Sensitivity Analysis of Traveling Wave-Based and Impedance-Based Fault Location Techniques

R. L. A. Reis, W. L. A. Neves, F. V. Lopes, D. Fernandes Jr.

Abstract—**In this paper, a sensitivity analysis of traveling wave (TW)-based and impedance-based fault location algorithms is performed. Sources of errors as current transformer (CT) saturation, fault characteristics, uncertain transmission line parameters, and coupling capacitive voltage transformer (CCVT)-induced transients are evaluated. To do so, simulated records taken from the Alternative Transients Program (ATP) in a 230 kV transmission network are used as input data for both categories of fault locators, whose performances are investigated in order to point out the more appropriate technique to be used in industry applications to improve the fault location process.**

Keywords—**Impedance-based fault location, protective relay, sensitivity analysis, transmission lines, traveling-wave based fault location.**

I. Introduction

TRADITIONALLY, impedance-based fault location methods have been used over the years for being considered the simplest and economical methodology for estimating the short-circuit distance. Indeed, since they use the fundamental voltage and current phasors as input data, they need low sampling rates, reducing the associated cost [1]. However, each specific impedance-based routine makes certain assumptions that may not hold true in different electric power systems, making the choice of the most suitable technique a challenging task [1], [2]. In these kind of algorithms, current transformer (CT) saturation, fault resistance, inaccurate transmission line parameters, load current, DC offset etc. are usually reported as limiting factors [1]–[3]. In addition to it, the performance of impedance-based fault locators may also be affected in cases in which the transmission relaying trips before the coupling capacitive voltage transformers (CCVT)-induced transients are completely damped [4].

With the recently technological advancement, traveling wave (TW)-based techniques have been embedded in protective devices with sampling rates in the order of MHz [5]. This kind of method has appeared as very accurate and faster than the impedance-based routines, since they are based on the identification of the fault-induced transients. Besides, TW-based routines are commonly reported as immune to the aforementioned limiting factors that affect impedance-based methods, although a scarce number of references that investigate in detail these scenarios are available in the literature [6], especially when both categories are evaluated together [7].

In [2] and [8], the theory overview and analysis of various fault-locating error sources in impedance-based techniques are presented, but the CCVT-induced transients are not evaluated. On the other hand, [1] lists some TW-based limiting factors, but simulation results are not presented. In [9], a sensitivity analysis of TW-based algorithms regarding the sampling rate effect is performed, however, the obtained results show only that higher sampling frequencies provide better fault-locating estimation results, which was already expected. Studies regarding both TW-based and impedance-based fault locators are performed in [7], in which extensive sensitivity analyses of the data acquisition system influence on the performance of both groups of methods are carried out, although only the CCVT-induced transients and anti-aliasing filters are evaluated. Therefore, this paper presents a detailed sensitivity analysis for both TW-based and impedance-based fault location techniques, pointing out some feasible solutions and trends for industry applications that could improve the fault location process.

In this way, the sensitivity analyses taking into account the CT saturation, fault resistance and inception angle, inaccurate transmission line parameters, and CCVT-induced transients are performed through a wide variety of fault simulations on a 230 kV transmission network using the Alternative Transients Program (ATP) [10]. From the obtained results, it is shown that number of sources of error that can affect the TW-based methods is reduced in comparison to those that influence impedance-based ones.

II. Fault Location Techniques

Here, classical TW-based and impedance-based fault location methods reported in literature are evaluated. To better understand the principles of the analyzed algorithms, consider the 230 kV power system shown in Fig. 1. The network consists of a transmission line with length ℓ connecting both Local and Remote power networks, which are represented by their respective Thévenin equivalent circuits, being $\hat{V}_L$ and $\hat{I}_L$ the voltage and current phasors at the Local End, respectively, and $\hat{V}_R$ and $\hat{I}_R$ the voltage and current phasors at the Remote End, respectively. The system parameters used in the ATP fault simulations are described in section III.

