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A state estimation approach for fault location in transmission lines considering data acquisition errors and non-synchronized records

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ABSTRACT

The performance of algorithms for fault location is directly related to the accuracy of its input data. Thus, factors such as errors in the line parameters, failures in synchronization of oscillographic records and errors in measurements of voltage and current can significantly influence the accuracy of algorithms that use bad data to indicate the faults location. This paper presents a methodology for fault location based on the theory of state estimation in order to determine the location of faults more accurately by considering realistic systematic errors that may be present in measurements of voltage and current. The methodology developed is innovative because, besides calculating the most likely fault distance obtained from measurement errors, the variance associated with the distance found is also determined, using the errors theory. The obtained results are relevant to show that the proposed estimation approach works even adopting realistic variances. Moreover, the fault location brings performance gains compared to a traditional algorithm, available in the literature.

Introduction

Fault location in transmission lines is a subject that has received attention from many researchers, since the formulation of exact algorithms is directly related to the reliability and continuity of supply of an electric power system. Accordingly, there are many papers with different proposals and several types of approaches in the literature. Some are based on fundamental phasors of voltage and current, formulated with data from a single terminal [1,2], from two terminals [3,4], and multi terminals [4,5]. Fault location algorithms based on the traveling waves' theory are also common in the literature [6,7] and have been outstanding because present results with high levels of accuracy. However, these methods also have some limitations, presenting poor performance in cases where electrical signals have low sampling rates, noise and describe faults that occur close to the zero crossing of the voltage waveform at the fault point [8]. In these situations, some algorithms based on fundamental phasors may present better performance and thus could replace or even work together with traveling wave based methods.

In the literature, approaches considering fault location without using impedance parameters of the line [9,10], or considering errors in measurements [11], and others that use data synchronized via GPS (Global Positioning System) [12,13] are also implemented to reduce, respectively, the inaccuracies arising from line data, measurement of voltage and current and synchronization of waveform records.

In this paper a methodology for fault location based on fundamental phasors and state estimation theory is presented. In this sense, some algorithms have been developed based on data from one terminal and two terminals. The algorithms based on data from one terminal [14,15] have limitations inherent to the use of data from a single end. The algorithm proposed in [16] uses data from two terminals and requires measurements from PMUs (Phasor Measurement Units), however, not all electric companies have this technology. In [17], the authors consider fault location estimation in a distributed parameters line model; however, do not model appropriately the variances of the measurements, assuming that they are very small and equally accurate to both correct and bad measurements. Furthermore, the authors use the synchronizations angle as a measurement, but a realistic variance is actually not available in real cases.

The state estimation methodology developed in this work is based on measurements data from both terminals of the line and does not require data measured by PMUs. The algorithm considers the presence of real systematic errors in the measurement of

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electrical quantities, which arise from digital recording and from calibration of instrument transformers (ITs). As will be shown, these errors affect the accuracy of a fault location process based on fundamental phasors of voltage and current. The systematic errors discussed in this work were established from the accuracy class of digital recorders, current transformers (CTs) and voltage transformers (VTs) which are used for protection purposes. Every instrument is associated with an accuracy class, which determine the maximum error in magnitude and angle that can be introduced by equipment in its measurements. These maximum errors were used as a base for mounting the proposed fault estimation scheme.

The fault location estimator was developed in two stages. At first, considering that the transmission line (TL) operates at steady state within the pre-fault condition, the most probable value of synchronization angle is obtained. This value is estimated taking into account the errors of digital recorders and instrument transformers in measurements of pre-fault voltages and currents. In the second stage, the most likely value of the fault distance is calculated from the data obtained by pre-fault estimator.

In addition to determining the most probable distance of fault, the methodology developed indicates the variance or error threshold associated with the estimated distance. So this is the main contribution of this work, the determination of probable fault location from errors in measurements and with a certain error margin (up or down). As in the literature there is no adequate modeling of systematic errors in measurements associated with state estimation for fault location, this paper also serves to fill this gap.

