REALISTIC METHODOLOGY FOR FAULT LOCATION AND PROTECTION TESTS BASED ON TRAVELING WAVES

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Abstract

The present work will address a new methodology, a system composed of software and hardware that is capable of accurately modeling all the components of the electrical system, including the transmission lines, and reproducing wave forms up to megahertz at secondary levels, thus contemplating all the necessary requirements for evaluating the traveling waves (TW) devices, without creating artificial pulses.

Commercial IEDs will be tested by the solution and the results will be presented for different fault types, incidence angles and fault locations. A practical comparison will also be made between fault locators based on impedance and locators based on traveling waves, demonstrating that the accuracy obtained by the TW algorithms is in the order of meters while the previous technology presents a range of kilometers.

1 Introduction

The interconnected electrical systems are day by day requiring faster and precise identification of faults to ensure its stability. Due to this need, more efficient location and protection algorithms are needed so that the impact of the defect is mitigated as quickly as possible. Among the various methods in the literature, algorithms based on traveling waves stand out for their high accuracy.

With the mastery of this technology, IED's manufacturers started to use TW not only for the identification of the fault location, but also for protection, aiming to reduce the total TRIP time. Thus, it is necessary to use test systems capable of checking such functionalities through voltage and current waveforms that best represent the real behavior of the electrical power system, including fundamental frequency and traveling waves. So, the use of software that performs transient conditions simulations in conjunction with hardware capable of reliably reproducing the simulated signals is essential for testing the TW devices.

2 Double-Ended Traveling Wave Fault Location

The double-ended traveling-wave-based fault-locating (DETWFL) method using traveling waves was first introduced in a transmission line protective relay in 2012 [1]. Since then, the DETWFL method has also been made available in ultra-high-speed (UHS) relays. TW-based fault locating is widely popular with transmission system operators, largely due to its field-proven track record with reported errors being within one tower span (300 m) on average, regardless of line length. The DETWFL method incorporated in UHS relays provides accurate results, but it requires TW data from the two line terminals. When relay-to-relay communications are available, the UHS relay can collect the necessary time stamps of the initial TW that arrives at each terminal when a fault occurs, automatically calculate the fault location using the DETWFL method, and make the result available to the user within tens of milliseconds. Relay-to-relay communications can be achieved by using a dedicated point-to-point fiber-optic channel (i.e., direct fiber) or an IEEE C37.94 multiplexed channel. However, there are situations where relay-to-relay communications may not be available. In this case, accurate fault location results can still be obtained by using the offline DETWFL methodology.

Fig. 1 shows a Bewley diagram, which is a time-spatial chart that shows TWs progressing along the time axis (vertically down) and simultaneously progressing along the distance axis (left to right and right to left), for a fault at location F on a line of length LL. The fault is M from the local terminal, L, and LL – M from the remote terminal, R. Faults launch TWs that propagate with a velocity (PV) equal to LL divided by traveling wave line propagation time, TWLPT (i.e., PV = LL/TWLPT).

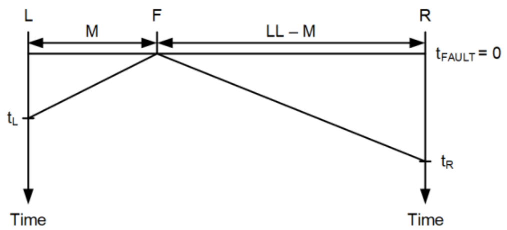


Fig. 1. Bewley-Lattice diagram - DETWFL method

When a fault occurs at time $t_{FAULT} = 0$, the first TW arrives at terminal L at time $t_L = M/PV = M \bullet TWLPT/LL$. Similarly, the first TW arrives at terminal R at time $t_R = (LL - M)/PV = (LL - M) \bullet TWLPT/LL$. Solving these two equations for fault location, M, we obtain the general equation used for DETWFL as (1).

$$M = \frac{LL}{2}\left(1 + \frac{t_L - t_R}{TWLPT}\right) \quad (1)$$

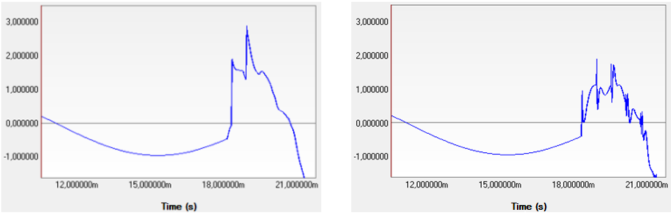
The TWLPT for the transmission line can be measured during commissioning by performing a line energization test. Since the accuracy of the calculated fault location from (1) is highly dependent on TW arrival times with submicrosecond resolution, the method the fault locator applies to estimate the TW arrival time is critical to its accuracy.