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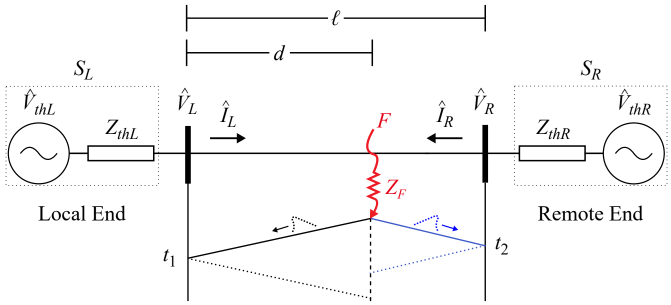

Fig. 1. One-line diagram of a 230 kV transmission network used for describing the fault location methods and in the ATP simulations.

A. TW-based Algorithm (TWFL)

The essential idea behind the TW-based routines consists on the identification of successive voltage and/or current fault-induced traveling waves in a monitored transmission line. This kind of method needs high sampling rates to accurately detect the propagation time of the traveling waves in order to estimate the fault location, which was reported in the past as a limiting factor in real applications [1]. However, this issue has recently been overcome with digital protective devices using sampling frequencies in the order of MHz [5].

According to [11], two-ended methods are more reliable and accurate since they need to detect only the first fault-induced incident traveling waves at the monitored line buses (t_1 and t_2 shown in Fig. 1), although a communication link between the line terminals is needed. In this paper, the two-terminal TW-based algorithm (TWFL) reported in [11] is used, in which the fault location $\tilde{d}$ is estimated by:

$$\tilde{d} = \frac{\ell + (t_1 - t_2) \cdot v}{2} , \quad (1)$$

where ℓ is the line length, t_1 and t_2 are the time instants at which the first fault-induced traveling waves are detected at local and remote buses, respectively, and v is the aerial mode traveling wave propagation speed, which was computed here as $v = 1/\sqrt{LC}$, being L and C the transmission line positive sequence inductance and capacitance, respectively. To detect t_1 and t_2, the method reported in [12] was implemented.

B. Impedance-based Algorithms

Impedance-based techniques use voltage and current fundamental phasors taken from digital relays to estimate the apparent impedance of the faulted-line path [1], [2]. Here, one- and two-ended methods were implemented. To estimate voltage and current phasors, the Full Cycle Discrete Fourier Transform is applied with a mimic filter for decaying DC offset removal [13], [14].

1) One-Ended Method (OEM): One-terminal algorithms are commonly reported as the simplest and economical way for implementing fault location schemes, which yield acceptable fault location estimates for most of the practical applications, and do not need any communication channel or data synchronization between local and remote buses [1], [2].

Here, the OEM reported in [15] was used, which estimates the fault distance $\tilde{d}$ by:

$$\tilde{d} = \frac{\text{imag}(\hat{V}_L \cdot \Delta\hat{I}_L^*)}{\text{imag}(Z_{L1} \cdot \hat{I}_L \cdot \Delta\hat{I}_L^*)} , \quad (2)$$

where $\Delta\hat{I}_L$ is the "pure fault" current phasor taken from the monitored line end and Z_{L1} is the positive sequence line impedance. The values of $\hat{V}_L$, $\hat{I}_L$, and $\Delta\hat{I}_L$ consist of loop quantities and they depend on the fault type [2].

2) Two-Ended Method (TEM): Despite the communication link between the transmission line ends is needed, the two-terminal phasor-based routines are considered as more reliable than the one-terminal algorithms, since more network information is used to estimate the fault distance. In these cases, phasor measurements taken from the remote end eliminate infeed errors caused by the fault impedance [1], [2].

