Influences of Electromagnetic Interferences on Two-Terminal Impedance-Based Fault Location Methods

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Abstract: Faults during transmission line operations are prone to occur, which reinforces the need for protection instruments to ensure the safety of facilities involved and, in case of power outages, to restore the energy supply in the least amount of time as possible. In this context, two terminal impedance-based fault locators are widely used in real installations, since they overcome limitations of single-terminal approaches. In this paper, a study is carried out to evaluate the performance of four classical fault location methods in a transmission system subjected to electromagnetic interferences (EMI). An overhead power line with 334 km is exposed to a hypothetical case of electromagnetic influence due to inductive coupling with a 28" underground pipeline. The system is modeled using the well-known Alternative Transients Program (ATP) and phase-to-ground faults are simulated, varying fault resistances and locations, in order to obtain a parametric response. Results show that fault location methods based on series impedances, propagation constants and characteristic impedances underperform in situations which the EMI are neglected, presenting errors as large as 60 km. However, methods that do not rely on line parameters show significantly improved accuracy and great robustness with respect to external EMI, presenting fault location estimation errors of only 5%.

Keywords: ATP/EMTP software, electromagnetic interferences, fault location, symmetrical components, two-terminal impedance-based methods, transmission lines.

1. INTRODUCTION

Transmission lines are a fundamental component of any electrical power grid, which directly affects the energy supply of entire regions, thus required to be robust and reliable structures.

Moreover, transmission lines demand vast use of external spaces, being often exposed to interferences in its vicinities, as well as adverse operating conditions caused by weather among other factors, which may give cause to faults and, ultimately, power supply interruptions. In this context, the study and development of fast and accurate fault locators have been carried out since the 1950s, intended to reduce the power supply restoration time, which is an important mitigation factor of both technical and economical issues, as reported by Saha et al. (2010); Dalcastagne and Zimath (2008); Stringfield et al. (1957).

Saha et al. (2010) recall that accurate fault location methods reduce operating costs by avoiding lengthy and expensive patrols. Also, this protection system expedites repair and may assist in reducing revenue loss caused by outages.

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Several methods for estimating fault locations have been reported in the literature and are presently used in the field. According to Phadke and Thorp (2009), these algorithms are usually subdivided in four groups:

- Traveling-wave-based methods;
- Impedance-based methods;
- Knowledge-based methods; and
- High-frequency-based methods.

Among the available fault location techniques, the application of traveling-wave (TW) methods on power transmission line networks have become increasingly attractive for utilities over the past years, due to its reliability and high accuracy, as remarked by Zimath et al. (2010). However, TW-based fault location devices require higher sampling rates, which makes equipment more expensive than those based on fundamental frequency components. For this reason, impedance-based methods are the most employed by power utilities companies, since devices perform with lower sampling frequency rates, increasing simplicity and reducing costs [Saha et al. (2010)].

The two-terminal impedance-based algorithms estimate the fault location using data from measurement devices installed at both transmission line ends. In contrast with the techniques depending on just one terminal data for estimating the fault location, two-terminal methods are not affected by the fault resistance and are reported by Saha et al. (2010) to be the most reliable impedance-based algorithms.

There are several types of two-terminal impedance-based algorithms which rely on different parameters to estimate the fault location. Generally speaking, the performance of these methods is influenced by data synchronization, fault characteristics and uncertainties in transmission lines parameters [Lopes et al. (2013)].

Due to the exposition of the transmission line to the external environment and the increasing urbanization of cities, these facilities are often subjected to EMI caused by inert, i.e. not designed to conduct electricity, metallic structures sharing the same right-of-way, such as fences, railroads and pipelines. It is well-known from the literature that EMI influences may give cause to hazards both to people and the inert facilities involved, in the form of touch and stress voltages. Moreover, recent studies report that the transmission lines under interference conditions are also subjected to impacts due to the presence of external metallic structures in its vicinities, leading to uncertainties in determination of transmission line parameters and, consequently, potential inaccuracies in fault locators and/or protection schemes configuration [Moraes et al. (2021a,b)].