3 Methodology

Other test solutions for functions based on traveling waves do not reproduce the complete behavior of the waveforms neither the real amplitude values. There are testers that just inject an artificial pulse of voltage or current to reproduce the traveling wave arrival time with limited quantity of pulses, others apply artificial pulses added to low frequency waveforms and there are also real-time simulators that reproduce the faithful waveform, but just at a low level, which is not suitable for connection with devices.
Artificial pulses are the ideal scenario for a TW algorithm to identify wavefronts, but they are not ideal for testing, as they do not represents the correct waveform and so do not guarantee a deep IED algorithm evaluation. In the situation of a real fault, the signals measured by the TW devices are complex (non-periodic signals with a wide frequency spectrum and several reflections) and the TW are presented with amplitudes that are totally different from those applied by artificial pulses.

3.1 Waveforms: Artificial x Real

Real waveforms come from simulators capable of reliably reproducing the behavior of all components of the electrical system, while artificial waveforms only inject fixed magnitude pulses at moments calculated as a function of the traveling wave propagation time in the line and from the point of fault.
Artificial waveforms cannot correctly represent the magnitude of traveling waves and not all of their reflections. This means that regardless of the fault point, fault impedance, short-circuit level and fault incidence angle, the injected pulse is always identical. Only real waveforms can represent the attenuation and distortion effects suffered by the traveling wave along the line. Fig. 2 exemplifies the differences.
Thus, when testing a device with algorithm for detecting traveling waves through an artificial signal, it is not being subjected to real operating conditions and its sensitivity is not tested either. From the presented differences about artificial and real waveforms it is easy to see that TW detection from artificial waveforms is much easier for any algorithm.



(a) (b)

Fig. 2. Sample current waveform: (a) artificial, (b) real

3.1.1 Low level x Secondary level

With real-time digital simulators it is possible to obtain and generate real waveforms, but they have level limitation, around ± 10Vpk. To test TW devices with these solutions, a special condition that bypasses the entire IED input circuit is required. This situation does not represent the real behavior in the field, as tests without secondary level injection do not guarantee the correct hardware response, for example, the analog inputs frequency response is not tested.

3.1.2 Sensitivity

Sensitivities are only tested by applying real waveforms with secondary levels. Tests with artificial waveforms do not check the response in a real fault, as the TW waveform has the same rise time and the peak amplitude in any condition.

3.1.3 Reflections

With artificial waveforms it is not possible to reproduce all reflections correctly, as the reflections have different magnitudes and distortions. Furthermore, artificial waveforms are usually capable of reproducing only one reflection. Therefore, real waveforms are the best condition for representing reflections.

3.2 Developed Tool

A system composed of software and hardware that is capable of accurate modeling all the electrical system components, including the transmission lines, and later reproducing the very high frequency waveforms together with the fundamental frequency at secondary levels, thus contemplating all the necessary requirements for evaluating the device under test.
Using the principle of superposition (Fig. 3), it is possible to separate the signal in two ranges of frequency: kilohertz and megahertz. The first is reproduced by a universal test set that can generate signals up to kHz and the signal complement is reproduced by an specific hardware (traveling waves test set) capable to reproduce signals up to MHz.

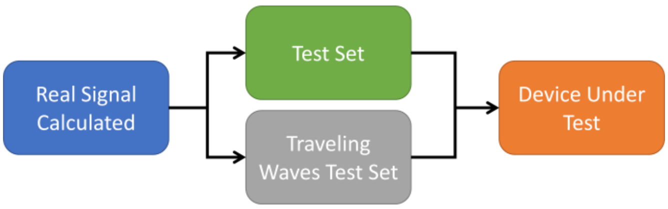


Fig. 3. Methodology.

