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Impact of Transmission Line Modeling Aspects on TW-Based Fault Location Studies

L. M. A. Ribeiro, G. A. Cunha, A. G. Martins-Britto, E. P. A. Ribeiro, F. V. Lopes

***Abstract*—This paper analyzes the impacts of different transmission line (TL) modeling approaches in Electromagnetic Transients Programs (EMTP) during the evaluation of traveling wave (TW)-based fault location (TWFL) functions. Massive EMTP fault simulations are carried out to compare the performance of TWFL solutions when the system model considers Bergeron or JMarti models, accounting for homogeneous or heterogeneous soil characteristics, as well as ideal or real transposition schemes. Firstly, TWFL errors are presented in the form of scatter plots to compare the relative performance between four fault location solutions when different modeling approaches are taken into account. Then, the fault location absolute errors are presented as boxplots individually for each analyzed TWFL method and modeling approach, allowing to perform quantitative analysis of the obtained errors. From these results, the impacts of the evaluated modeling strategies on the assessed TWFL methods are addressed, highlighting the model features that can yield more challenging scenarios during the evaluation of TWFL solutions.**

***Keywords*—Transmission line modeling, frequency-dependent models, line transposition, soil heterogeneity, TW-based fault location methods, fault location absolute errors.**

I. Introduction

DUE to the advances in signal processing and A/D converters, the sampling rates used in measurement devices and communication systems have increased over the years, allowing micro-processed relays to apply the TW's theory in protection and fault location applications [1]. Consequently, these technologies have gained notoriety in the power system relaying scientific community, in such a way that TW-based algorithms have been already embedded in commercially available protective devices.

TW-based studies are typically carried out in a microsecond time scale. Thereby, the filtering processes must be able to extract the correct information from signals in a wide range of frequencies. Hence, there has been an increasing attention from developers and device manufacturers of TW-based applications on power systems modeling strategies, mainly when EMTP-type softwares are used to test and validate TW functionalities.

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When TL modeling in EMTP platforms is required for testing purposes, although distributed parameter frequency-dependent lossy line models are commonly assumed to be the most realistic ones, it is a common practice to simplify some other line features in relation to the real-world scenario. These simplifications can facilitate modeling and simulation procedures, being commonly accepted during the assessment of phasor-based methods. However, there are simplifications which when extended to TW analysis, as many people usually do, they can compromise the accuracy and reliability of studies on TW-based functions. Among the modeling characteristics that are often disregarded, transposition schemes and soil heterogeneity along the TL stand out [2], [3]. In addition, some works in the literature still use frequency independent TL models during TWs studies, disregarding the TL parameters frequency dependence, which have been already proven to exist in practice [4], [5].

In [5] the authors explain that frequency-dependent line models must be used to properly represent the range of frequencies that may take place in electromagnetic transients during line fault cases. Similarly, in [4], it is shown that there are relevant differences in the TW propagation patterns when frequency-dependent and independent line models are used. According to [4], from a comparative analysis between real and simulated records, it is concluded that the JMarti model results in more realistic line transients than those obtained when frequency-independent line models are used, leading simulations to be closer to the real-world scenarios, specially from the point of view of TWs. The identified differences are more relevant in ground mode TWs, highlighting the need for investigations about the impact of ground resistivity variations on fault-induced line transients.

Despite the literature offers a substantial amount of studies that evaluate TWFL solutions considering different fault conditions and system models [6], [7], the impacts of combinations of different TL EMTP modeling strategies are scarcely addressed, so that there is no consensus on some modeling aspects that must be either taken into account or avoided during TWs studies. Furthermore, from the best knowledge of the authors, works that correlate a wide variety of modeling aspects, quantifying their impacts on TWFL methods and pointing out related difficulties that may arise during incident and fault-reflected TW detection procedures are still scarce in the literature. As a consequence, there is a preliminary idea that detailed models will always pose more critical scenarios to TWFL methods, although clear proofs on such subject have not been reported in the open literature.

Aiming to fill the referred gap in the literature related to the subject addressed in this paper, comprehensive studies on different TL modeling aspects (considering frequency-dependent and independent line models, transposition schemes and soil heterogeneities) are performed, investigating their respective impacts on four TWFL solutions, which require the detection of only incident TWs, such as the classical double-ended TWFL method, or the detection of incident and fault-reflected TWs, such as the classical single-ended TWFL method and other alternative double-ended techniques. Hence, the influence of system models with different levels of detail are assessed, taking as reference a given simplified model for the sake of comparison with the remaining system models. The results show that detailed models tend to be more critical for TWFL methods, although this is not a rule.

II. TWFL Principles

When an abrupt voltage variation occurs on a TL, current and voltage transients are induced. These electromagnetic transients are called TWs and propagate from the fault point through the line toward both terminals [8]. Based on the TW phenomenon, several TWFL algorithms have been developed. Some methods depend only on the first incident wave detection at both line ends, while others depend on the proper identification of waves reflected from the fault point [9], [8]. Among these methods, most depend also on information about the TW propagation speed or propagation time, so that the TL electrical parameters must be known, which is a source of error due to possible uncertainties that may arise due their frequency dependence and/or environmental features variation along the right-of-way [6].

