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# Impedance-based fault location methods: Sensitivity analysis and performance improvement

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ABSTRACT

This paper deals with analysis and improvement of two-terminal impedance based fault location methods for transmission lines. Firstly, a customised sensitivity analysis (CSA) for this class of methods is discussed, which allows a more comprehensive analysis than those so far used for evaluating the robustness to uncertainties of the input parameters (such as phasors and electrical line parameters). Second, a customised modal transformation (CMT) is derived from CSA, aiming to improve impedance-based fault location methods for performance. Such an approach uses the Park transformation along with a cost function obtained from the CSA. To assess the effectiveness of the developed approach, four two-terminal fault location methods from the literature, using both distributed parameter line model and only fault data, are considered. Evaluation tests based on Alternative Transients Program (ATP) simulations have shown that the proposed approach presents results quantitatively superior than other approaches from the literature confirming its applicability.



## 1. Introduction and problem statement

The most common transmission line fault location methods are based on either power frequency measurements (impedance-based methods) or high frequency transients (travelling wave methods) [1]. In this paper, only impedance-based methods are considered, which exhibit low cost and do not require high sampling rate. In general, this method class uses the following input parameters: line length, voltage and current phasors of one or two terminals of the transmission line, electrical parameters (series resistance, series inductance, and shunt capacitance), and synchronism angle [2]. One-terminal fault location techniques [3–5] do not require a communication channel to transmit the data from the far to the local end, but their accuracies are impacted by some assumptions necessary to circumvent the fact that the fault resistance value is not known [6]. As a consequence, such approaches can lead to significant errors even if the input parameter measures present high accuracy. On the other hand, two-terminal fault location methods [7–11] are more accurate, usually requiring no approximation and depending mainly on the input parameters accuracy. In practice, these parameters are not generally available with the required precision due to several factors, such as phasor estimation errors and inaccuracies of potential transformers (PTs), current transformers (CTs), and line parameters. Such factors lead to errors of different levels depending on the features of the algorithm used.

A very common practice used for assessing the accuracy of impedance-based fault location methods is to consider that each input parameter has a minimum and a maximum value (both arbitrated) around its nominal value [6–11]. Then, considering a set of $N$ input parameters, there are $2^N$ combinations of maximum and minimum input parameter values. For each combination, the fault location method is applied and a fault location estimate is obtained, giving rise to a fault location error. Such an approach presents the following main drawbacks:

1. For a complete analysis of a fault location method, all input parameter accuracies should be considered, leading to a great amount of outcomes to be assessed.
2. The outcomes obtained are somewhat limited to compare two or more fault location methods for robustness.

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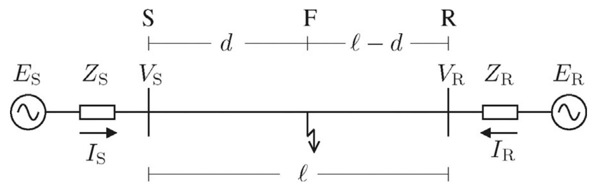


**Fig. 1.** One-line diagram of a faulty power system.

3. The considered combinations are extreme cases, with very low probability of occurrence. On the other hand, the cases around the nominal values, which have larger probability of occurrence, are not generally evaluated. As a consequence, this approach is not reliable.
4. Error cancelling is highly probable.
5. This approach is inadequate to improve fault location methods for performance.

To overcome these drawbacks from former works, this paper proposes a novel approach by using the well-known sensitivity analysis, modelling each input parameter as an independent random variable. Moreover, such a strategy can be used to enhance the performance of fault location methods.

In [12], a global sensitivity analysis is used to one-terminal fault location methods. Such an approach considers only a few input parameters which must be estimated a priori, leading to a procedure somewhat complex to be applied. In this paper, we propose a local sensitivity analysis customised to impedance-based fault location methods, termed customised sensitivity analysis (CSA), which allows verifying and assessing in an extensive way the behaviour of such methods in the face of input parameter uncertainties. To asses the CSA, we focus on two-terminal fault location methods, since their fault location estimate errors are almost entirely due to input parameter errors. The second goal of this paper is to introduce a technique for enhancing the robustness of impedance-based fault location methods to input parameter errors. For a given fault condition, such a technique searches for the best modal transformation by finding the reference axis angle $\theta$ of the Park transformation [13] that minimises a cost function obtained from the CSA, resulting in an optimised transformation, termed customised modal transformation (CMT). To assess the effectiveness of the proposed approach, evaluation tests based on the Alternative Transients Program (ATP) [14] are carried out. In such tests, four fault location methods from the literature [7–10], using both distributed parameter line model and only fault data, are considered.