Here, the TEM reported in [2] is evaluated, in which the fault point $\tilde{d}$ is computed by:

$$\tilde{d} = \frac{\hat{V}_{L2} - \hat{V}_{R2} + Z_{L2} \cdot \hat{I}_{R2}}{(\hat{I}_{L2} + \hat{I}_{R2}) \cdot Z_{L2}} , \quad (3)$$

where $\hat{V}_{L2}$ and $\hat{V}_{R2}$ are the negative sequence voltages at local and remote ends, respectively, $\hat{I}_{L2}$ and $\hat{I}_{R2}$ are the negative sequence currents at local and remote line ends, respectively, and Z_{L2} is the negative sequence transmission line impedance. For three-phase balanced faults, (3) may still be applied just by replacing the negative sequence components by positive sequence ones [2].

III. Analysis and Results

The sensitivity analysis of each analyzed method is performed by means of several ATP fault simulations in the 230 kV transmission network shown in Fig. 1, which is modeled with actual parameters and considering frequency-constant distributed transmission line model [6]. The electric power system line parameters are presented in Table I, and its Thévenin equivalents are presented in Table II.

TABLE I
Transmission Line Parameters

Sequence Components	R (Ω/km)	X (Ω/km)	ωC (μS/km)
Positive	0.0980	0.5100	3.2520
Zero	0.5320	1.5410	2.2930

TABLE II
Power Network Thévenin Equivalent Parameters

Source	$\hat{V}_{th}$(p.u.)	Z_{th}			
		$R_1(\Omega)$	$X_1(\Omega)$	$R_0(\Omega)$	$X_0(\Omega)$
S_L	$1.02\angle 0°$	0.8713	25.661	1.0141	18.754
S_R	$0.98\angle -10°$	0.9681	28.513	1.1268	20.838

In each short-circuit scenario, the ATP oscillographic records are used as input data in the evaluated fault location techniques, whose performances are assessed according to the estimated fault distance error ε, which is computed as:

$$\varepsilon(\%) = \frac{|d - \tilde{d}|}{\ell} \cdot 100 \ , \qquad (4)$$

where d is the actual fault location, $\tilde{d}$ is the estimated fault distance, and ℓ is the transmission line length, which was taken here as 300 km. In each sensitivity analysis, the fault distance was varied from 10 to 290 km, with steps of 35 km.

The oscillographic records were generated using a sampling rate of 1 MHz for applications with the TW-based fault location algorithm, and a sampling frequency of 960 Hz for the phasor-based methods, in which the current and voltage waveforms were taken from ideal CT and CCVT installed at both local and remote buses of the system shown in Fig. 1, respectively (except for the analysis in sections III-B and III-C, in which realistic models of CT and CCVT are taken into account). For the OEM and TEM, the fault distances were estimated taking into account three cycles after the fault-induced transient detection. For the TWFL, the time instants (t_1 and t_2) used in (1) were considered as the first fault-induced traveling waves detected at the local and remote buses, respectively, regardless to be voltage or current waves.

Basically, for the subsequent analysis, the ATP short-circuit simulations were performed fixing the fault type, resistance and inception angle (except for the analysis in section III-D, in which the fault resistance and inception angle are varied). In this way, a scenario in which the fault characteristics has minimally affected the fault-induced transients and, consequently, the fault location methods performance was sought. Thus, after several tests, the situation of an AG fault, with resistance of 1 Ω and inception angle of 0° was chosen as the default case.

A. Inaccuracies in Transmission Line Parameters

Although the utilities know the transmission line parameters, these values may present uncertainties, which may affect the performance of protective devices. In this way, the impact of possible inaccuracies in the positive and zero sequence line parameters on the performance of the fault locators described in section II is evaluated. To do so, simulations considering ideal line parameters (see Table I) and inaccuracies in the order of ±20% in relation to the actual nominal parameters are taken into account. In this way, in each fault simulation, the values of R, X and ωC were simultaneously varied. The simulation results are depicted in Figs. 2 and 3.

From the obtained results presented in Fig. 2, it can be seen that only the one-terminal method was affected by inaccuracies in the zero sequence transmission line parameters. This is due to the fact that this kind of technique uses zero sequence values to compute the compensation factor for line-to-ground faults, which is used as input data in the algorithm. Therefore, variations in the zero sequence line parameters increase the computed compensation factor error, which affects the OEM accuracy. On the other hand, the TEM and TWFL were immune to inaccuracies in the zero sequence parameters, since they do not depend on these values to estimate the fault location.