Thus, in this paper it is presented an analysis of four classical two-terminal impedance-based fault location methods in a case of a transmission line subjected to EMI. The case is based on a real transmission system located in Brazil, which is composed of a 500 kV double-circuit transmission line with 334 kilometers extension. A 28" underground pipeline is introduced in the same right-of-way occupied by the power line to represent the inert metallic structure exposed to energized conductors.

Tests using the EMTP/ATP are performed in order to evaluate and demonstrate the effects of the uncertainties on line parameters caused by electromagnetic interference mechanisms and, consequently, on the performance of the two-terminal fault locators under investigation.

The obtained results indicate that the effects caused by EMI on line parameters may seriously jeopardize the performance of the two-terminal impedance-based methods that rely on sequence parameters, increasing the error of fault location estimations in more than 20%, which represents about 60 kilometers in the transmission line under study, in cases which present EMI sources are neglected. However, the two-terminal impedance-based methods that do not depend on the knowledge of line parameters to converge to a fault location estimation have shown to be more reliable and accurate, yielding estimation errors of less than 5% with respect to the actual fault position.

2. TWO-TERMINAL IMPEDANCE-BASED FAULT LOCATION METHODS

2.1 Method I: Method of Girgis et al. (1992)

This two-terminal fault location algorithm is extensively reported in literature, for being based on synchronized data measurements. Also, the method of Girgis uses a lumped parameters line model approach in which only the series impedances are taken into account in the formulation [Girgis et al. (1992)].

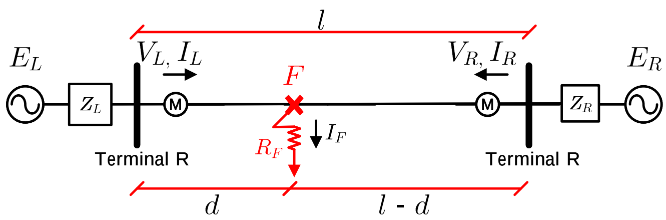

Figure 1. Single line diagram of a transmission system with fault occurring at point F.

Considering the scheme presented in Figure 1 and the point F as the fault location, $\hat{V}_F$ is computed taking into account two paths. First it is considered the fault path on the left side of the fault location and then the fault path on the right side, being derived the corresponding loop equations. Equating both expressions, the algorithm formulation is obtained as [Girgis et al. (1992)]:

$$V_L^{abc} - V_R^{abc} + l \cdot Z_{abc} \cdot I_R^{abc} = d \cdot Z_{abc} \cdot (I_L^{abc} + I_R^{abc}), \quad (1)$$

in which l is the line extension, in units of length; V_F^{abc} is the vector of voltage phasors at the fault point, in volts; V_L^{abc} and V_R^{abc} are the voltage phasors at terminals L and R, respectively, in volts; I_L^{abc} and I_R^{abc} are the current phasors at terminals L and R, respectively, in Ampères; and Z_{abc} is the series impedance matrix of the transmission line, in ohms per unit length, computed from the zero and positive sequence parameters [Dommel (1986)].

It is possible to recast (1) in matrix form as:

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$$Y_{abc} = M_{abc} \cdot d, \tag{2}$$

$$\begin{bmatrix} Y_a \\ Y_b \\ Y_c \end{bmatrix} = \begin{bmatrix} M_a \\ M_b \\ M_c \end{bmatrix} \cdot d, \tag{3}$$

in which:

$$M_i = \sum_{j=a,b,c} Z_{i,j} \cdot (\hat{I}L^j + \hat{I}R^j), \text{ for } i = a, b, c\ , \tag{4}$$

$$Y_i = \hat{V}L^i + \hat{V}R^i + l \cdot \sum_{j=a,b,c} Z_{i,j} \cdot \hat{I}_R^j, \text{ for } i = a, b, c\ . \tag{5}$$

Solving equation (3) for d, the estimated fault location (d_{est}), in units of line length, is determined by:

$$d_{est} = (M^+ M)^{-1} M^+ Y, \tag{6}$$

in which M^+ is the conjugate transpose of M.