Fig. 1 represents the Bewley diagram [10] of fault-induced TWs propagating on a given TL. The line depicted in Fig. 1 also presents the test system simulated in this paper, whose characteristics are varied accordingly to different modeling approaches. The monitored TL connects the local bus (Bus 1) to the remote bus (Bus 2), including adjacent lines. In the presented figure, d is the fault distance from Bus 1 and L is the line length. Moreover, the first incident TWs arrive at buses 1 and 2 at the instants $t1_1$ and $t2_1$, respectively. $t1_3$ and $t2_4$ are the instants at which the TWs reflected from the fault point reach buses 1 and 2, respectively. The instants at which these reflected waves arrive from adjacent lines at local and remote terminals are denoted, respectively, by $t1_2$ and $t2_2$. Finally, TWs refracted though the fault point arrive at buses 1 and 2 at $t1_4$ and $t2_3$, respectively.

In most TWFL techniques, signals are decoupled by means of a modal transformation in order to avoid the misinterpretation between aerial and ground mode TWs that are superposed in phase quantities. In [11], for instance, false peaks are identified due to the presence of ground mode TWs when the Bergeron line model is used. Thereby, since Clarke's modal transformation has been successfully used in real three-phase systems, it is also employed in this work, resulting in the modal waves TW1 (alpha), TW2 (beta) and TW0 (ground or zero) modes [1].

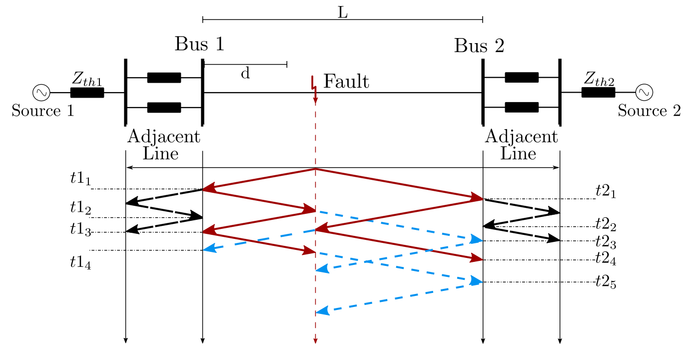


Fig. 1. Bewley diagram.

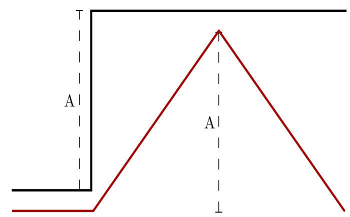


Fig. 2. Optimal DS filter response.

After decoupling the signals, in this paper, the Differentiator-Smoother (DS) filter is applied to the aerial mode signals. It extracts TWs amplitude and polarity information by converting fault-induced step-like changes on aerial mode signals into triangular-shaped outputs, as depicted in Fig. 2. This filter is also capable of maintaining in its outputs the same amplitude and polarity of the original step-change, allowing proper evaluation of TWs features [12].

In this paper, four different TWFL methods are applied to analyze how the TL modeling assumptions can affect the fault location results. The evaluated techniques are: Classical two-terminal method (C2T) [9], Classical One-Terminal method (C1T) [9], Settings-Free Two-Terminal Asynchronous method (FLO) [6] and Settings-Free Two-Terminal method (GIL) [13]. Aiming to obtain the reflected TW from the fault, as required by C1T, FLO and GIL methods, the methodology reported in [14] and [15] is applied here.

The time stamps depicted in Fig. 1 are used to explain the formulations of the analyzed TWFL methods. To evaluate the C2T, only the first incident TWs at both line terminals and the propagation velocity (v) are used, while C1T needs the first and the fault-reflected TW at the monitored terminal [9]. Thus, the C2T and C1T methods calculate the fault distance d from the local bus using respectively:

$$d = 0.5 \cdot [L - (t2_1 - t1_1) \cdot v]. \quad (1)$$

$$d = 0.5 \cdot (t1_3 - t1_1) \cdot v. \quad (2)$$

In contrast, the FLO and GIL methods require the first incident and fault-reflected TWs to be detected. FLO depends on these detections at both TL terminals [6], whereas GIL requires the detection of reflections at only the reference terminal. Also, GIL segregates the algorithm into two formulations, which are applied for faults at the first and second TL half sections [13]. The fault location formula applied in the FLO technique is given by:

$$d = \frac{t1_3 - t1_1}{(t1_3 - t1_1) + (t2_5 - t2_1)} \cdot L, \tag{3}$$

whereas GIL applies (4) and (5), respectively, for a faults within the first and second TL halves:

$$d = L \cdot \frac{0.5}{1 + \frac{t2_1 - t1_1}{t1_3 - t1_1}}, \tag{4}$$

$$d = L \cdot \left(1 - \frac{0.5}{1 + \frac{t1_1 - t2_1}{t1_4 - t1_1}}\right), \tag{5}$$

being d expressed in kilometers in all presented formulas.

III. Test System Description

In order to investigate the impact of transposition schemes, soil heterogeneities and frequency-dependent parameters on TWFL approaches, eight different systems have been modeled and simulated in the Alternative Transients Program (ATP). The effects of frequency dependence of TL parameters are analyzed by considering constant and frequency-dependent TL models, namely, Bergeron (Be) model, which is a distributed-parameter line representation, typically set to operate at a constant frequency (here 60 Hz) [16], and JMarti (JM) model, which in turn emulates the TL parameters frequency dependence over a pre-defined frequency range [17].

Another studied aspect regards the TL transposition scheme. In several researches, TLs are modeled as ideally transposed (IdT), considering a mathematical process that maintains the mutual coupling between phases equal. On the other hand, real transposition (T) can be also modeled in EMTP programs, consisting of untransposed sections organized in accordance to the chosen transposition scheme. In this paper, ATP transposition blocks are used to connect the untransposed sections with lengths equal to $\frac{1}{6}$, $\frac{1}{3}$, $\frac{1}{3}$ and $\frac{1}{6}$ of the total line length, whose positions change at each section. In addition, the line is modeled with an equivalent soil resistivity, i.e. homogeneous soil (HS) as typically taken into account in most TWs studies, and also with a non-homogeneous soil (NHS), in which the soil resistivity varies longitudinally among the regions determined by the transposition scheme, resulting in four distinct resistivity values.

