ULTRA-HIGH SPEED TRANSMISSION LINE PROTECTION PERFORMANCE IN TIME DOMAIN DUE TO SEVERAL CONTINGENCY SITUATIONS

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Abstract

Nowadays, line protective relays utilizing traveling-wave (TW) technology are increasingly being adopted in power system. Similar to any protection solution, the ease of testing is crucial for user comprehension of the technology and application in the field. However, the testing tools available today, including laboratory simulators and relay test sets, do not reproduce signals bandwidth necessary for testing line protection and fault locators based on TW technology. This paper will explore the utilization of a system composed of both software and hardware capable of accurately modeling all components of an electrical system, including transmission lines with variable and frequency-dependent parameters, and reproducing waveforms up to the megahertz range on secondary levels.

The study will demonstrate the effectiveness of an ultra-high-speed (UHS) transmission line protection system that operates in the time domain, utilizing incremental magnitudes. This protection system is based on the principles of traveling waves (TW) to identify and locate faults. Consequently, an Intelligent Electronic Device (IED) will undergo numerous contingency situations to assess the performance of the protection function based on traveling waves. The evaluation will consider parameters such as correct fault location (with errors limited to the transmission tower span length) and protection function delay (values approximately around 1ms).

1 Introduction

Traveling waves are electromagnetic transients generated when voltage has its value suddenly changed as in a fault event, for example. The waves travel along the transmission line with a speed very close to the light and through an accurate measurement of the difference between the arrival times of wave fronts at the transmission line terminals the fault distance can be found. Fault locators based on traveling waves emerged as an alternative to location algorithms based on impedance values because of their high accuracy.

Due to the implementation of this technology, IED manufacturers began to use it not only to identify the fault location, but also on protection systems trip, in order to reduce operating time through ultra-high-speed functions.

References [1] and [2] describe the principles of a traveling wave-based differential scheme and a TW directional element for line protection. Using traveling waves and incremental units in time-domain line protection, the TW-based protection function samples currents and voltages at a frequency of 1 MHz and has extremely low trip delay. When protecting power systems, every millisecond counts. Faster fault clearing improves client and employee safety, improves system stability, minimizes devices wear, improves power quality, limits property damage, and saves lives.

Also, it is necessary to use test systems capable of measuring such functionalities through voltage and current waveforms that best represent the real behavior of the electrical power system (EPS), including Traveling Waves. In this context, the use of software that performs simulations of transient conditions together with hardware capable of reliably reproducing the simulated signals is essential to test devices with this technology.

2 Test Methodology

The test system used consists of a combination of software and hardware, designed to reproduce very high frequency waveforms, along with the fundamental frequency, at secondary levels. This approach allows the reproduction of all reflections of traveling waves, with their different magnitudes and distortions. Furthermore, the system makes it possible to evaluate the sensitivity of algorithms based on TW.

To ensure accurate evaluation of IED device algorithms in real fault situations, a test system is required that can accurately reproduce the complex signals measured by protection devices. These signals are non-periodic, have a wide frequency spectrum and have multiple reflections.

2.1 Test Tool

The test system has the ability to accurately model all electrical system components, including transmission lines. The tool allows reproducing very high frequency waveforms, along with the fundamental frequency, at secondary levels. This covers all the necessary requirements for evaluating devices with traveling wave based algorithms.

Using the principle of superposition (as illustrated in Figure 1), it is possible to separate the signal into two frequency ranges: kilohertz and megahertz. The kilohertz range is reproduced by a universal test set, which can generate signals up to 3kHz. The complement of this signal is reproduced by specific hardware (traveling waves test set), capable of reproducing signals of up to MHz.

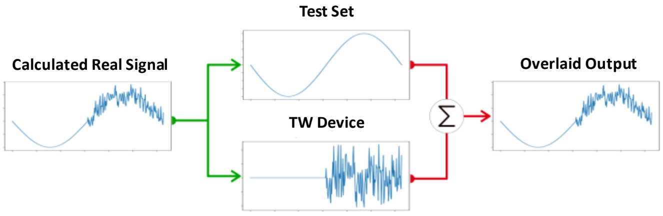

Figure 1 – Methodology

To superposition works properly, both hardware must be synchronized by the same time source and the trigger must occur at the same time. This is the only way to guarantee that the generated signal will exactly represent the simulated signal.