It is important to notice that this method does not account for shunt capacitive effects on the transmission line and may introduce errors in long lines which this effect cannot be avoided [Saha et al. (2010)].

2.2 Method II: Method of Johns & Jamali, as reported by Sadeh et al. (2000)

Differently of the method of Girgis, this approach takes into account the shunt capacitance effects of the transmission line in the fault location process and, because of that, it is considered one of the most accurate two-terminal techniques reported in the literature, as noted by Lopes et al. (2014).

This algorithm is also obtained from the computation of $\hat{V}_F$ from the right and left fault path loops, but using distributed line parameters, in which the line propagation constant γ and the characteristic impedance Z_C are accounted in the formulation, in addition to the line length, current and voltage phasors at line terminals [Saha et al. (2010)]. Then, the estimated fault location (d_{est}) is determined using:

$$d_{est} = \frac{\tanh^{-1}\left[\frac{-\hat{V}_R \cdot \cosh(\gamma \cdot l) + Z_C \cdot \hat{I}_R \cdot \sinh(\gamma \cdot l) + \hat{V}_L}{Z_C \cdot \hat{I}_L - \hat{V}_R \cdot \sinh(\gamma \cdot l) + Z_C \cdot \hat{I}_R \cosh(\gamma \cdot l)}\right]}{\gamma}. \tag{7}$$

In this method two different estimated fault locations are obtained due to the fact that the algorithm uses different modal voltage and current quantities inputs. Thus, the performance is dependent on the fault type classification to select the appropriate excited aerial-mode and, consequently, the estimated fault distance [Dalcastagne and Zimath (2008)].

2.3 Method III: Method of Radojevic, described by Preston et al. (2011)

Intending to improve the reliability of then available approaches, Radojevic proposed a method based on synchronized data measurements that does not require the knowledge of line parameters, which circumvents inaccuracies intrinsic to such variables [Lopes et al. (2013)].

However, the algorithm is determined solely from the lumped line series impedance in formulation and imprecisions can appear in long lines such that shunt capacitances cannot be disregarded, since the capacitive currents may reach values comparable of those of currents in the fault path [Preston et al. (2011)].

Similarly to the precedent methods, the fault location is determined by considering the $\hat{V}_F$ in the both paths, though in Radojevic's procedure the line parameters are eliminated from the formulation. As a result, the estimated fault location can be obtained as:

$$d_{est} = \frac{(\hat{V}_{L1} - \hat{V}_{R1}) \cdot \hat{I}_{R2} - (\hat{V}_{L2} - \hat{V}_{R2}) \cdot \hat{I}_{R1} \cdot l}{(\hat{V}_{L1} - \hat{V}_{R1}) \cdot (\hat{I}_{L2} + \hat{I}_{R2}) - (\hat{V}_{L2} - \hat{V}_{R2}) \cdot (\hat{I}_{L1} + \hat{I}_{R1})} \tag{8}$$

in which, the subscripts '$_1$' and '$_2$' represent the positive and negative sequence quantities, respectively.

It should be highlighted that this method uses a different approach for symmetrical fault cases, for which, in balanced power systems, negative sequence quantities will not exist Sadeh et al. (2000).

2.4 Method IV: Method of He et al. (2011)

As in Method II, this algorithm is based on a distributed parameters line model, accounting for the capacitive effect of the line [He et al. (2011)].

However, Method II is based on the determination of the line propagation constant γ and impedance characteristic Z_C to converge to an estimation of the fault position, whereas the technique proposed by He et al. (2011) uses the Newton iterative algorithm, resulting in improved accuracy for fault location estimations He et al. (2011).

The initial value of the estimated fault location (d_{est}), represented by x, is computed using:

$$x = \frac{\ln\left[\frac{0.5 \cdot (\hat{V}_{R1} + \hat{I}_{R1} \cdot Z_C) - 0.5 \cdot (\hat{V}_{L1} - \hat{I}_{L1} \cdot Z_C) e^{\gamma l}}{0.5 \cdot (\hat{V}_{L1} + \hat{I}_{L1} \cdot Z_C) e^{-\gamma l} - 0.5 \cdot (\hat{V}_{R1} - \hat{I}_{R1} \cdot Z_C)}\right]}{2 \cdot \gamma}, \tag{9}$$

in which, the subscript '$_1$' represent positive sequence quantities.