The studied TL models present the same configuration shown in Fig. 1, being $L = 235.274$ km. The adjacent lines are 70 km long and the system operates at rated voltage and frequency equal to 230 kV and 60 Hz, respectively. The tower configuration, conductor data and soil resistivity values (ρ_0) are based on a real transmission system located in northern Brazil. Soil resistivity values are listed in Table I, with different values for each section in the NHS model, and a single HS parameter given by the arithmetic average of the NHS values. Also, the tower configuration and conductor data are illustrated in Fig. 3.

TABLE I
SOIL RESISTIVITY VALUES

1°Section $\rho_0(\Omega \cdot m)$	2°Section $\rho_0(\Omega \cdot m)$	3°Section $\rho_0(\Omega \cdot m)$	4°Section $\rho_0(\Omega \cdot m)$	HS $\rho_0(\Omega \cdot m)$
92.34	346.95	546.19	79.51	266.25

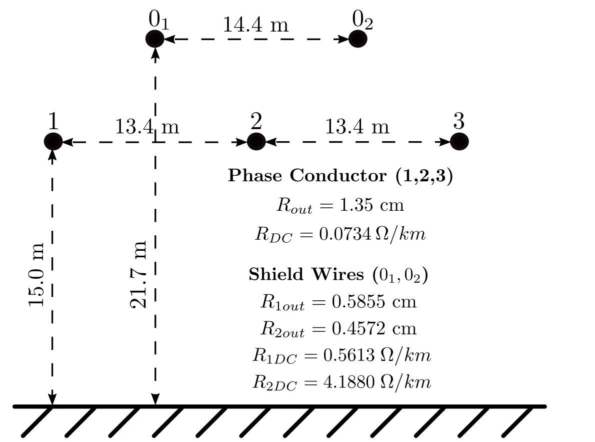


Fig. 3. TL tower geometry.

TABLE II
POWER SYSTEMS SCHEMES

System	Model	Soil	Transposition
1	Be	HS	IdT
2	Be	HS	T
3	Be	NHS	IdT
4	Be	NHS	T
5	JM	HS	IdT
6	JM	HS	T
7	JM	NHS	IdT
8	JM	NHS	T

TABLE III
PROPAGATION SPEEDS FOR EACH SYSTEM

System	Propagation Speed (m/s)	Compared to c
1 to 4	290286243.06	96.83%
5 and 7	295574120.60	98.59%
6	295759899.43	98.66%
8	295945911.95	98.72%

IV. Results and Analyses

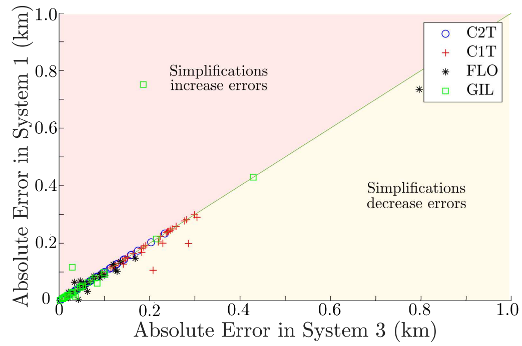
Table II describes the evaluated systems. The System 1 is considered the most simplified model, whereas System 8 is taken as the most realistic one. System 1 is used as the reference for the sake of comparison, allowing the identification of modeling complexity aspects that affect the analyzed TWFL approaches.

For each power system model, the propagation speed v is obtained by line energization maneuvers simulated in ATP, considering the line length L and the estimated propagation time τ, i.e., $v = \frac{L}{\tau}$. Different v values were verified in most JM systems, while Be line models presented the same result. v values for each system are shown in Table III, being their percentages in relation to the speed of light ($c = 299792458$ m/s) also listed.

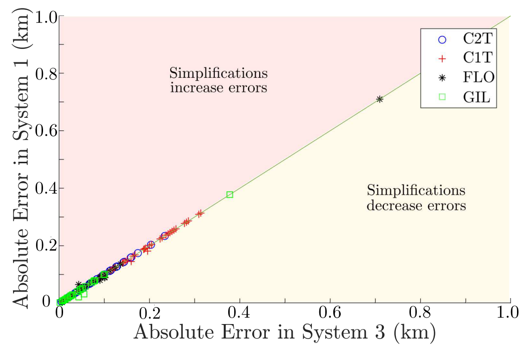
The proposed evaluation is divided in three parts. Firstly, the systems are compared varying only one modeling variable per time, namely, frequency dependence of TL parameters, soil features or transposition schemes. Then, all modeling variables are combined. To carry out these tests, single-phase A-to-ground faults (AG) and double-phase faults (BC) were simulated in ATP, considering d varying from 3% up to 96% of L, i.e., 32 fault distances. Hence, considering these fault distances for the eight evaluated systems, and assuming that two fault types were taken into account, a total of 512 simulations were carried out. As it is intended to evaluate only the performance of TWFL methods, faults are assumed to be solid, initiating at the voltage peak at the fault point. To compare the relative performance between the analyzed TWFL methods and to quantitatively analyze their errors, the obtained fault location errors are firstly presented as scatter plots, being then shown in a boxplot format, highlighting the median, 25th and 75th percentile error values.