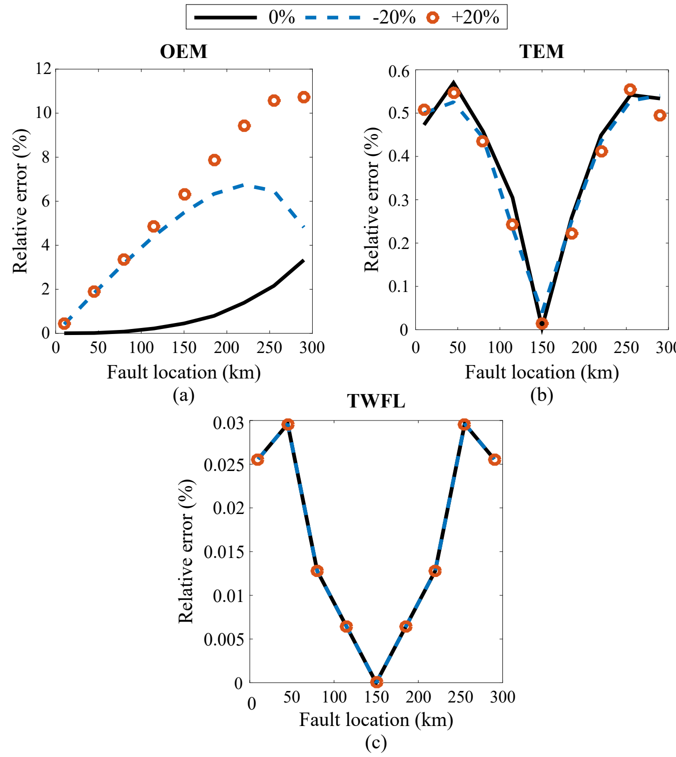

Fig. 2. Impact of inaccuracies in the zero sequence transmission line parameters on the performance of fault location methods: (a) OEM; (b) TEM; (c) TWFL.

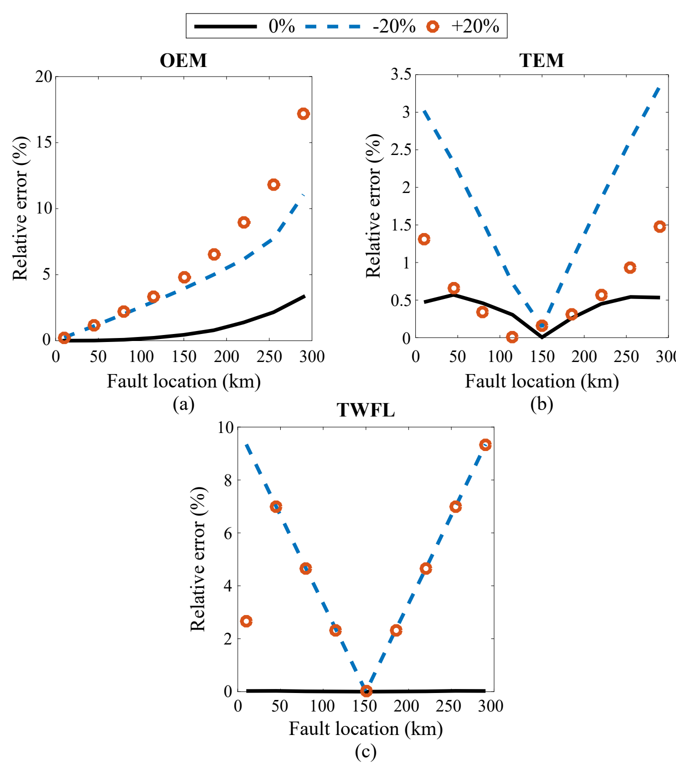

Fig. 3. Impact of inaccuracies in the positive sequence transmission line parameters on the performance of fault location methods: (a) OEM; (b) TEM; (c) TWFL.