For the superposition to work correctly, both hardware must be synchronized by the same time base and trigger generation at the same time instant. Only then is it guaranteed that the generated signal will exactly represent the simulated signal.
It is noteworthy that through this technology it is even possible to playback a megahertz COMTRADE file containing all the traveling waves signals at secondary levels.

3.3 Software

The PS Simul software, developed in Brazil since 2009, had its first version released in 2014, and is available on the company's website in a FREE [2] version. This software, created with the main purpose of allowing the user to model complex power, control systems and to simulate electromagnetic and electromechanical transients, works with a very friendly interface, with a series of resources that facilitate the obtaining and evaluation of results, data entry, visualization, among others. In order to enable the creation of any power and/or control system, library with more than 400 components are available, including several not covered by any other transient simulation software. In addition to carrying out the simulations, the software allows the reproduction / acquisition of the signals by the test set.

3.3.1 Resources

The software can be used to perform any type of electromagnetic studies such as insulation coordination, lightning strikes, transient recovery voltages, energizations, saturations of current transformers, motor starting, overvoltages, power quality, control logics, etc. PS Simul also allows run complex simulations, such as involving HVDC and renewable energy. For these cases a lot of components are available such as: rectifier / inverter bridges; wind sources (average, ramp, noise and gust); wind turbines; photovoltaic panels); DC-DC converters; and others.
Among the various software features, we can highlight:

- *Hybrid solution method*: solves the differential equations applying trapezoidal + interpolation + Euler to avoid the occurrence of numerical oscillations during switching;
- *Global variables (constants)*: allows adjustments common to several blocks at a single point;
- *Automated multiple tests*: possibility to change of one or more system constants;
- *Transmission line faults*: application of faults without the need to divide the transmission line manually;
- *Transformers*: short circuit between turns of the transformer through access to its windings;
- *Reports:* creates complete reports;

3.3.2 Hardware connection

As mentioned before, it is possible to reproduce and acquire signals by PS Simul. To do that are available in the software library inputs and outputs blocks for binary/GOOSE and analog/*Sampled Values*. The output components are used so that the results obtained in the simulation environment can be reproduced on real devices. The input components will be used to enable the signals acquired by the test sets channels to be used in the software.
The digital input signals are used by a repetitive process, running recursively and this procedure is identified for any changes in logic levels or just for the rising or falling edges. In this methodology, the signal is applied, for example, to modify the simulation in order to command the opening and closing of the circuit breakers or at any other circuit points that involves boolean digital logic. This process of signal generation and acquisition occurs by automatic overlapping of stages with the circuit feedback, thus configuring a closed loop system in stages with excellent results. It is worth highlighting that this methodology is only possible due to the IED’s trip repeatability, which have great accuracy in the acquisition and processing of signals. In addition, the effectiveness of the repetitive method for conducting closed-loop tests has already been compared with the methodology used by real-time simulation systems [3, 4], where it has been proven that the results for testing applications in protection devices are the same.

3.4 Hardware

To meet this application, there are some models of universal test set: CE-6707, CE-6710, CE-7012 and CE-7024. To this paper, the CE-7012 hardware has been chosen, with 6 current channels, with the generation capacity of 50A RMS and 430VA per channel, and 6 voltage channels with 300V RMS and 100VA of capacity each.
The hardware capable to generate megahertz signals is the CE-TW1 that has 3 voltage channels with ±100Vpk and 3 current channels with ±7.5Apk. As it works with a MHz digital to analog converter it is possible to generate any signal, being able to reproduce real and artificial signals.
All devices needs to be time-synchronized and in this case was used CE-GPS as source of synchronism.

4 Signal Fidelity

In order to calculate faithful signals, PS Simul has in addition to the traditional lumped models like PI and RL, four different models with distributed parameters capable to reproduce traveling waves: Loss-less, Bergeron, Frequency Dependent Phase and Frequency Dependent Mode.
Bergeron model is essentially an ideal model represented by a distributed inductance L and a capacitance C. However, the Bergeron model goes a step further to include a lumped resistance property to approximate system losses.
In the Frequency-Dependent (FD) models the system resistance R is distributed across the system length (along with L and C) instead of lumped at the end points. More importantly, the FD models are solved at a number of frequency points, thereby including the system frequency dependence. The Frequency Dependent Phase model considers the frequency dependence of internal transformation matrices, thus accurately representing unbalanced and balanced systems. On the other hand, Frequency Dependent Mode model assumes a constant transformation and is therefore only accurate when modeling balanced systems.