A. Individual analysis of modeling variables

Here, three studies are carried out based on the obtained scatter plots. The first analysis evaluates the impact of transposition schemes on the TWFL accuracy, so that Systems 1 and 2 are compared in Fig. 4. The second study assesses the soil heterogeneity impact by plotting Systems 1 and 3, as shown in Fig. 5. Finally, the third analysis investigates the impacts of TL parameters frequency-dependence on TWFL errors, as depicted in Fig. 6. To improve the figures legibility, errors greater than 1 km classified as outliers are not shown.

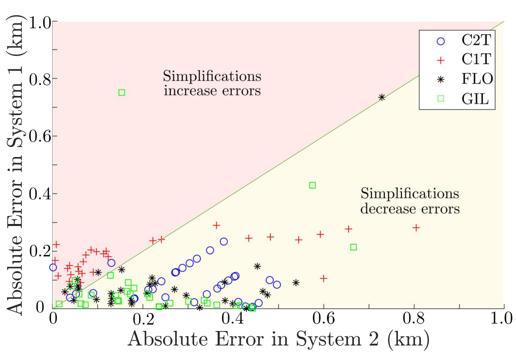


(a) AG Fault

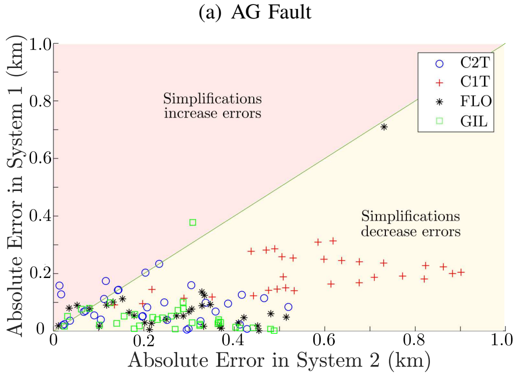


(b) BC Fault

Fig. 5. Analysis 2 - absolute error between System 1 and System 3, analyzing soil schemes. Most of the points are on the diagonal, so compared to System 1, NHS does not significantly influence on errors.

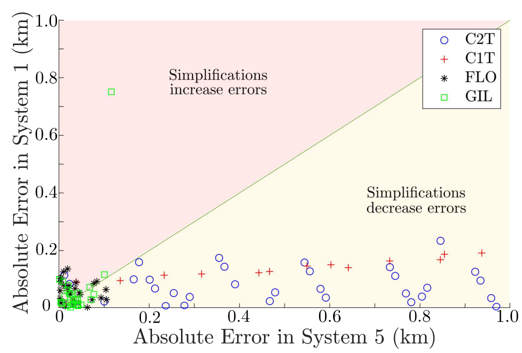


(a) AG Fault

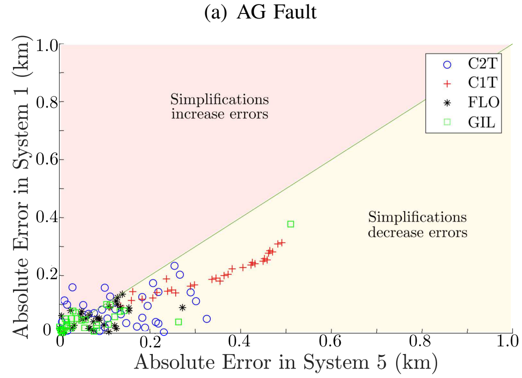


(b) BC Fault

Fig. 4. Analysis 1 - absolute error between System 1 and System 2, analyzing transposition schemes. Most of the points are on yellow area, so compared to System 1, errors increase with the real TL transposition.



(a) AG Fault



(b) BC Fault

Fig. 6. Analysis 3 - absolute error between System 1 and System 5, analyzing TL model schemes. Most of the points are on yellow area, so compared to System 1, errors increase for a system with frequency-dependent parameters.

In the literature, scatter plots are commonly used as a way to contrast the performance of the fault location obtained for different scenarios, such as depicted in [6], [18], [19]. The scatter plots present a coincidence diagonal, which represents the region on which both evaluated systems present similar performance, and two areas above (pink area) and below (yellow area) the coincidence line. In this paper, points on the superior region (pink area) represent cases in which the modeling simplifications in System 1 increase the TWFL errors, whereas points on the inferior region (yellow area) represent scenarios in which the modeling simplifications in System 1 decrease the TWFL errors. One should notice that the Y-axis is taken as the reference for the sake of comparison, being always associated to the most simplified system model among those evaluated in this paper.

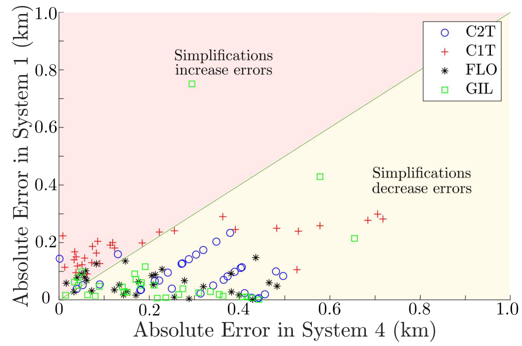
From Figs. 4(a) and 4(b), it is noticed that errors increase when the real TL transposition is modeled. When an IdT TL is considered, v is always the same along the line, but in the T model, there are four untransposed sections throughout which different v values can be verified in each phase, resulting in uncertainties that can affect the TWFL performance.