In relation to inaccuracies in the positive sequence line parameters, it can be seen in Fig. 3 that all evaluated routines were affected. In fact, the OEM uses the Z_{L1} in its formulation (see section II-B), in such a way that variations in Z_{L1} increased the fault location estimated errors. Regarding the TEM performance, which uses negative sequence values in its description (see (3)), the Z_{L1} changing also increased the fault location errors, since usually Z_{L2} is considered equal to Z_{L1}. Regarding the TWFL performance, although Z_{L1} is not presented in its formulation (see (1)), the positive sequence line parameters are used to compute the traveling wave propagation speed.

B. CT Saturation

In this section, the main goal is determine if the distortion in the secondary current signal caused by a saturated CT can affect the evaluated fault location techniques. To illustrate the effects of a CT saturation in the secondary measurements, it is shown in Fig. 4 the current signals for the same fault described in section III located at 10 km and at 290 km away from the Local End of the power system depicted in Fig. 1. The used CT model is reported in [16]. The primary and secondary waveforms were normalized in per unit values.

From Fig. 4, it can be seen that significant differences in the measurements take place when the CT is saturated, mainly for faults next to the monitored bus.

Here, the fault distances were estimated considering cases of unsaturated and saturated CTs at both local and remote buses of the power network presented in Fig. 1. The obtained results are shown in Fig. 5.

From the results presented in Fig. 5, it is noted that only the phasor-based routines were affected by the CT saturation. In fact, a signal distortion caused by a CT saturation impacts on the performance of phasor estimation algorithms, and consequently, the impedance-based fault location methods, since they use the fundamental phasor information as input data to estimate the fault distances.

Regarding the OEM performance, the highest errors are obtained for faults applied next to the monitored line buses. In fact, greater levels of CT saturation are noticed in these cases, which leads to greater errors in the computed current phasors, affecting the OEM performance. As the fault moves away from the monitored bus, the CT saturation level is less evident, leading to smaller errors in the fault location technique. On the other hand, since the TEM uses current samples taken from saturated CT installed at both line buses, the highest errors are found for faults next to the buses. In these analysis, the TWFL has proved to be immune to such a phenomena.

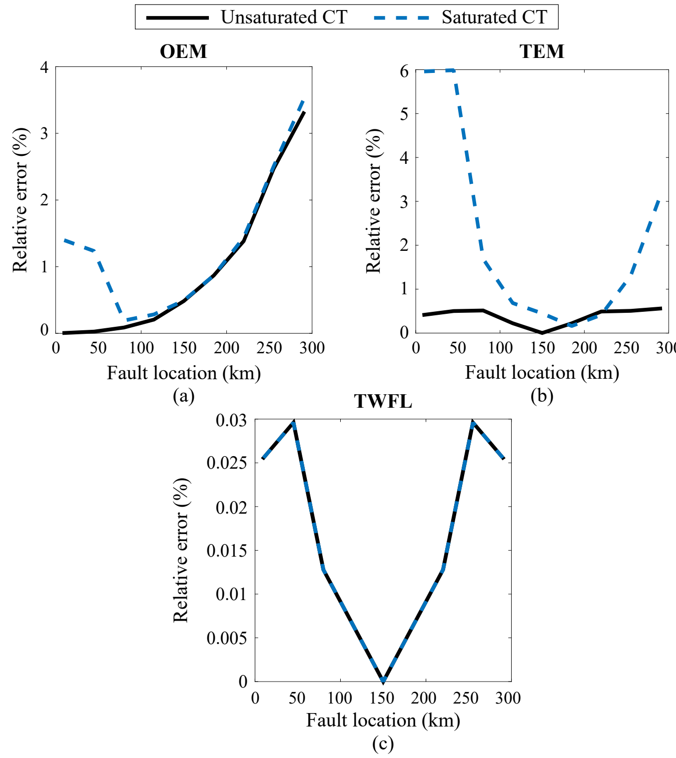

Fig. 5. Impact of a saturated CT on the performance of fault location methods: (a) OEM; (b) TEM; (c) TWFL.