Tests were performed in transmission lines simulated in software ATP (Alternative Transients Program) [18] as well as in transmission lines from a Brazilian electric company. The results show that the fault location via state estimation implies performance gains compared to a traditional location algorithm that are based on the theory of voltage and current fundamental phasors.

In section 'Instrument transformers' of this paper an overview of instrument transformers is presented, as well as the influence of their systematic errors in transmission lines fault location. In section 'State estimation' a theory of state estimation is reviewed through a quick summary. In section 'Methodology for fault location from theory of state estimation' the proposed fault location estimator in transmission lines is detailed. In section 'Detection and identification of bad measurements and pseudo-measurements', the procedure for detecting and identifying possible bad measurements in the estimation process is illustrated and in section 'Results', the results obtained with the application of the methodology to real and simulated fault cases are analyzed.

Instrument transformers

Basic characteristics

Instrument transformers are electric equipments designed and manufactured specifically to supply electric instruments of measurement, control and protection. There are two types of: current transformer (CT) and voltage transformer (VT). These equipments are able to reduce high values of currents and voltages to values that may be supported by protection relays and other electronic equipments installed in the electric Power System.

Each transformer has a particular accuracy class (or simply, accuracy), which is established by the manufacturer and indicates the maximum possible error contained in magnitude and angle of voltages or currents measured by the equipment. Thus, one may state that a CT or a VT works within its accuracy class if the point specified by its phase displacement and its ratio error is within the parallelogram corresponding to its accuracy class.

It is noteworthy that fault location algorithms use current and voltage data from protection CTs and VTs. In this sense, voltage transformers, inductive or capacitive, have typical accuracy class of 1.2 while current transformers have typical accuracy classes of 5–10 [19–21].

International standards [19,20], as well as the Brazilian standard [21], generally do not establish error limits in angle for protection current transformers. Therefore, if a CT has accuracy class of 10, the standard establishes only that this equipment is within its accuracy class if it presents maximum error of 10% when the secondary current is in the range between the nominal value and twenty times that amount. This specification is sufficient if we consider that the sampled currents are only used for protective equipment sensitization. However, to use these currents in algorithms for fault location, information about the error in angle would be of great importance to determine more reliably the location of a fault.

Errors introduced by instrument transformers

Systematic errors are recurrent in all measurements performed by ITs. When there is only systematic error in a measurement, the difference between results obtained in different measurements and the true value is always the same. These errors, for example, may be entered in a measurement by calibration process, effects of the environment, failures in reading made by the observer [22]. In this work, only the influence of the calibration errors from accuracy class will be examined in the performance of an algorithm for fault location.

Influence of instrument transformers errors on transmission lines fault location

Simulations performed in 138 kV and 230 kV transmission lines, using ATP, showed that there are combinations of calibration errors from instrument transformers that can significantly influence the accuracy of fault location algorithms based on voltage and current fundamental phasors. For example, considering a phase-to-earth fault occurring at the beginning of a 138 kV transmission line, one obtains a location error of approximately 0.34%, if the voltage and current signals do not have systematic errors. However, if only the CTs errors of two terminals of the line are combined according to Fig. 1, the location error may reach up to about 5%.

As a second example, a 230 kV transmission line was considered with a phase-to-earth fault occurring at the end of the line. There was a location error of about 0.7% when the signals of voltage and current had no systematic errors. For CT and VT errors of only one terminal of the line combined according to Fig. 2, the maximum error (in absolute value) increased to approximately −5%.

The simulation results suggest that the systematic errors arising from instrument transformers calibration may harm the performance of fault location algorithms, as can be seen in Figs. 1 and 2. Other simulations considering different points of faults in these two transmission lines also led to this conclusion. It is noteworthy that the fault location algorithm used in the study is based on the theory of voltage and current fundamental phasors taken from both ends of a transmission line. This algorithm is well known in the literature and is used in some electric power companies [4]. According previous considerations, a technique for estimating fault location that seeks to minimize the effect of these measurements errors becomes important.

State estimation

The state estimation is a mathematical tool developed for modeling power system and process measurements in real time. These