Figs. 5(a) and 5(b) show that NHS models do not significantly affect the studied TWFL methods, since most points are on the diagonal coincidence line. All evaluated methods are based on aerial mode TWs, which are slightly affected by soil characteristics. Indeed, the soil effects are expected to be more pronounced in TWFL methods that depends on the detection of ground mode TWs, but such procedure has been avoided in most TWFL schemes due to the high attenuation and dispersion of ground mode transients.

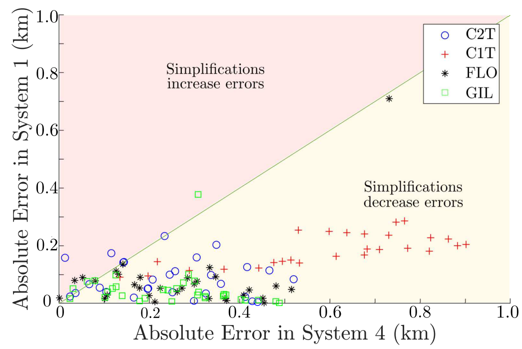
Finally, from Figs. 6(a) and 6(b), it is seen that most points are on yellow area, i.e. for a power system with constant parameters, errors are smaller than those observed for a system with frequency-dependent parameters. Besides, it can be verified that the methods FLO and GIL present better performance than C2T and C1T, since they do not require v settings, overcoming problems due to uncertainties caused by line parameters variations. Another important finding is that the TWFL errors are less dispersed and smaller for the ungrounded fault cases, since the ground mixing mode does not occur, whereas different modes are coupled in AG fault cases when reflections and refractions occur at the fault point [20]. Hence, it results in additional distortions on the analyzed signals and can affect TWFL methods.

B. Combined analysis of modeling variables

In this subsection, two different TL modeling characteristics are combined, maintaining the remaining feature fixed. Then, all the three evaluated modeling aspects are combined, resulting in four new case studies. Firstly, Fig. 7 shows the impacts of the transposition scheme and soil heterogeneities simultaneously. The performance shown in Figs. 7(a) and 7(b) are very similar to the cases in which the real transposition is considered, as presented in Fig. 4. This behavior is expected, since the NHS has shown to be not critical to the evaluated TWFL methods, which in turn depend only on the analysis of aerial mode TWs. Thereby, it can be concluded that the transposition T is the most relevant feature in this scenario.

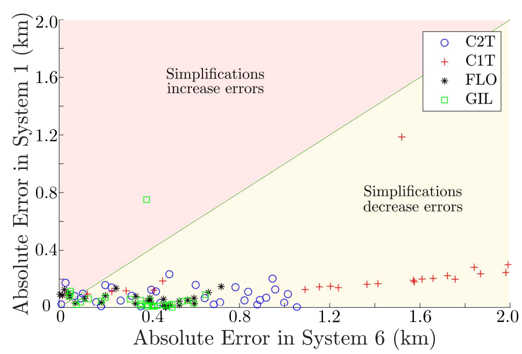


(a) AG Fault

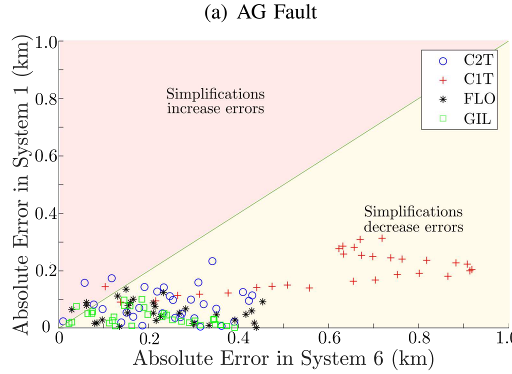


(b) BC Fault

Fig. 7. Analysis 4 - absolute error between System 1 and System 4, analyzing soil and transposition schemes. Most of the points are in the yellow area, so that, compared to System 1, errors increase with the real TL transposition and a NHS.

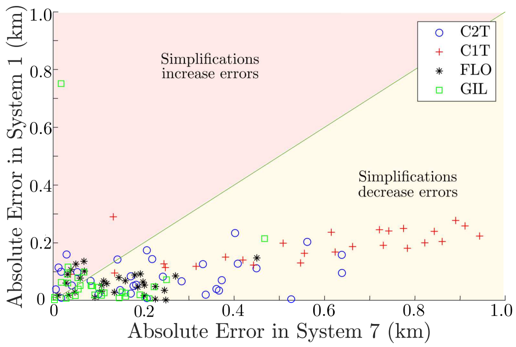


(a) AG Fault

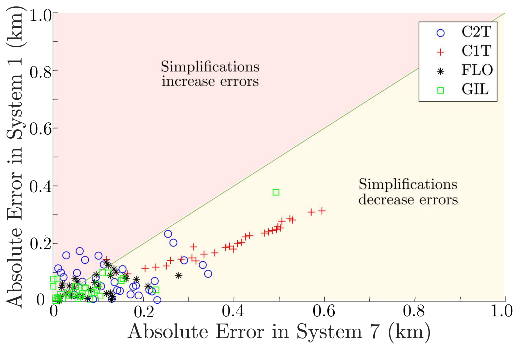


(b) BC Fault

Fig. 8. Analysis 5 - absolute error between System 1 and System 6, analyzing TL model and transposition schemes. Most of the points are in the yellow area, so that, compared to System 1, errors increase with the real TL transposition and a system with frequency-dependent parameters.