Through this technology it is even possible to reproduce a COMTRADE file in order of megahertz containing all the traveling waves signals in secondary levels.

2.2 Software

PS Simul [3] has been developed in Brazil since 2009, had its first version released in 2014, and a free version is available on the company's website [4]. This software aims to allow the user to model complex electrical power and control systems, in addition to simulate electromagnetic and electromechanical transients. Also, PS Simul works with a very friendly interface, with a series of resources that facilitate obtaining and evaluating results, entering data, waveform visualization and etc. To enable the creation of any power and/or control system, a library of over 400 components is 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 by the test sets.

PS Simul has several features worth mentioning. One of them is the hybrid solution method, which uses the trapezoidal method together with interpolation and Euler to avoid numerical oscillations during switching. In addition, the software allows the use of global variables, which facilitates the definition of adjustments common to several blocks in a single point. It also offers the possibility of carrying out multiple automated tests, allowing the modification of one or more system constants. Another important feature is the simulation of faults on the transmission line, which can be applied without the need to manually split the line. The software also simulates short circuits in transformers, allowing short circuits between turns of the transformer through access to its windings. Finally, the software generates complete reports, providing all relevant information.

As mentioned earlier, it is possible to reproduce and acquire signals through PS Simul. For this purpose, the input and output blocks for binary/GOOSE and analogue/Sampled Values are available in the software library. The output components are used so that the results obtained in the simulation environment can be reproduced in real devices. The input components will be added to allow the signals acquired by the test set inputs to be used in the software.

Digital input signals can be added to feedback the simulation through an iterative process, executed recursively. In this methodology, the signal is applied, for example, to modify the simulation in order to command the opening and closing of circuit breakers or at any other point in the circuit involving digital logic. This signal generation and acquisition process occurs by automatic overlapping of stages with the circuit feedback, thus configuring a closed-loop system in stages with excellent results. This methodology is only possible due to the repeatability of the IEDs trip, which have great precision in the acquisition and processing of signals. In addition, the performance of the iterative method for carrying out closed-loop tests has already been compared with the methodology used by real-time simulation systems [5, 6], where it was proven that the test results in protection devices are the same for both methodologies.

The software can be used to carry out any type of electromagnetic study, such as insulation coordination, electrostatic discharges, transient recovery voltages, power-ups, current transformer saturations, motor starting, overvoltage, power quality, control logic and etc. PS Simul also allows performing complex simulations, such as cases involving HVDC and renewable energy. For these cases, several components are available, such as: rectifier/inverter bridges, wind sources (average, ramp, noise and gust), wind turbines, photovoltaic panels, DC-DC converters and others.

2.3 Hardware

To meet this application, there are some models of universal test set: CE-6707, CE-6710, CE-7012 and CE-7024. For this paper, the CE-7012 hardware was chosen, which has 6 current channels, with a generation capacity of 50A RMS and 430VA per channel, and 6 voltage channels with 300V RMS and 100VA capacity each.

The hardware capable of generating megahertz signals is the CE-TW1, which has 3 voltage channels with ±100Vpk and 3 current channels with ±7.5Apk. As the hardware works with a MHz digital-analogical converter, it is possible to generate any simulated signal that is within the working frequency range and the maximum secondary amplitude [7].

To guarantee the correct functioning of the test devices, the CE-GPS was used as the time synchronization source. Figure

2 illustrates the testing device for traveling waves and Figure 3 shows the test setup used.