Then, the voltage phasor at the fault point ($\hat{V}_F$) is estimated by considering measurements taken from both line ends. Thus, a objective function is defined as in (10).

To apply the Newton iterative method, one has to compute the first-order derivative of $F_{dis}(x)$ with respect to x, which is given in (11).

Then, once calculated the initial boundary of the fault distance estimation $x = x_0$, $F_{dis}(x_0)$ and $\frac{\partial F_{dis}(x_k)}{\partial x}$, the Newton iterative method is applied in variable x as:

$$x_{k+1} = x_k - \frac{F_{dis}(x_k)}{\frac{\partial F_{dis}(x_k)}{\partial x}}, \tag{10}$$

in which, x_{k+1} is the fault distance estimated in the k_{th} iteration.

A tolerance and maximum iteration number are specified to determine when x_{k+1} is taken as d_{est}. If the difference between the current and previous sample is less than the specified tolerance or the iteration number is greater than the maximum iteration stipulated the iterative function stops and $x_{k+1} = d_{est}$. In this paper, the tolerance and maximum iteration number used are of 10^{-5} and 5, respectively.

3. SYSTEM UNDER STUDY

3.1 Description of the Scenario

The power supply system in Amazonas, Brazil, is fed through a 334 kilometers long power line. This transmission system consists of a double-circuit transposed line that operates at 500 kV, triangular phase conductor arrangement, two shield wires, as shown in Figure 2.

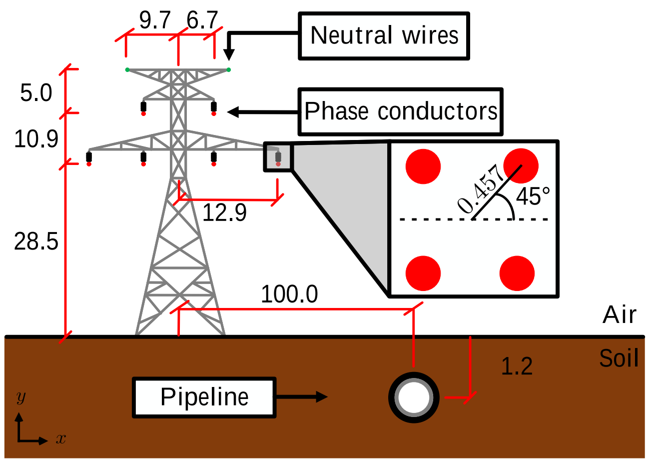

Figure 2. Cross-section view of the shared right-of-way, all distances in meters.

The line is energized with a current of 1.5 kA per phase, with ABC-CBA sequence, 60 Hz frequency and its is grounded at both terminal substations through earth resistances of 1 Ω. Each phase of the transmission line is composed of four bundled conductors in square arrangement, as illustrated in Figure 2. Table 1 describes the transmission line conductors and the corresponding electrical characteristics.

An underground carbon steel pipeline under preliminary design stage is assumed to share the same right-of-way, representing the electromagnetically coupled interfered circuit.

Table 1. Specifications of the transmission line conductors

Conductor	**Internal radius [m]**	**External radius [m]**	**DC Resistance [Ω/km]**
AAAC -27	-	0.01462	0.068016
ACSR Dotterel	0.0046228	0.0077089	0.306336

The 28" diameter pipeline is buried 1.2 meters deep and shares the right-of-way at 100 meters parallelly to the transmission line axis along its extension. The pipeline is grounded at the terminals through resistances equal to 10 Ω. The characteristics of the pipe metal and its insulating coating are shown in Table 2.