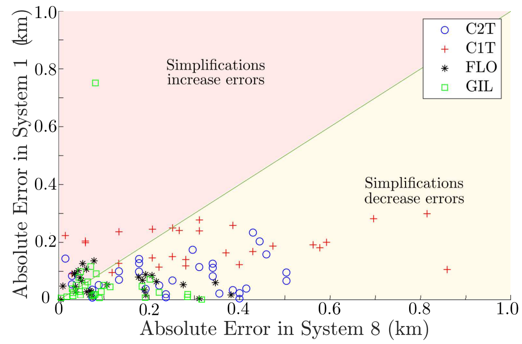


(a) AG Fault

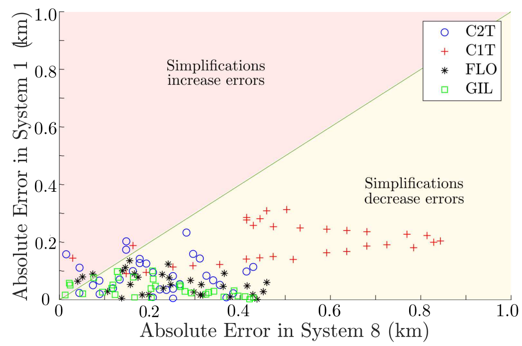


(b) BC Fault

Fig. 9. Analysis 6 - absolute error between System 1 and System 7, analyzing TL model and soil schemes. Most of the points are in the yellow area, so that, compared to System 1, errors increase with a system with frequency-dependent parameters and a NHS.



(a) AG Fault



(b) BC Fault

Fig. 10. Analysis 7 - absolute error between System 1 and System 8, analyzing TL model, soil and transposition schemes. Most of the points are in the yellow area, so that, compared to System 1, errors increase with the real TL transposition, a system with frequency-dependent parameters and a NHS.

Combining JM with T, the errors dispersion increases, as shown for the System 6 in Fig. 8. Accounting for TL frequency-dependent parameters and real transposition schemes corresponds to the same scenario analyzed in Fig. 4 and Fig. 6, in which the simplifications tend to decrease the TWFL errors. Thus, errors are expected to be more dispersed, and as concluded from Fig. 6, it is noticed that the JM model affects more in grounded fault cases, since the TWFL errors shown in Fig. 8 are greater for AG faults than for BC ones.

Concomitantly, when JM and NHS are evaluated simultaneously, as shown in Fig. 9, it is observed that higher dispersion takes place in the errors shown in Fig. 9(a) than in Fig. 9(b), which can be explained by the mixing mode effect in AG faults. It is also observed that the obtained errors are more dispersed in Fig. 9 than in Fig. 6, demonstrating that the NHS model also raises errors when JM is taken into account, whereas for Be line model the soil structure does not present relevant impact.

Finally, the last analysis of this subsection is performed by combining the different line models, soil heterogeneities and transpositions types, contrasting System 1 (considered the most simplified model) against the System 8 (considered the most realistic model). As shown in Figs. Fig. 10(a) and Fig. 10(b), most points take place in the yellow area, which is a behavior which attests that more complex TL modeling indeed pose more difficulties on TWFL methods. Even so, from the presented cases, it can be noticed that some scenarios present a different behavior, unlike the preliminary expectations.

C. Absolute errors comparison

In this subsection, boxplots obtained from the TWFL absolute errors are analyzed to evaluate the errors variability for each method. In the boxplots, the first quartile, median and third quartile are represented by the bottom edge, central line and top edge, respectively. Figs. 11 and 12 illustrate the boxplots for all the systems clustered by the TWFL algorithm for the AG and BC fault, respectively. To improve the figures legibility, the few outliers found with errors greater than 3 km and 2 km are not shown in Figs. 11 and 12, respectively, without loss of reliability of the obtained conclusions.

It is observed in Fig. 11 that the error median is below 2 km for all cases. Also, the C1T method presents larger errors due to the challenging procedure of identifying the fault-reflected TW. It is also noticed that the impact of frequency-dependence on TWFL errors is more relevant in C2T and C1T algorithms, being also observed that the systems with even code numbers present larger errors than those with odd code numbers, which proves the effects of transposition schemes specially on FLO and GIL techniques.

The median error in Fig. 12 is below 1 km for all scenarios and also the third quartile, in general, is lower than in Fig. 11, confirming that for faults involving ground, the fault location errors tend to be higher because of the mixing mode phenomena. In the Fig. 12, the increase in errors due to transposition schemes is emphasized in all techniques.

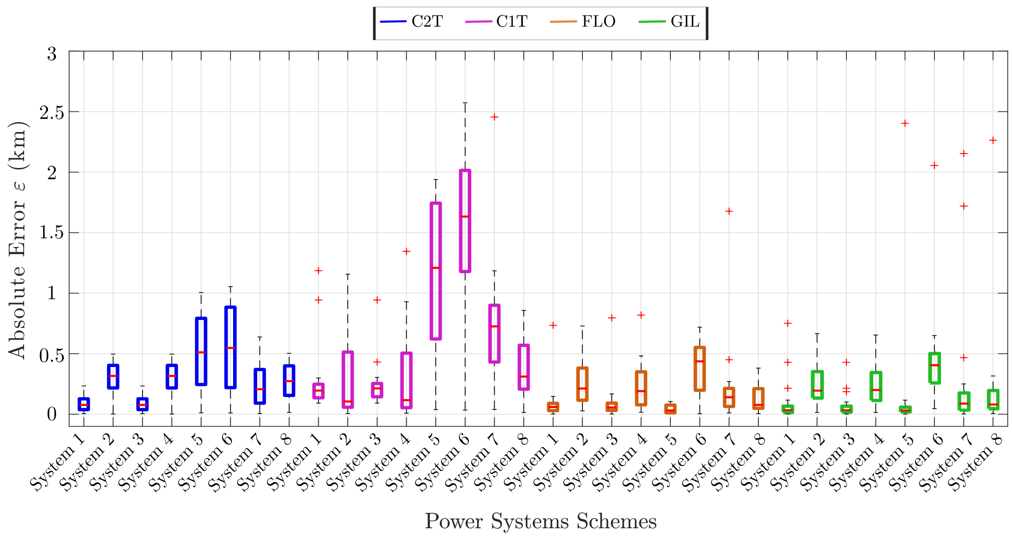


Fig. 11. Boxplot representing the absolute errors for all power systems schemes separated by TWFL methods considering AG fault.

