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Fault location scheme for multi-terminal transmission lines using unsynchronized measurements

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ABSTRACT

In this paper, a simple alternative fault location algorithm for multi-terminal transmission lines using unsynchronized measurements is proposed. The developed data synchronization procedure is employed to identify the faulted leg before the fault location is calculated. The fault location algorithm is independent of the fault resistance and source impedance variations. The proposed faulted leg identification and location algorithm is extensively tested for all major fault types and different high fault resistances. The results show that the proposed multi-terminal fault location algorithm is fast, accurate and immune to power system transients.

Introduction

Fault location on overhead power transmission lines remains a subject of great interest and has been intensively studied over the years [1–15]. Fault locators, compared to protection relays, are expressly designed to pinpoint the exact location of faults on transmission lines to expedite the process of repair and power restoration. Multi-terminal power transmission systems such as teed-feeders (three-terminal lines) are economically and environmentally attractive. However, their protection design is challenging. Multi-terminal lines pose additional problems due to remote-end in-feeds from other connecting lines and the incident fault impedance [1–3].

Numerous schemes, which utilize the fundamental frequency of voltage and current phasors in fault detection and location, have been proposed in the literature. These algorithms can be broadly categorized as single-end measurement algorithms [4–7], two-end measurement algorithms [8–12] and multi-terminal fault location algorithms [1–3,10,15].

Two-ended measurement algorithms collect signals from both ends of a transmission line and offer superior performance compared to single-end algorithms due to their apparent insensitivity to source impedance, fault resistance and remote-end in-feed [9,11]. Additionally, signal measurements obtained for algorithm evaluation might come from time-synchronized data recorders with the aid of PMUs (Phasor Measurement Units) and GPS, or from asynchronous fault data recorders that do not share a common time Refs. [13,14].

Fault location algorithm for teed-feeders that carries out data synchronization by selecting a common reference and equating the voltages at the teed-point is proposed in [1]. Super-imposed component extraction and modal transformation is used for fault distance calculation. However, the authors assume synchronization mismatch of only a few data samples and the delivered algorithm wasn't tested for large or obtuse synchronization angles. The three-terminal protection scheme that uses Clarke transformation to decouple the inter-phase quantities and develop a fault detection index is proposed in [2]. The algorithm offers high-speed response but needs synchronized data measurement from PMUs and GPS.

A simple protection approach for multi-terminal transmission lines using synchronized voltage measurements is presented in [3]. The process can be applied to both transposed and untransposed lines but requires source impedance data. Also, fault distance calculation results indicate the dependence on the type of fault and the fault resistance involved. Generally, the percentage error in distance calculation increases with higher fault resistance.

Fault location algorithms for two-terminal systems using unsynchronized data measurements are presented in [9–11]. An iterative procedure is developed in [9] where the unknown synchronization angle can be found using the Newton–Raphson technique. A similar iterative procedure is presented in [11] where a modified secant method is used to obtain the value of the unknown

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synchronization angle. In [10], a non-iterative fault location and synchronization procedure is developed by using incremental positive sequence quantities for symmetrical faults, and simultaneously using positive and negative sequence quantities for unsymmetrical faults. All of the procedures presented in [9–11] result in multiple pairs of synchronization angle and fault distance values. The multiple solutions must be carefully treated with specially developed conditions to select the correct pair of angle and distance.

The PMU-based fault location schemes provide the advantage of being insusceptible to source impedance behind the relay, fault resistance involved and any remote in-feed from far end terminals [15]. However, the fact remains that GPS assisted PMUs are still not as widely adopted as they could be due to economic considerations. Therefore, data obtained from asynchronous fault recorders need to be corrected by using a complex synchronization operator ($e^{j\delta}$), where δ is the synchronization angle. Moreover, the application of two-end fault location algorithms on multi-terminal lines would require $2n$ fault data recorders, where n is the number of system terminals.

In this paper, a simple alternative offline-stage fault location algorithm is developed using unsynchronized measurements from one fault data recorder placed on each terminal bus as shown in Fig. 1. The multi-terminal system used in this paper is a four generator EHV system with five transmission lines that need to be protected. The basic principles of two and three-terminal line protection are extended to a multi-terminal system such as the one shown in Fig. 1 while devising the proposed algorithm. The distributed parameter line model is strictly used to represent high voltage transmission lines such that their behaviors resemble real-world system dynamics.