Table 2. Pipeline characteristics

Parameter	**Value**
External radius [m]	0.3556
Internal radius [m]	0.3461
AC Resistance [Ω/km]	0.0870287
Reactance [Ω/km]	0.0866951
Metal resistivity [Ω.m]	1.72×10^{-7}
Coating electric permittivity [F/m]	1.257×10^{-6}
Coating resistivity [Ω.m]	1×10^{8}
Coating thickness [m]	3×10^{-3}
Depth-of-cover [m]	1.2

In previous studies by Moraes et al. (2021a,b), it was observed that, as far as the zero sequence impedance outcome is concerned, the soil resistivity is less prevailing than the actual presence of the interfered pipeline metal interacting with the power line conductors, thus affecting less the fault location errors under EMI conditions. Then, for this work, a uniform soil composed of a single semi-infinite layer, with electrical resistivity equal to 1000 Ω.m is assumed, with no loss of generality.

3.2 EMTP/ATP Equivalent System

Figure 3 presents the equivalent EMTP/ATP model used to simulate the phase-to-ground faults in the phase A of circuit 1 of the transmission line under investigation.

In order to assess the performance of the two-terminal impedance-based methods, the simulated faults are applied to four points along the transmission line length (20%, 40%, 60% and 80%), with four distinct values of fault resistances (0.0001, 50, 100 and 150 Ω), so different sensitivity scenarios are also observed. Two different situations are considered in calibration of the fault locators: neglecting the existence of EMI and considering the EMI on calculation of line parameters.

$$F_{dis}(x) = \hat{V}^{L}_{F1} - \hat{V}^{R}_{F1} = \frac{(\hat{V}_{L1} - \hat{I}_{L1} \cdot Z_C)}{2} e^{\gamma \cdot (l-x)} + \frac{(\hat{V}_{L1} + \hat{I}_{L1} \cdot Z_C)}{2} e^{-\gamma \cdot (l-x)} - \left[\frac{(\hat{V}_{R1} - \hat{I}_{R1} \cdot Z_C)}{2} e^{\gamma \cdot x} + \frac{(\hat{V}_{R1} + \hat{I}_{R1} \cdot Z_C)}{2} e^{-\gamma \cdot x} \right] \quad (10)$$

$$\frac{\partial F_{dis}(x_k)}{\partial x} = \gamma \cdot \left[-\frac{(\hat{V}_{L1} - \hat{I}_{L1} \cdot Z_C)}{2} e^{\gamma \cdot (l-x)} + \frac{(\hat{V}_{L1} + \hat{I}_{L1} \cdot Z_C)}{2} e^{-\gamma \cdot (l-x)} - \frac{(\hat{V}_{R1} - \hat{I}_{R1} \cdot Z_C)}{2} e^{\gamma \cdot x} + \frac{(\hat{V}_{R1} + \hat{I}_{R1} \cdot Z_C)}{2} e^{-\gamma \cdot x} \right] \quad (11)$$

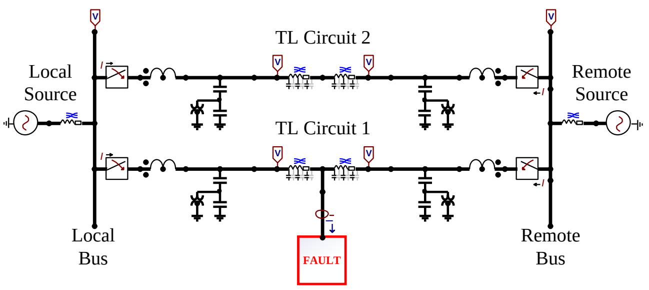

Figure 3. ATP/EMTP based model for short-circuits simulation.

The line parameters are calculated using the TRALIN software, a computational module present in the Current Distribution Electromagnetic Interference Grounding and Soil Structure Analysis (CDEGS) package, which is worldly reputed as the industry-standard for the calculation of EMIs [Dawalibi (2014); Dawalibi and Donoso (1993)]. This program is reported to calculate impedance and admittance parameters from arbitrary overhead and underground arrangements of conductors on uniform or multilayered soils. Also, TRALIN can plot electric fields, scalar potentials, radio noises and audible noises at the conductors profiles.

The system symmetrical parameters calculated using software TRALIN are presented in Table 3.