The Frequency Dependent (Phase) model is numerically robust and more accurate than any other commercially available line/cable model, and thus, is the preferred model to use.
As mentioned before, the simulated signal is separated in two, with the low frequency being generated by a conventional test set and the high frequency being reproduced by special amplifiers capable of responding to a wide frequency spectrum (DC - MHz).
Synchronization is responsible for ensuring that there are no signal slips and the result of the combined waveforms is shown in an oscilloscope capture below (Fig. 4).

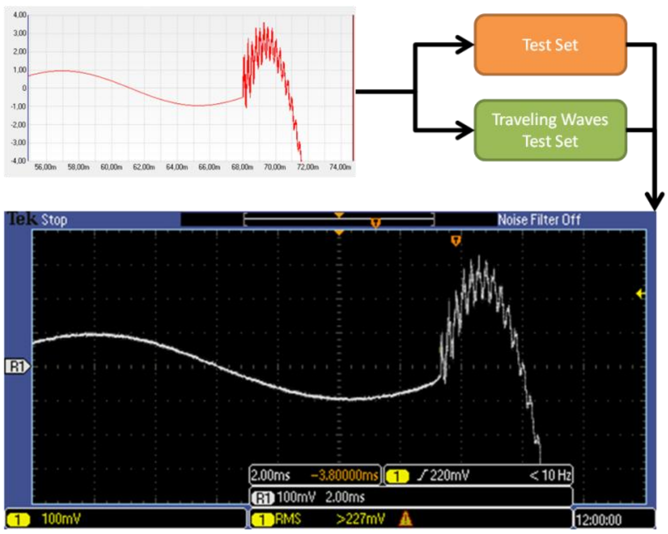


Fig. 4. Calculated signal at PS Simul x Oscilloscope capture

5 Remote Generation

There are several tests that require generation in different locations using different test sets in addition to tests on devices with TW technology, such as teleprotection scheme tests, line/bar differential protection tests, coordination and selectivity tests, and others.
These applications are often tested using isolated test equipment that does not communicate with each other, that is, control and analysis are decentralized.
The decentralization of control creates numerous adverse conditions for test equipment users, and errors in execution and interpretation of results can easily occur.
If the test must be carried out on site or it is not possible to use only one test set, the PS Simul software has a feature called remote generation (Fig. 5), which allows a user to control several test set simultaneously regardless of the geographic distance between them, either through a local network or through the cloud. This allows all results to be centralized in a single location, maximizing gains in skilled labor, analysis of results and agility in testing.

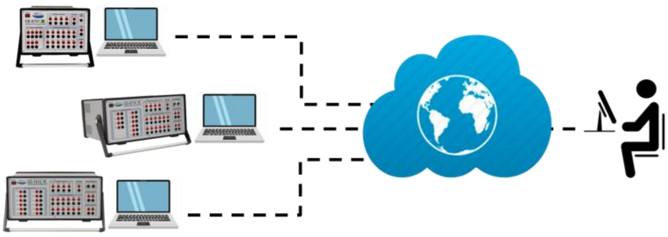


Fig. 5. Remote Generation

6 Case Study

In order to make the comparisons, tests were carried out on a system that has characteristics similar to those of the Brazilian basic power system in terms of voltage levels, typical transmission line geometry and short circuit levels, focusing on fault location. The modeled circuit includes two substations represented by their equivalent systems and between them, transmission lines (230 kV class) and the groups of instrument transformers were all modeled as showed in Fig. 6.
In the tests, PS Simul performs the simulation of the modeled system, sending the analog signals, directed to this purpose in the software environment, to the tests sets. Once this is done, the equipments will reproduce the signals (voltages and currents) and apply them to the devices under test.
The elaborated system was submitted to a total of 57 test scenarios repeating 3 times each totalizing 171 tests, where several internal fault conditions were simulated, with variation of the fault type, incidence angle and location.
The same tests were performed on three commercial models of devices from two different manufacturers, including digital registers, fault locator relays and time-domain protection relays. All the 513 tests were made with real waveforms, in order to verify the behavior of the devices in terms of fault location. Table 1 briefly describes the evaluated scenarios.