Figure 2 - CE-TW1

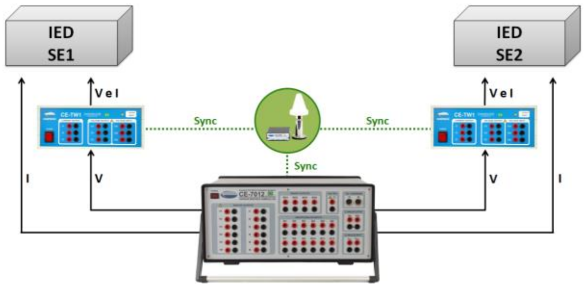

Figure 3 - Test Setup

3 Signal Accuracy

In order to calculate accurate signals, PS Simul has, in addition to the traditional models of transmission lines with concentrated parameters such as PI and RL, four different models with distributed parameters capable of reproducing traveling waves: no loss, Bergeron, variable and frequency-dependent parameters (modal and phase domain).

Bergeron's model is essentially an ideal model represented by a distributed inductance L and capacitance C. However, Bergeron's model goes a step further by including a concentrated resistance property to approximate system losses.

In models with variable and frequency-dependent (FD) parameters, the system resistance R is distributed along the length of the system (with L and C) rather than concentrated at the endpoints. FD models are solved at various frequency points, including the system frequency dependence.

The frequency-dependent model in the phase domain considers the frequency dependence of the internal transformation matrices, thus accurately representing unbalanced and balanced systems. On the other hand, the frequency-dependent model in the modal domain assumes a constant transformation and is therefore only accurate when modeling balanced systems. The phase domain model is numerically robust and more accurate than any other commercially available line/cable model and is therefore the preferred model to use.

As previously mentioned, the simulated signal is split in two: 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 jitters and an example of the combined waveforms is shown in the oscilloscope capture below (Figure 4).

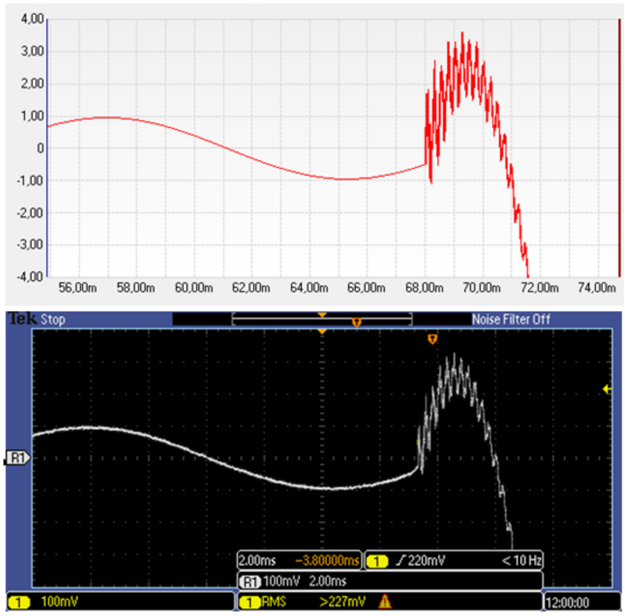

Figure 4 - Calculated Signal on PS Simul x Oscilloscope Capture

4 Study Case

In order to analyze the behavior of the protection function based on traveling waves, tests were carried out on a system that has characteristics similar to those of the Brazilian power system in terms of voltage levels, typical transmission line geometry and short-circuit levels, focusing on trip delay and fault location. The modeled circuit includes two substations represented by their equivalent systems and between them, transmission lines (class 230 kV – 100km) and instrument transformer groups were all modeled as shown in Figure 5.

The IEDs were parameterized with two zones in the direction of the transmission line, with zone 1 up to 70% of the line length and zone 2 with 120% of the protected transmission line. No teleprotection scheme was configured, as the intention was to compare the instantaneous actuation times of the protection based on traveling waves in relation to the traditional distance protection without any logic or scheme influencing the final actuation time. Exactly for this reason, analyzes were carried out only for the times of zone 1.

In the tests, PS Simul performs the simulation of the modeled system, injecting the analogical signals, directed for this purpose in the software environment, to the tests set. Once this is done, the devices reproduce the signals (voltages and currents) in such a way as to apply them to the devices under test.

The developed system was submitted to a total of 76 test scenarios, repeating 3 times each, totaling 228 tests, where several internal failure conditions were simulated, with variation in the type of failure, angle of incidence and location.