Table 3. Symmetrical parameters of the system

	Neglecting EMI	Considering EMI
Z_0 [Ω\km]	0.3242+j1.0879	0.1732+j0.6562
Z_1 [Ω\km]	0.0185+j0.1564	0.0136+j0.1389
Y_0 [μS\km]	j4.4785	j4.4785
Y_1 [μS\km]	j12.4143	j12.4143

It is noticed that the zero sequence impedance has a notable discrepancy of 67.26% when the EMI is neglected in the model. Positive and negative sequence impedances are less affected, but even so there is a difference of 12.84% between the scenarios which the effect of the electromagnetically-coupled pipeline on the line parameters are considered or not.

Shunt admittances do not present significant discrepancies, due to the fact that, at power system frequencies, the capacitance is independent of the interfered pipeline buried beneath the ground, due to the shielding effect of the intrinsically conductive earth layer, as documented by Moraes et al. (2021a).

4. RESULTS

Figures 4 to 7 present the absolute errors of the two-terminal impedance-based Methods I, II, III and IV, respectively, considering and neglecting the effects of EMI on transmission line parameters.

The Method I accuracy is affected by the presence of the EMI. The absolute error in this method increases in all scenarios, but it is worse when the fault location is at 80% of the transmission line length. This greater absolute error is due to the fact that the Method I is based on lumped

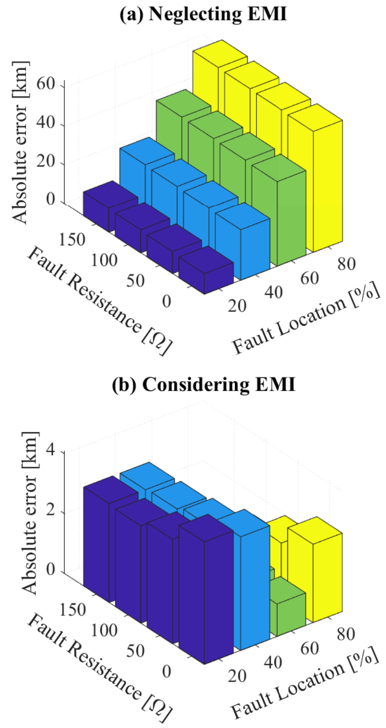

Figure 4. Fault location errors using Method I for phase-to-ground fault.

parameters, i.e. series impedance, which are considerably impacted by the presence of the interfering structure in vicinities of the transmission line.

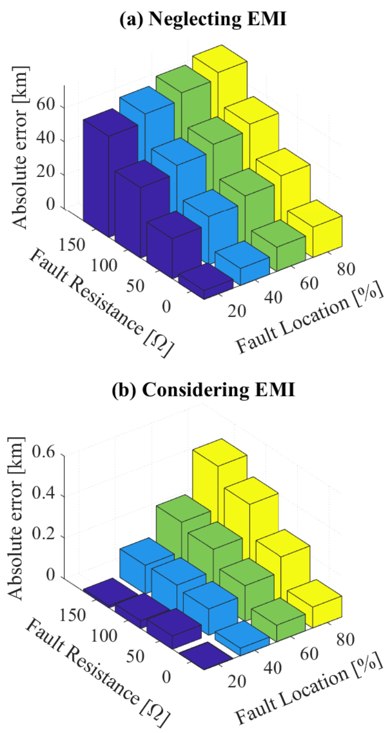

Figure 5. Fault location errors using Method II for phase-to-ground fault.

It is observed that Methods II and IV are the most impacted by the pipeline presence in the close vicinity of the transmission line being studied. These two fault locators are based on propagation constants and characteristic impedances. The EMI changes values of modal parameters, and consequently, introduces discrepancies on the values of the propagation constant and characteristic impedance of the system, especially for ground modes. Moreover, with EMI neglected, Methods II and IV present an increase on fault location estimation errors with greater fault resistances.