A non-iterative data synchronization procedure is proposed using known pre-fault measurements. Data synchronization can be carried out in a single-shot fashion without any constraints on the amount of synchronization required by the system. Different from the algorithms presented in [9–11], the proposed data synchronization procedure, presented in section 'Data synchronization and faulted leg identification procedure', provides the additional advantage of working as a faulted leg identification method as well. Therefore, there is no need for Clarke transformation based detection methods as described in [1–3]. Section 'Fault location scheme' presents the fault location formulation for the four-terminal system used in the paper. The formulation results in five distance functions, one for each line, which not only identify the faulted leg but also clearly point out the correct tee-point, are given in section 'Algorithm evaluation'.

Data synchronization and faulted leg identification procedure

The multi-terminal system of Fig. 1 is assumed to have a fault data recorder placed on each terminal bus. The synchronization procedure begins with the designation of one of the terminal buses as the common reference point. In this case, bus 4 is used as the common reference. The technique is designed such that data from other ends can be synchronized without any restriction on the amount of synchronization needed by the system before the fault location process can be initiated. Thus, the synchronization procedure works for both acute and obtuse synchronization angles. The various types of faults differ in the type of sequence component quantities present in voltages and currents during faulted operation. Of all the different fault types, the presence of positive sequence quantities is common for both symmetrical and non-symmetrical faults. Therefore, only positive sequence phasors are used for the data synchronization process and fault location scheme. It should also be noted that the synchronization procedure developed in this section is suitable for implementation on a digital micro-processor.

Data synchronization

Once the three-phase quantities are decoupled using symmetrical component transformation, the relationship between positive sequence voltage and current at location x from any bus can be expressed as [11]:

$$\frac{\partial V_1}{\partial x} = Z_1 I_1$$
$$\frac{\partial I_1}{\partial x} = Y_1 V_1 \tag{1}$$

where V_1 and I_1 are the positive sequence voltage and current, respectively, Z_1 is the positive sequence impedance and Y_1 is the positive sequence admittance.

The solution of the above two decoupled equations can be written in a two port network form by applying the boundary conditions as follows:

$$\begin{bmatrix} V_{s1} \\ I_{s1} \end{bmatrix} = \begin{bmatrix} \cosh(\gamma_1 l) & Z_{c1}\sinh(\gamma_1 l) \\ \sinh(\gamma_1 l)/Z_{c1} & \cosh(\gamma_1 l) \end{bmatrix} \begin{bmatrix} V_{R1} \\ I_{R1} \end{bmatrix} \tag{2}$$

where V_{S1} and I_{S1} are the positive sequence voltage and currents at the sending end, respectively, and V_{R1} and I_{R1} are the positive sequence voltage and current at the receiving end, respectively. γ_1 is the positive sequence propagation constant and l is the line length.

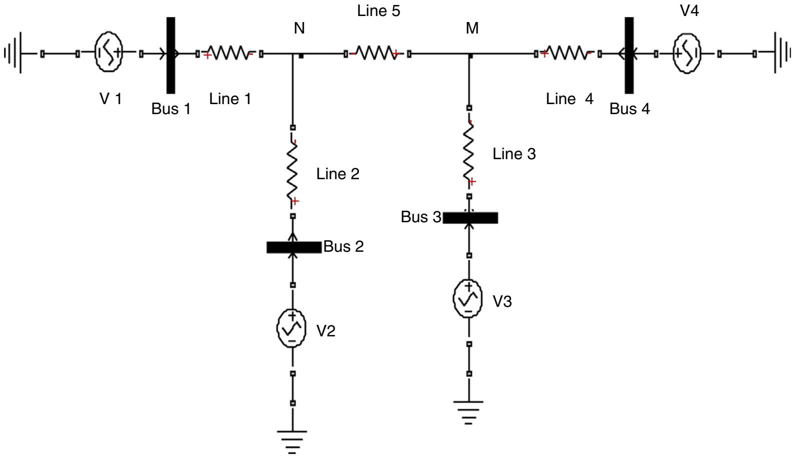

Fig. 1. Multi-terminal system.