C. CCVT

In steady-state operation, the CCVT performance is acceptable for the most demanding protection applications. On the other hand, the CCVT-induced transients during line faults may affect the performance of protection and fault location algorithms, since the secondary voltage signals may be different from their respective primary ones [4], [7]. To illustrate the effects of CCVT measurements, it is shown in Fig. 6 the CCVT dynamic behavior during a fault with inception angle equals to zero. The CCVT digital model is reported in [16].

From Fig 6, it is shown that discrepancies appear in the CCVT measurements, which may affect the performance of protection functions. Higher differences would be noticed for other fault inception angles [7].

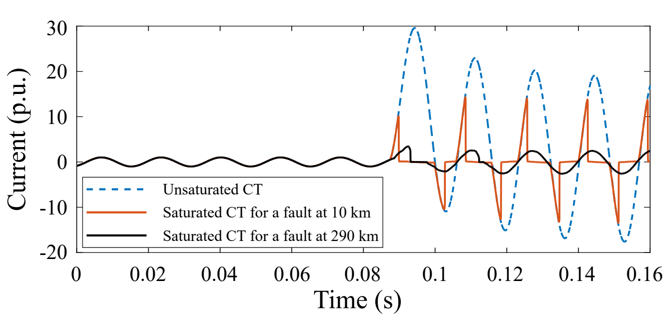

Fig. 4. Effects of CT saturation on the secondary measurements.

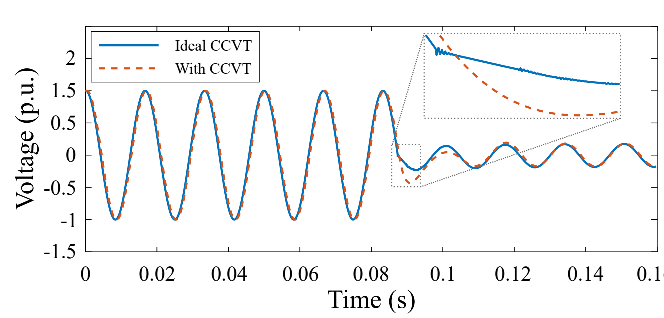

Fig. 6. Effect of CCVT measurement for a zero crossing fault.

To evaluate the impact of CCVT on the performance of the analyzed fault locators, the short-circuit distances were estimated considering voltage measurements taken from an ideal CCVT and from the analyzed CCVT model. The obtained results are depicted in Fig. 7.

From the obtained results presented in Fig. 7, it can be seen that the use of voltage measurements taken from the CCVT provided distinct results in relation to the ideal equipment. Regarding the impedance-based methods, the CCVT-induced transients directly affect the phasor estimation routines, and consequently, the performance of OEM and TEM may be compromised. It is important to highlight that the errors depicted in Figs. 7(a) and (b) taking both ideal and CCVT voltage measurements are close to each other since the fault distances were estimated considering three cycles after the fault detection. Higher errors would be obtained if a smaller number of cycles after the fault detection were taken into account, since in these cases the CCVT-induced transients are more evident.

Regarding the TWFL performance, higher errors are obtained when CCVT voltage measurements are taken into account. This is due to the fact that this CCVT digital model considerably attenuates high frequency components [6], which in turn affects the fault detection task. In this way, the most TW-based applications use current signals as input data, although if the CCVT frequency response amplifies high frequency components, better results can be obtained even than using current measurements [7].

D. Fault Characteristics

The influence of fault resistance and inception angle on the performance of the analyzed methods are evaluated in this section. Resistances values of 1 Ω, 40 Ω, and 100 Ω were taken into account. On the other hand, inception angles of 0°, 30°, 60°, and 90° were considered. The obtained results are shown in Figs. 8 and 9.

From the obtained results presented in Fig. 8, it is noted that higher values of fault resistances cause higher estimated fault distance errors. In fact, the apparent impedance computed by OEM is directly affected since greater reactance errors are computed. In addition to it, higher errors were obtained for faults applied far away from the monitored bus, since in these cases the transmission line capacitive effect is greater. On the other hand, the TEM and TWFL were barely affected.