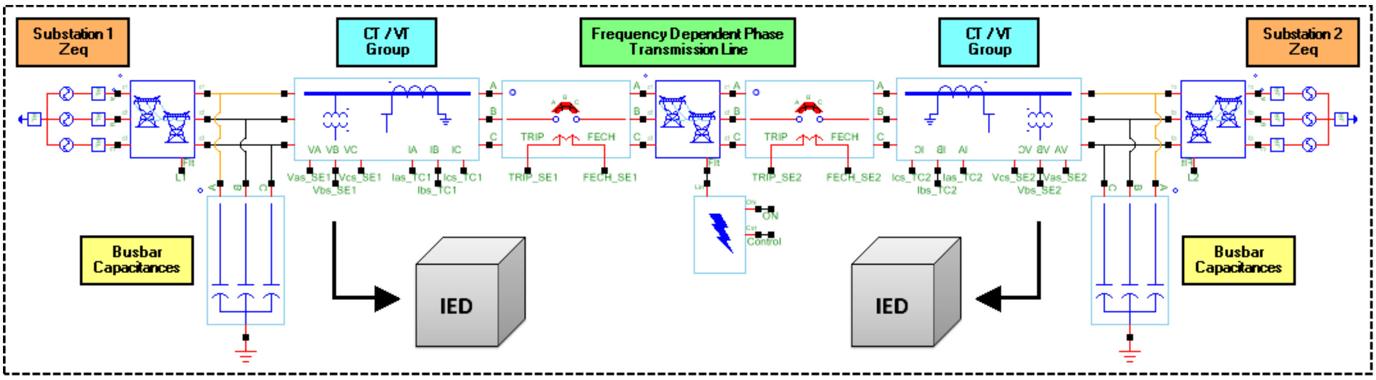


Fig. 6. System modeled on PS Simul

Table 1 Tests description

Fault Type	Fault Location	IED's	Number of Cases
A-G	Loop: 5km a 95km	A	57 per fault type
BC-G	Step: 5km	B	171 per IED
ABC	19 Different Locals	C	Total: 513

6.1 Detailed scenario

For the purpose of exemplifying the comparisons made, the results obtained in the case of an A-G fault at 35% of the transmission line, with an incidence angle of 30º, were used. In this case, considering an average of three points, the fault location error obtained was 9m which is despicable comparing with the location error of 560m calculated by the traditional impedance method.
The voltages and currents injected in the IEDs at this case are presented bellow (Fig. 7).