## 2. Power system notation

The one-line diagram shown in Fig. 1 depicts the notation adopted for the power system model used in this paper. Its main element is a homogeneous transmission line (for non-perfectly transposed lines, each case should be studied individually using an adequate modelling as discussed in [7,15,16]) of length $\ell$ with a fault of resistance $R_F$ at point F, located at a distance $d$ from sending end S and, consequently, at a distance $\ell - d$ from receiving end R. Voltage sources $E_S$ and $E_R$ with series single-phase impedances $Z_S$ and $Z_R$ represent the Thévenin-equivalent circuits connected at each line terminal, no mutual coupling is considered on these equivalent circuits. The line parameters per unit length are $R_u$, $L_u$, and $C_u$ (the shunt conductance is negligible). The series impedance of the line is $Z_u$ and its shunt admittance is $Y_u$ (both per unit length). The line propagation constant is $\gamma = \sqrt{Y_u Z_u}$ and $Z_c = \sqrt{Z_u/Y_u}$ is the characteristic line impedance (surge impedance). The voltage and current phasors at terminals S and R are denoted, respectively, $V_{S\{a,b,c\}}$, $I_{S\{a,b,c\}}$, $V_{R\{a,b,c\}}$, and $I_{R\{a,b,c\}}$, where the subscripts a, b, and c denote the three line phases.

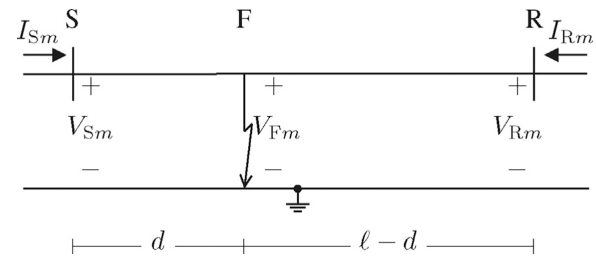


**Fig. 2.** Schematic diagram of a decoupled single-phase transmission line with a fault at point F.

To model the three-phase line under fault condition through decoupled single-phase circuits, either the symmetrical component decomposition or a modal transformation must be applied and a sequence/mode must be chosen to represent the faulty power system. To denote any mode of any transformation, a subscript $m$ is used (see Fig. 2).

Although any set of symmetrical or modal components could be adopted, both zero-mode and zero-sequence ($m = 0$) should be avoided due to the uncertainties arising from $\gamma_0$ and $Z_{c0}$ determination.

To consider unsynchronised measurements, the voltage and current phasors acquired at sending end S are multiplied by the synchronism operator $\exp(j\delta)$, where $\delta$ is the synchronism angle. It is also useful to consider a normalised fault location, i.e., $\bar{d} = d/\ell$. In addition, assuming that the fault-location estimate is $\hat{d}$, the normalised fault location error $\epsilon$ (in percent) is defined as

$$\epsilon = \frac{\hat{d} - d}{\ell} \times 100. \tag{1}$$

## 3. Impedance-based fault location methods

In this section, we introduce the four two-terminal fault location methods [7–10] considered in this research work. All of them are based on the power system model depicted in Figs. 1 and 2, adopting a distributed parameter line model (considering the shunt capacitance effect, which is more relevant for both extra high voltage (EHV) and long transmission lines) and only fault data. This latter is preferred because under fault condition, the CTs are working in their full measurement range [17].

Now, let us consider a homogeneous three-phase line decoupled in the single-phase transmission line S-R illustrated in Fig. 2. Considering a distributed parameter line model, the voltage at fault point F calculated from terminal S phasors is

$$V_{Fm}^{S} = [V_{Sm}\cosh(\gamma_m d) - I_{Sm} Z_{cm} \sinh(\gamma_m d)]e^{j\delta}. \tag{2}$$

Similarly, the voltage at fault point F evaluated from terminal R phasors is obtained by

$$V_{Fm}^{R} = V_{Rm}\cosh[\gamma_m(\ell - d)] - I_{Rm} Z_{cm} \sinh[\gamma_m(\ell - d)]. \tag{3}$$

Now, assuming that the measurements taken at S and R are synchronised ($\delta = 0$), the voltage phasors at point F determined either by (2) or (3) are equal. Therefore, equaling (2) and (3), after some algebra, the distance $d$ is found, i.e,

$$d = \frac{\tanh^{-1}(-B/A)}{\gamma_m} \tag{4}$$

where $A = Z_{cm}\cosh(\gamma_m \ell) I_{Rm} - \sinh(\gamma_m \ell) V_{Rm} + Z_{cm} I_{Sm}$ and $B = \cosh(\gamma_m \ell) V_{Rm} - Z_{cm}\sinh(\gamma_m \ell) I_{Rm} - V_{Sm}$. Expression (4) is the result given in [7] and referred in this paper as Method I. If unsynchronised measurements ($\delta \neq 0$) are considered, only the