Regarding the obtained results presented in Fig. 9, it is noted that the phasor-based techniques were almost not affected by variations in the fault inception angle. In fact, the used phasor estimation procedure do not take any quantity that depend on phase angles in its formulation, leading the OEM and TEM to be practically immune to this feature. On the other hand, different results were estimated with the TWFL. The best estimations were obtained for an inception angle equal to 90°, which is the time instant at which higher fault-induced transients are generated, making the fault detection procedure easier. Higher errors were estimated for 0° and 30°, cases in which the fault-induced transients are considerably attenuated.

In general, it was attested that the one-terminal impedance-based algorithm was more affected by the features evaluated in the sensitivity analyses performed in this paper, in which

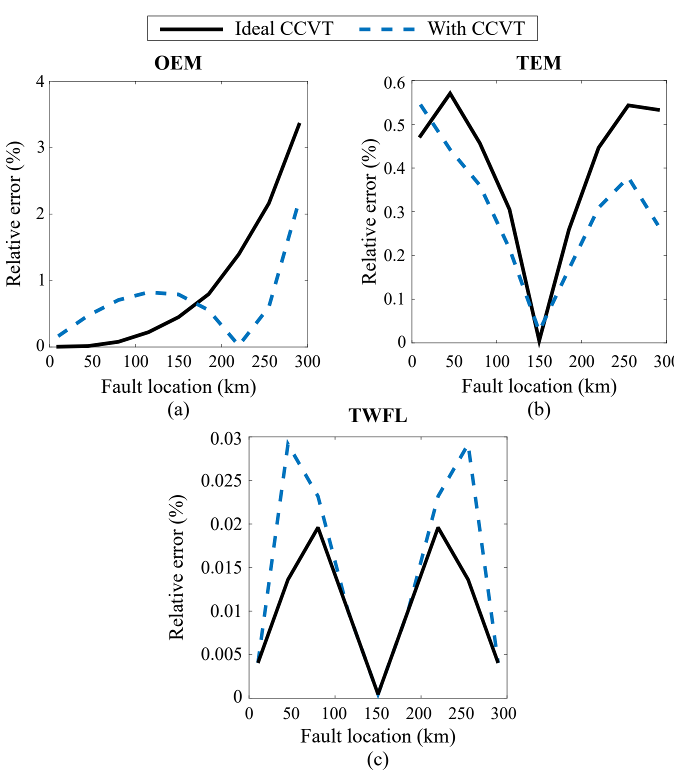

Fig. 7. Impact of CCVT on the performance of fault location methods: (a) OEM; (b) TEM; (c) TWFL.