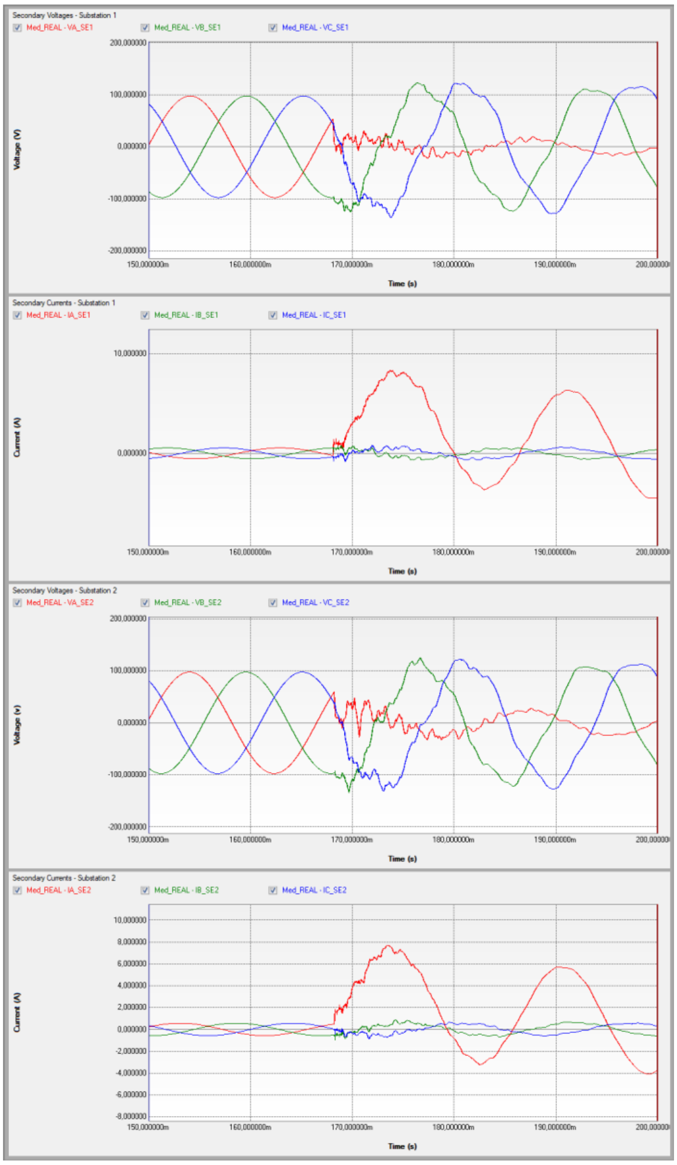


Fig. 7. Voltages and Currents – A-G fault at 35%

Bewley-Lattice diagram, which allows the user to locate the fault, is available in PS Simul software. It is necessary to define the line length and the traveling wave propagation time. The user manually defines the TW arrival times with the cursors and there is also the option to apply a filter and the derivative to the signals to facilitate this identification. Fig. 8 shows the phase A filtered current signals at both terminals and the cursors positioning highlights the location in 35% of the transmission line. In this diagram, it is easy to see that the simulated signal has all the reflections represented.

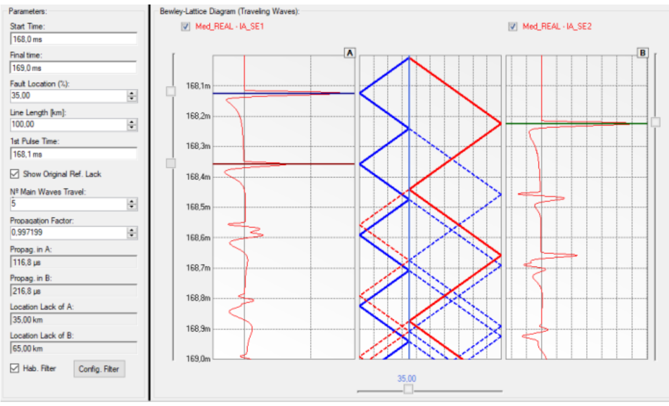


Fig. 8. Bewley-Lattice Diagram

7 Results

The traveling wave propagation time in the transmission line defined in the IEDs was measured through simulations of energizations and external faults. These methods are preferred to achieve higher accuracy with the traveling wave based fault locating method instead of using the theoretical value calculated by the line model, as the latter does not take into account traveling wave attenuation and distortion.
The graphs presented illustrate for each fault type (A-G – Fig. 9, BC-G – Fig. 10 and ABC – Fig 11) and theoretical fault location (5% to 95% - Step 5%) in the transmission line, a fault location error in meters. Each point in the graphs corresponds to the average error of three tests performed at same conditions. It is important to note that the repetition of each point is also intended to verify the IED repeatability.