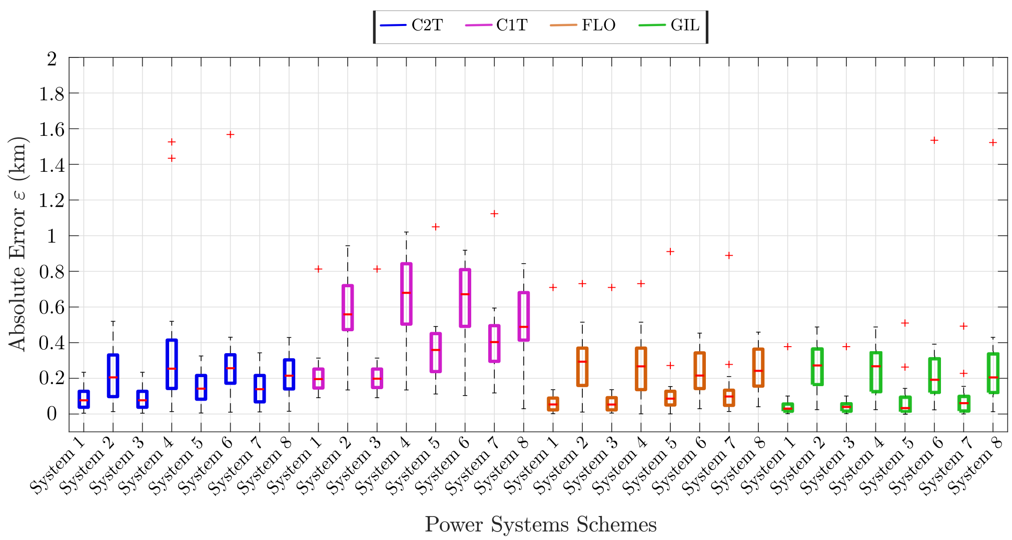


Fig. 12. Boxplot representing the absolute errors for all power systems schemes separated by TWFL methods considering BC fault.

TABLE IV
AVERAGE ERRORS PER SYSTEM

System	Average error for AG fault (km)	Average error for BC fault (km)
1	0.1149	0.1076
2	0.4642	0.3337
3	0.1078	0.1084
4	0.2426	0.4681
5	0.7377	0.1715
6	0.7074	0.4145
7	0.3843	0.1875
8	0.5545	0.3571

TABLE V
AVERAGE ERRORS PER TWFL TECHNIQUE

TWFL	Average error for AG fault (km)	Average error for BC fault (km)
C2T	0.2962	0.1976
C1T	0.8127	0.5208
FLO	0.2781	0.1983
GIL	0.2698	0.1576

To provide further information on quantitative TWFL error analysis, average errors are presented in Table IV for each system and in Table V for each evaluated TWFL algorithm, considering the cases in which the methods operated as expected. In fact, observing both tables, double-phase faults tend to present lower average errors than single-phase-to-ground faults. It is also noticed that more complex system models tend to result in larger TWFL errors, but this is not a rule. Indeed, when the same systems group are contrasted against the studies shown in the previous subsections, it is noticed that the median tends to increase. In addition, Table V confirms that TW reflected detection is a source of TWFL errors, as well as algorithms that do not require TL electrical parameters (such as TW propagation speed) contribute to a more accurate fault location.

V. Conclusions

This paper investigates the impact of TL modeling aspects on TW-based fault location methods (called here TWFL) when EMTP softwares are used. Three different characteristics of TL modeling were evaluated, namely: frequency-dependent parameters, soil heterogeneities an different transposition schemes. As a reference for all evaluations, a simplified system model commonly applied for EMTP tests was considered, consisting of a TL modeled as Bergeron (Be) with homogeneous soil (HS) and being ideally transposed (IdT). A total of eight systems were modeled and compared with the reference simplified model. AG and BC fault simulations were taken into account, varying also fault distance at 32 different points. A total of four TWFL methods were evaluated and the respective absolute errors were assessed by comparisons carried out via scatter plots and also using boxplots to illustrate statistics on the obtained absolute fault location errors, such as the median as well as maximum error in 25% and 75% of the cases represented by the first and third quartiles of the boxplot, respectively. Finally, the average errors were also analyzed, providing an overall view on the obtained results.

The obtained results show that considering a more detailed power system model and including more realistic aspects tend to increase the TWFL absolute errors when compared to the most simplified system considered in this paper. Such a finding is observed for all the evaluated methods, except by the fact that those methods that do not require settings based on TL parameters have shown to be more reliable. Indeed, from the results, the more simplified the TL model is, the smaller the absolute errors are, except for the soil heterogeneities when using the Be model, which consisted in the only case in which additional modeling complexity did not result in larger TWFL errors. In this context, the transposition scheme and TL parameters frequency dependence shown to be a noticeable modeling aspects that can increase TWFL errors.