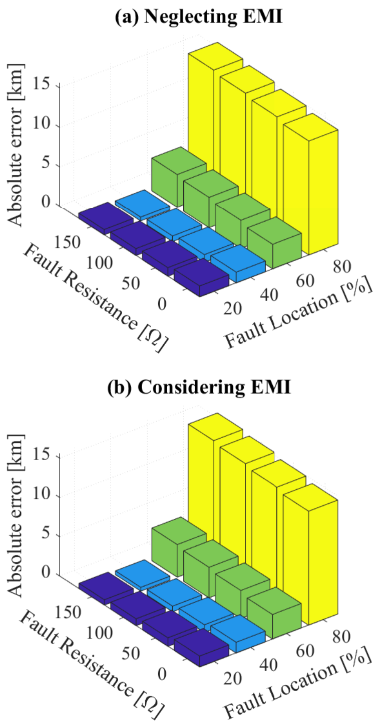

Figure 6. Fault location errors using Method III for phase-to-ground fault.

Method III is the two-terminal impedance-based approach presenting the highest accuracy in interferences conditions. This occurs because this algorithm does not use line parameters to estimate the fault distance. Then, this method shows that it is not impacted by the presence or absence of an interfering structure electromagnetically coupled with the transmission line.

It is noticed that the presence of EMI affecting the power line conductors causes greater impact on the fault location methods which are fundamentally dependent on the transmission line parameters to converge to a fault location estimation. Then, it is important to highlight that the presence of interfering structures must be handled carefully and properly accounted for when parametrizing fault location devices based on line sequence impedances and/or admittances. On the other hand, methods that are irrespective of transmission line parameters are unaffected by the presence of the interfering pipeline, which is a viable solution for transmission systems subjected to EMI.

5. CONCLUSIONS

Transmission lines are required to be reliable and robust installations, for the sake of safety and quality of the power system energy supply. Thus, protection and fault locators systems are fundamental to improve the restoration time in the event that a fault or power outage should occur.

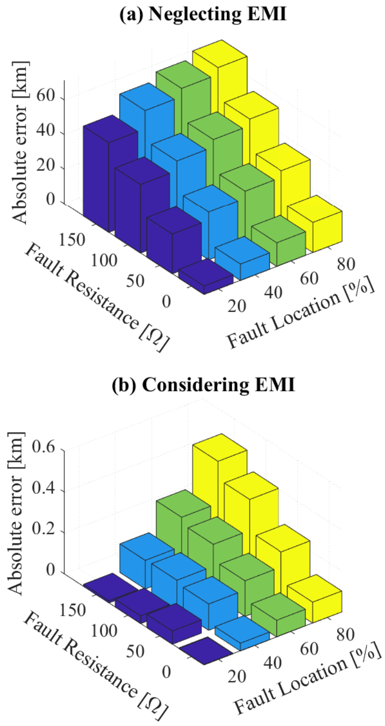

Figure 7. Fault location errors using Method IV for phase-to-ground fault.

Moreover, transmission lines most often spans for several kilometers of external environments, and commonly share the space with other infrastructure, such as pipelines and railroads. These inert metallic structures in proximity with the energized conductors of the transmission line may subject the interfered facilities and people involved to risks and, also, may influence on line parameters and protection schemes of the transmission systems.

In this paper, four classical two-ended impedance-based fault location methods, namely: Girgis, Johns & Jamali, Radojevic and He, were evaluated in a situation of electromagnetic interferences between a real 500 kV transmission line, located in Amazonas, and a hypothetical 28" underground pipeline still under preliminary design phase. Tests using the EMTP/ATP were performed, varying the fault location and the fault resistance on phase-to-ground fault simulations.

From the results discussed throughout the text, it is clear that the EMI affects directly the performance of the fault location methods, especially the approaches heavily reliant on transmission line parameters: Girgis, Johns & Jamali and He. It is clearly observed that it is fundamental to account for the presence of EMI on calibration and set-point of fault location devices based on such techniques in order to guarantee the fault position estimation accuracy. The presence of EMI influences the system line parameters and corresponding modal quantities, which may cause deviations of up to 60 kilometers with respect an actual fault incidence point.

Alternatively, methods that do not fundamentally depend on the knowledge of line parameters, such as the Radojevic algorithm, performed well in all considered scenarios, irrespective of accounting for the EMI in its development, proving to be a reliable and accurate fault location estimation technique for cases which interfering structures might be present.

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