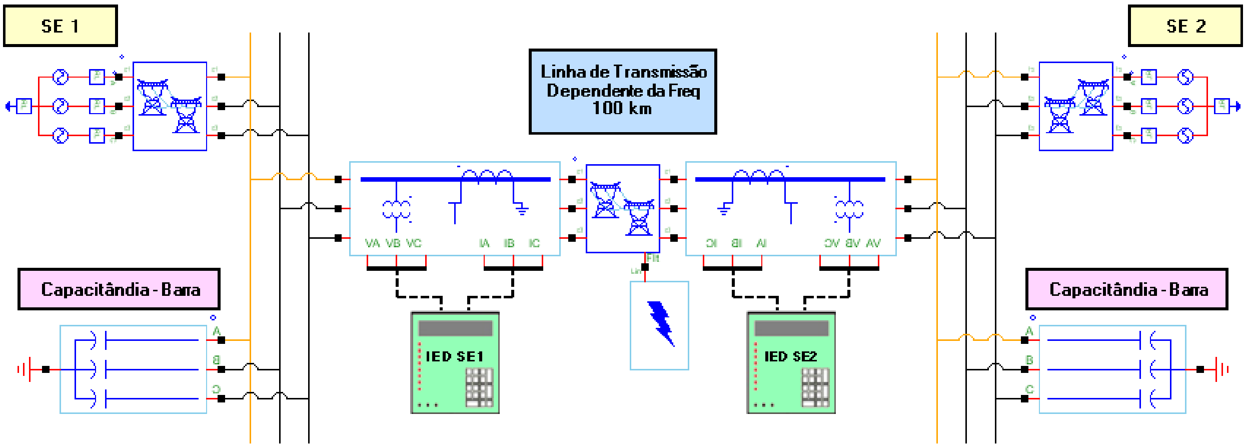

Figure 5 - System Modeled on PS Simul

The tests were carried out in a commercial model of IED that has, in addition to the traditional distance phasor protection, protection functions in the time domain. All 228 tests were performed by injecting the realistic waveforms resulting from the simulations, in order to verify the behavior of the devices in terms of protection actuation time and fault location. Table 1 briefly describes the evaluated scenarios.

Table 1 - Tests Description

Fault Type	Fault Location	Cases Numbers
A-G BC-G BC ABC	Loop: 5km to 95km Step: 5km 19 different locals	19 Locas 4 Types 3 repetitions Total: 228

5 Results

Aiming to compare the actuation times of the protection function based on traveling waves with the traditional function 21, only the actuation times of zone 1 of the IEDs were evaluated, as previously explained. Only the actuations that occurred in up to 90% of the reach of zone 1 were considered, that is, 63% of the transmission line, because from this point, according to the manufacturer, the times can increase exponentially.

The graphics presented illustrate, for each type of fault (A-G – Figure 6, BC-G – Figure 7, BC – Figure 8 and ABC – Figure 9) and location of the fault (5% to 95% - Step of 5%) in the transmission line, the protections actuation times (based on traveling waves and based on impedance) of substations SS1 and SS2. Each point in the graphs corresponds to the average time of three tests performed under the same conditions. It is important to note that the repetition of each point also has the purpose of verifying the repeatability of the IED.