In real-world scenarios, it is expected that power systems will present characteristics close to those verified in the most complex system model considered in this paper. Hence, the obtained results can be useful for those who need to model lines in EMTP platforms for the sake of TWFL evaluation. Indeed, the results demonstrate how TWFL methods can be affected by different line modeling strategies, pointing out that some features can favor or compromise the TWFL performance results. Thus, as a general conclusion, it is demonstrated that testing TWFL algorithms by using simplified TL models may be not appropriate, depending on the desired simulation accuracy, since these models may not represent realistic scenarios. Besides, as a byproduct, it was observed that, due to the mixing mode, grounded faults are more adverse from the point of view of fault-induced TWs detection, being more critical for techniques that require fault-reflected TWs to be detected. Also, it is demonstrated that the methods which do not require the propagation speed parameters present lower errors in most cases, which indicates that including models that pose uncertainties in line parameters is an important modeling aspect for EMTP simulations when TWFL methods are under investigation.

References

[1] E. O. Schweitzer, A. Guzmán, M. V. Mynam, V. Skendzic, B. Kasztenny, and S. Marx, "Locating faults by the traveling waves they launch," in *2014 67th Annual Conference for Protective Relay Engineers*, 2014, pp. 95–110.

[2] J. D. Glover, M. S. Sarma, and T. J. Overbye, *Power System Analysis and Design;*, 5th ed. CENGAGE Learning, 2011.

[3] A. Martins-Britto, "Realistic modeling of power lines for transient electromagnetic interference studies," Ph.D. dissertation, 07 2020.

[4] L. M. A. Ribeiro, G. A. Cunha, E. P. A. Ribeiro, A. G. Martins-Brito, and F. V. Lopes, "Analysis of traveling waves propagation characteristics considering different transmission line emtp models," *5th Workshop on Communication Networks and Power Systems (WCNPS 2020)*, pp. 1–6.

[5] K. Sidwall and P. Forsyth, "Advancements in real-time simulation for the validation of grid modernization technologies," *Energies*, vol. 13, p. 4036, 08 2020.

[6] F. V. Lopes, K. M. Dantas, K. M. Silva, and F. B. Costa, "Accurate two-terminal transmission line fault location using traveling waves," *IEEE Transactions on Power Delivery*, vol. 33, no. 2, pp. 873–880, 2018.

[7] G. A. da Cunha, F. V. Lopes, and T. da Rocha Honorato, "Influence of traveling wave detection sensitivity on transient pattern recognition-based single-ended fault location approach," in *2019 Workshop on Communication Networks and Power Systems (WCNPS)*, 2019, pp. 1–5.

[8] M. M. Saha, J. J. Izykowski, and E. Rosolowski, *Fault Location on Power Networks*, 1st ed. Springer Publishing Company, Incorporated, 2009.

[9] P. F. Gale, P. A. Crossley, Xu Bingyin, Ge Yaozhong, B. J. Cory, and J. R. G. Barker, "Fault location based on travelling waves," in *1993 Fifth International Conference on Developments in Power System Protection*, 1993, pp. 54–59.

[10] L. V. Bewley, "Traveling waves on transmission systems," *Transactions of the American Institute of Electrical Engineers*, vol. 50, no. 2, pp. 532–550, 1931.

[11] H. Chalangar, T. Ould-Bachir, K. Sheshyekani, S. Li, and J. Mahseredjian, "Evaluation of a constant parameter line-based twfl real-time testbed," *IEEE Transactions on Power Delivery*, vol. 35, no. 2, pp. 1010–1019, 2020.

[12] E. O. Schweitzer, B. Kasztenny, and M. V. Mynam, "Performance of time-domain line protection elements on real-world faults," in *2016 69th Annual Conference for Protective Relay Engineers (CPRE)*, 2016, pp. 1–17.

[13] M. Gilany, D. k. Ibrahim, and E. S. Tag Eldin, "Traveling-wave-based fault-location scheme for multiend-aged underground cable system," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 82–89, 2007.

[14] A. Guzmán, B. Kasztenny, Y. Tong, and M. V. Mynam, "Accurate and economical traveling-wave fault locating without communications," in *2018 71st Annual Conference for Protective Relay Engineers (CPRE)*, 2018, pp. 1–18.

[15] E. O. III, Schweitzer, A. Guzman-Casillas, B. Z. Kasztenny, Y. Tong, and M. V. Mynam, "Traveling wave based single end fault location," May 21 2019, US Patent 10,295,585.

[16] H. W. Dommel, "Digital computer solution of electromagnetic transients in single-and multiphase networks," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-88, no. 4, pp. 388–399, 1969.

[17] J. R. Marti, "Accurate modelling of frequency-dependent transmission lines in electromagnetic transient simulations," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 1, pp. 147–157, 1982.

[18] F. V. Lopes, P. Lima, J. P. G. Ribeiro, T. R. Honorato, K. M. Silva, E. J. S. Leite, W. L. A. Neves, and G. Rocha, "Practical methodology for two-terminal traveling wave-based fault location eliminating the need for line parameters and time synchronization," *IEEE Transactions on Power Delivery*, vol. 34, no. 6, pp. 2123–2134, 2019.

[19] E. Schweitzer, B. Kasztenny, M. Mynam, A. Guzman, N. Fischer, and V. Skendzic, "Defining and measuring the performance of line protective relays," in *Western Protective Relay Conference*, 10 2016.

[20] A. G. Phadke and J. S. Thorp, *Computer Relaying for Power Systems*, ser. Power Systems. Chichester, England: John Wiley and Sons Ltd, 2009.