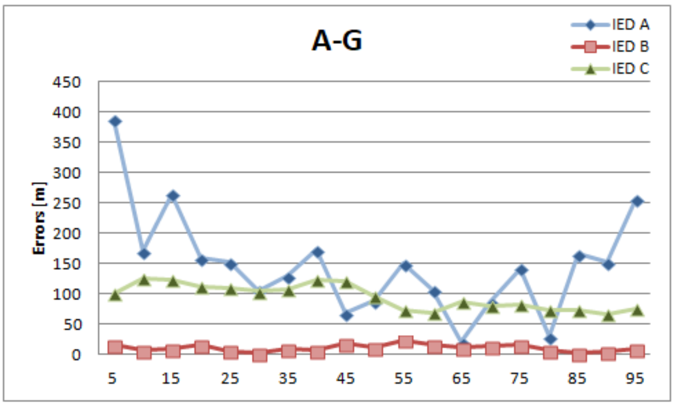


Fig. 9. Errors A-G fault

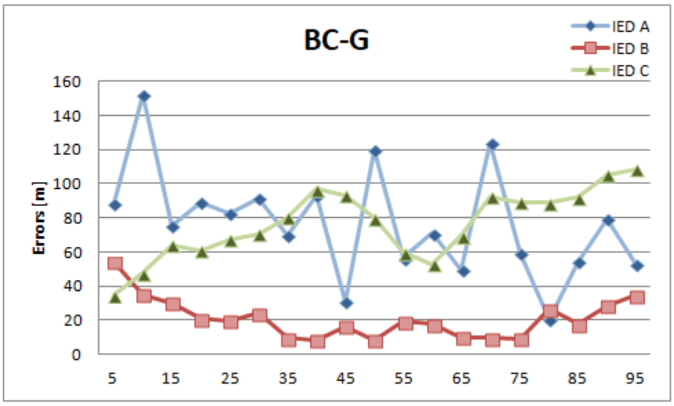


Fig. 10. Errors BC-G fault

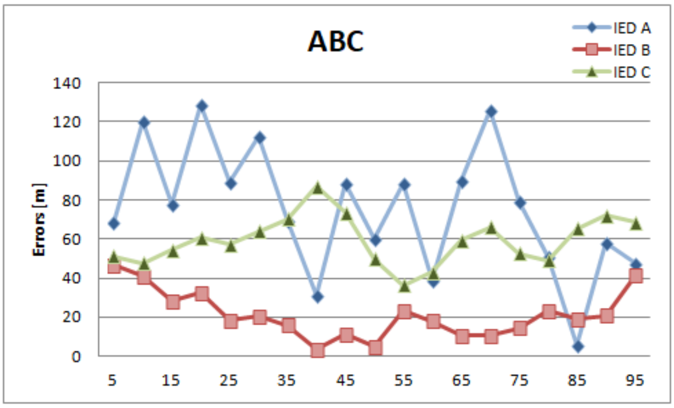


Fig. 11. Errors ABC fault

As expected, the location errors were very small, less than 0.4% of the line length for all devices. Most errors were less than 0.15% (150m in this case), which is smaller than one tower span.

The fault location errors by the traditional method of calculation through the measured impedance were also cataloged. It was verified that these errors can reach the order of kilometers while the method based on traveling waves finds values in the order of meters. Fig. 13 demonstrates the behavior of errors by impedance location method compared with errors by application of real TW waveform for A-G fault at IED B.

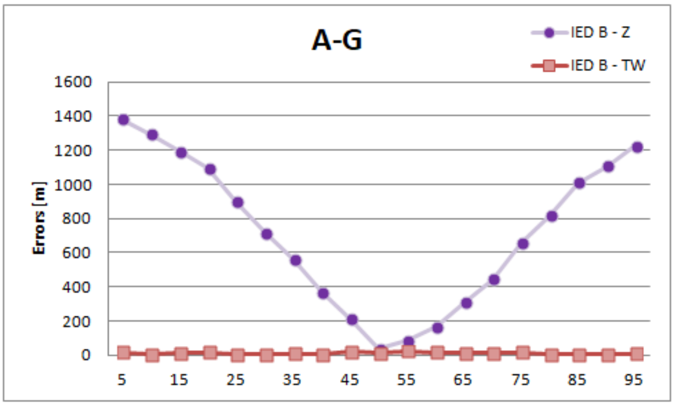


Fig. 13. Errors: Real TW x Impedance – A-G

8 Conclusion

The study presented test results on three commercial IEDs by simulating 171 contingency scenarios in each of the devices, totaling 513 tests, aiming to prove the accuracy of the proposed method thought the correct functioning of the fault location algorithms.

As expected, the fault locations based on TW presented errors much lower than the errors presented by the traditional impedance method as they are in the order of meters while impedance reaches the order of kilometers. Extremely precise fault location on overhead power lines can significantly reduce costs for utilities. It enables operation and maintenance engineers to respond more rapidly to events, get to the site of faults faster and correct defects.

The tests with the new methodology showed how important is to test the IED in conditions close to real ones, as this will be the scenario found by the IED on site. For this reason, the use of PS Simul was extremely important, as it has reliable models of electrical system components, resulting in realistic waveforms.

In order to carry out the tests, it is not enough to obtain realistic signals, it is also necessary to have hardware capable of reproducing them. In this sense, the CE-TW1 proved to be a very powerful tool, due to its ability to generate voltages and currents at the secondary level in megahertz.

For future works, the suggestion is to compare the traditional impedance fault location algorithm with the TW algorithm for different conditions of fault location, incidence angle, fault type and fault resistance.

9 References

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