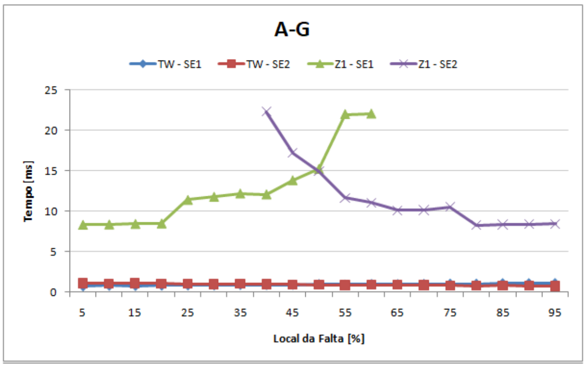

Figure 6 - Actuation Times A-G Fault

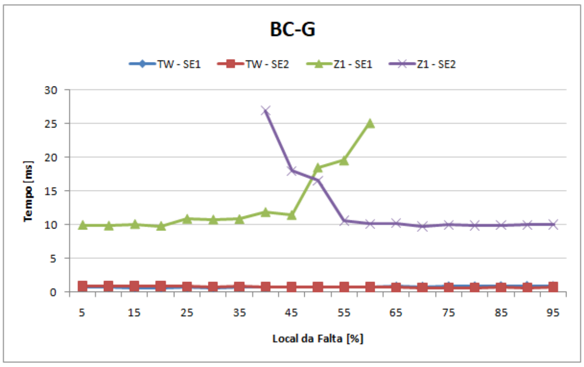

Figure 7 - Actuation Times BC-G Fault

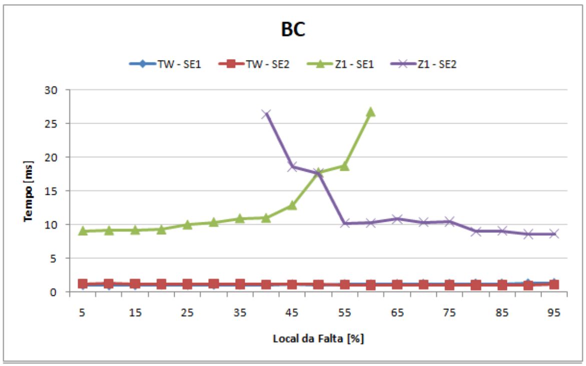

Figure 8 - Actuation Times BC Fault

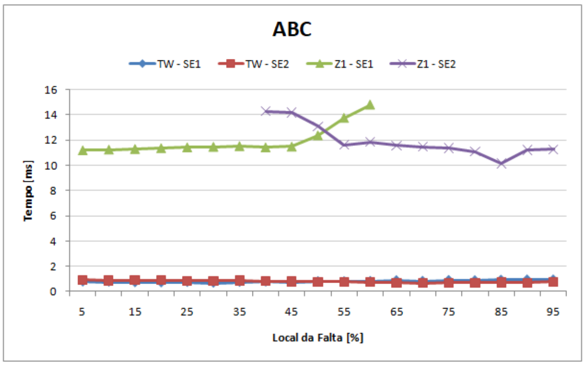

Figure 9 - Actuation Times ABC Fault

From the images, it is possible to verify that the actuation times of the traditional impedance protection function (21-Z1) vary with the fault location and are all greater than 8ms, while the protection function based on traveling waves works, mostly, with times below 1ms. Table 2 shows the minimum, average and maximum values of IEDs actuation times in the two substations for the protection functions based on TW and impedance.

Table 2 - Actuation Times Statistics

	SS1		SS2	
	TW	21 (Z1)	TW	21 (Z1)
Min [ms]	0,646	8,355	0,646	8,250
Aver [ms]	0,929	12,744	0,918	12,223
Max [ms]	1,341	26,757	1,306	27,035

Grouping the actuation times of protection function based on traveling waves for each substation (Figures 10 and 11), the farther from the IED terminal, the greater the actuation time, and this is due to the propagation time of the wave on the transmission line. Each point on the images is the average of three test results.