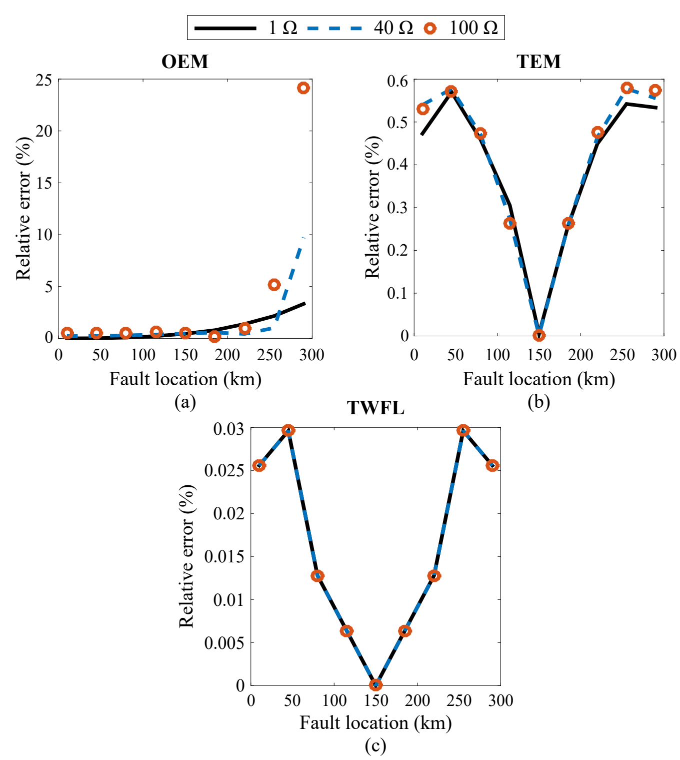

Fig. 8. Impact of fault resistances on the performance of fault location methods: (a) OEM; (b) TEM; (c) TWFL.

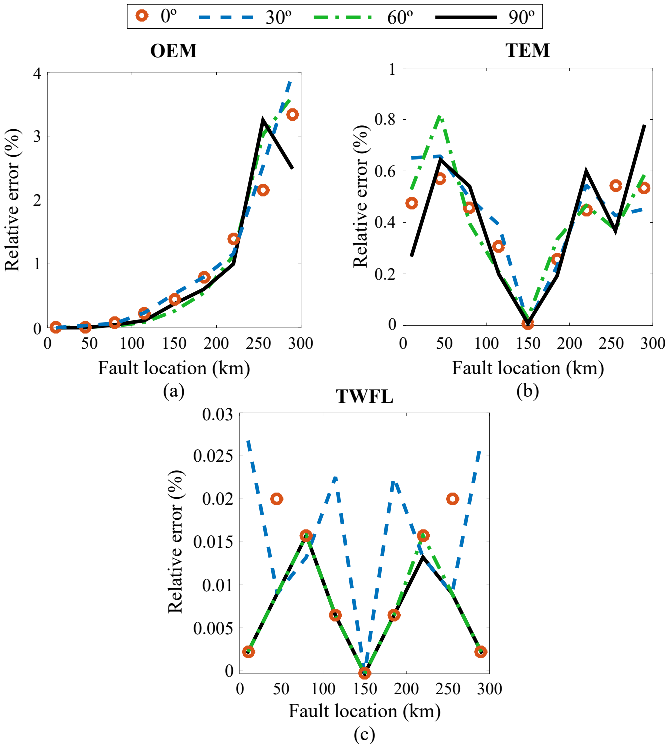

Fig. 9. Impact of fault inception angles on the performance of fault location methods: (a) OEM; (b) TEM; (c) TWFL.

the greater errors were obtained for faults applied far away from the monitored transmission line bus due to the greater capacitive line effect, causing inaccuracies in the computed apparent impedance. On the other hand, the two-terminal phasor-based technique has appeared to be more immune to the analyzed features in relation to the OEM, since smaller errors were obtained. In fact, these results were expected since more information about the power network are used to estimate the fault distance. In the same context, the TW-based routine provided the best results, appearing as an important tool to be used in industry applications.

It is worth mentioning that the evaluated two-terminal TWFL method needs a communication link between the line ends, which is commonly reported as more accurate although it is more expensive. In cases in which the communication link is not available, one-ended TW-based routines appear as a promising tool, even though more sensitivity analyses are still needed to compare both one- and two-ended routines.

IV. Conclusions

Sensitivity analyses on the performance of TW-based and impedance-based fault location algorithms were performed. Basically, the impact of inaccurate transmission line parameters, CT saturation, CCVT-induced transients and fault characteristics were investigated by means of several ATP fault simulations.

From the obtained results, the one-ended impedance-based fault location technique has shown to be more affected by zero and positive sequence line parameters uncertainties, CT saturation and CCVT-induced transients. In addition to it, higher errors were also obtained for short-circuits applied far away from the monitored line bus due to the increased line capacitive effect. Better results were estimated with the two-terminal impedance-based fault location routine, which is already expected since more information about the power network is used as input data.

On the other hand, the two-terminal TW-based fault location method has proved to be more immune to the analyzed features, since better estimation results were obtained, which makes it an important tool to be used in industry applications.

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