 \phi_k \end{bmatrix} \tag{5}$$

Where $k = 1, \ldots, n$, n is the total number of points used to create the voltage sag profiles, where in this example $n = 5$. The voltage sag profiles are illustrated in Fig. 2.

2.2. Fault distance calculation

Once, the voltage sag profiles equations have been formulated, fault distance d can be calculated. From our study, we found that the voltage sag profiles can be classified either a non-linear or linear type. For a long line, generally, the voltage sag profile is non-linear and for a short line the profile is a linear.

2.2.1. Non-linear type

The solution of fault distance d can be derived either using (2) and (3). Both solution of fault distance from the sending node (node S) are given in (6) and (7).

$$d = \left(-a_1 \pm \sqrt{a_1^2 - 4a_2(a_0 - V_{1,F}^{(\text{meas})})}\right) \Big/ 2a_2 \tag{6}$$

$$d = \left(-b_1 \pm \sqrt{b_1^2 - 4b_2(b_0 - \phi_{1,F}^{(\text{meas})})}\right) \Big/ 2b_2 \tag{7}$$

where $(V_{1,F}^{(\text{meas})}, \phi_{1,F}^{(\text{meas})})$ are the voltage sags measured at the monitored node due to fault at point F. Since there are two possible answers for (6) and (7), the chosen distance, d should be the one that fulfilled this condition:

$$0.0 \leqslant d \leqslant l_{SR} \tag{8}$$

Ideally, both distance obtained from (6) and (7) should have the same value. However, due to error in the data measurement and/or in the calculation process, the values could be different. The different is presented as a mismatch, σ as illustrated in Fig. 2. Thus, to differentiate between these two type of distance, distances obtain

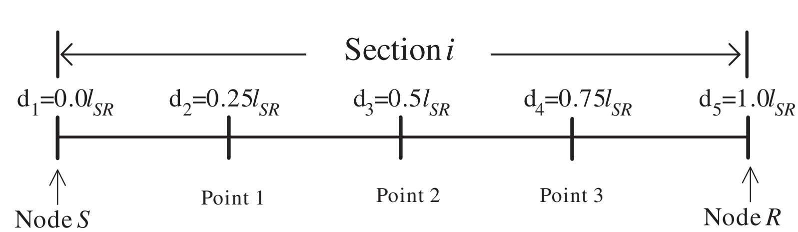

Fig. 1. Simulated fault location on a line section i.