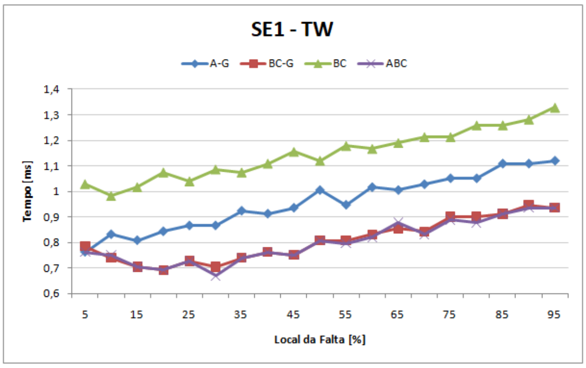

Figure 10 - Actuation Times TW SS1

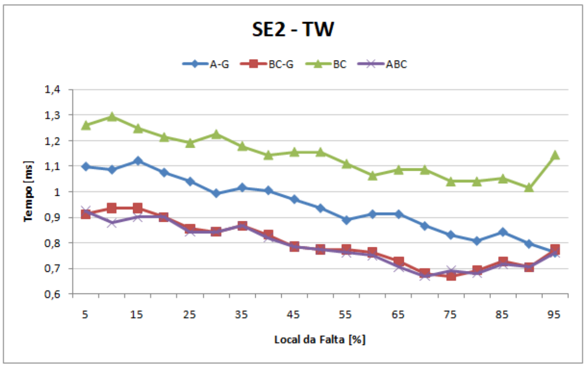

Figure 11 - Actuation Times TW SS2

Fault location errors by TW were all below 60m. Figure 12 shows the average error of three test points for each fault type and location. Other comparisons between fault location algorithms can be found in [8].

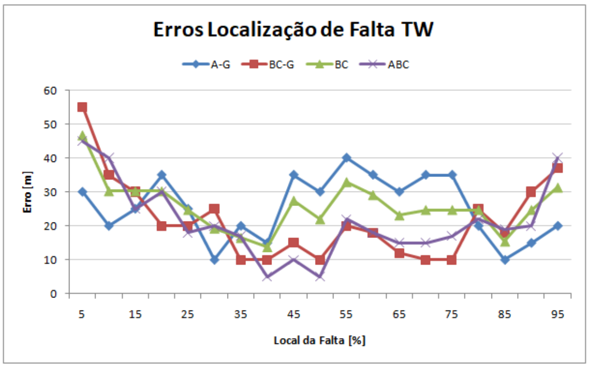

Figure 12 - Fault Location Errors

According to the data presented, it is possible to verify and it is important to emphasize that the protection function based on TW actuated correctly in 100% of the tests carried out with an average time less than 1ms and with location errors less than 0.06% of the line length (60m, in this case), which is smaller than a transmission tower span length.

5.1 Detailed Scenario

For information purposes, details are presented for the case of a BC-G fault in 45% of the transmission line. For this case, the actuation time of protection based on TW was 751us for the device located in substation 1 (IED_SS1) and 785us for the IED in substation 2 (IED_SS2). The distance protection operated with the following times: 11.45ms for IED_SS1 and 17.97ms for IED_SS2. The voltages and currents simulated and later reproduced by the tests set, in addition to the records of IED protection actuations in this case, are shown in Figure 13.

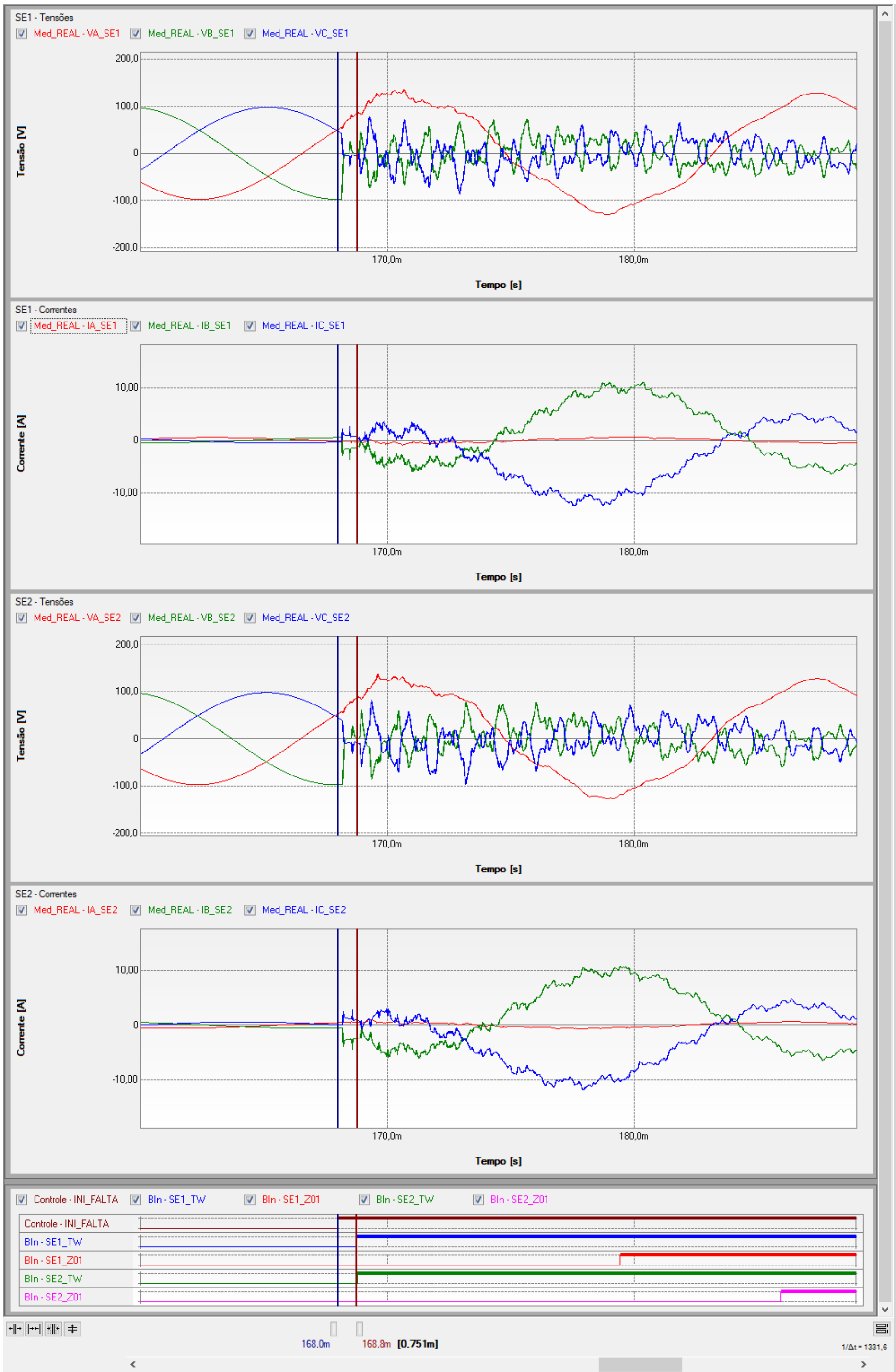

Figure 13 - Details: BC-G Fault in 45% of the Line

5 Conclusions

This paper shared test results on a commercial IED simulating 76 contingency scenarios, totaling 228 tests, aiming to compare the operating times of protection based on traveling waves with traditional distance protection 21. Also, it was verified the correct operation of fault location algorithms by traveling waves.

The TW-based protection function operated correctly in all tested scenarios with times, in more than 90% of cases, below 1ms. This quick protection response is critical to the operation of the electrical system and can be crucial to ensure protection selectivity. Despite having relatively longer times, the traditional impedance protection function also operated correctly in all cases, covering faults along the entire protected line length.

As expected, fault locations based on TW presented errors much lower than the errors normally presented by the traditional impedance method, since they are in the order of meters while the impedance method reaches the order of kilometers. Extremely accurate fault location on transmission

lines can significantly reduce costs for utilities. It enables operations and maintenance professionals to respond more effectively to events, get to faults faster, and correct errors.
The tests showed how important it is to test the IED in conditions close to real ones, as this will be the scenario encountered by the IED at the installation site. For this reason, the use of PS Simul was extremely important, as it has reliable models of the electrical power system components, resulting in realistic waveforms. Allied to the software, it is also necessary to have hardware capable of reproducing the simulated signals in a reliable manner, which is why the CE-TW1 was used, which has the capacity to generate voltages and currents at a secondary level in megahertz.
For future work, the suggestion is to compare the sensitivity of protections based on traveling waves, incremental magnitudes and impedance against the variation in fault resistance.

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