Performance Assessment of a Line Protection Implemented With Process Bus and GOOSE Through Transient Closed Loop Tests

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***Abstract*-- This paper aims to present an experience of using the process bus (Sampled Values) and GOOSE in the implementation of a line differential protection function (87L). During the tests, a Brazilian tool with operational characteristics equivalent to those of real-time simulation systems was employed, allowing all stages of dynamic assessment of IEDs (*Intelligent Eletronic Device*) to be carried out. All tests were performed in closed loop including, in addition to tests in the IEC 61850 universe, conventional tests using hard cabling by copper wiring for sending and receiving signals, which were done for later comparison of the results obtained.**

***Keywords*: Line Differential Protection, IEC 61850, Sampled Values, GOOSE, Closed Loop, PS Simul.**

I. Introduction

FOR an operation of an electrical system to take place effectively, the correct functioning of the IED's is essential, since non-actuation or undue actuation can cause unnecessary shutdowns until a system collapse. Therefore, the importance of evaluating the performance of protective equipment is notorious when in real defective conditions, especially when considering the economic impact generated by interruptions in the system.

IEC 61850 is increasingly present in new substations and in retrofits of old substations around the world. This standard [1] basically defines how to send / receive information in three different ways: Client-Server, GOOSE (*Generic Object Oriented Substations Events*) and SV (*Sampled Values*). Report communication (Client-Server) through MMS (*Manufacturing Message Service*) and the exchange of GOOSE messages, at high speed, are already established and being widely used. However, the information traffic of current and voltage digitized through the Ethernet Network (*Sampled Values*) is still something relatively new for the professionals of the area. The application of the Process Bus fascinates some members of the community and causes distrust to others. This is due to the fact that this topic of the standard deals with a paradigm shift, which means abandoning the traditional method used for decades that apply secondary voltages and currents obtained from instrument transformers.

The traditional test method through injection of signals in the permanent state, without typical transients of the system, is no longer sufficient to ascertain the behavior of the protection devices, since phenomena such as CT saturation, frequency variations, ferroresonances and harmonics affect the performance of the relays significantly. In order to increase the reliability of the relays, manufacturers have implemented numerous solutions through filters and new algorithms, but the literature illustrates that transient conditions are still the biggest challenges to the effective performance of IED's [2].

The first transient tests performed on IED's were based on obtaining transient waveforms through digital simulators or oscillographs and from test cases capable of reproducing these signals, and applying them to the device under test in order to ascertain the protection behavior. In these conditions, the IED's responses were not considered to change the voltage and current signals that were being applied, that is, the test results did not fully match the reality. For this, it is necessary that the behavior of the system be considered in view of the response of the device under test, and this dynamic is currently known as closed loop testing.

Closed loop tests have been widely used through real-time simulation systems, capable of interacting with the device under test in a time fast enough for the equipment's response to be able to change the simulation and consequently the signals to be sent to the device in the next time step, usually 50 us. However, the use of this solution is still very restricted, as it is made up of large equipment that is difficult to move and expensive.

This work proposes to present a new tool developed in Brazil that allows the realization of closed loop tests using a different methodology from the real time simulators capable of performing the same tests and obtaining the same results, both by the hard cabling and the environment of the IEC 61850 standard.

The paper will not address some challenges in the use of the IEC 61850 standard, such as traffic overloads, network reconfiguration and network failures, as they have already been widely discussed in other works [3, 4, 5].

II. Development

In the open loop testing methodology, it is necessary first to perform the system simulation in software for studies of electromagnetic transients. Later, in order to the obtained waveforms to be reproduced in the IED's, it is necessary to

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export the signals in a standardized format (COMTRADE format, for example). After that, you can import such files into software that controls the test set. The test set is responsible for amplifying and injecting the signals from the files in the IED, allowing the user to check their behavior. Such methodology does not consider the response of IED's in the system and requires a lot of time, organization and effort in the process of carrying out multiple cases and repetitions.

Currently, discovering only the performance of the IED face of a disturbance is not enough, it is mandatory to investigate the influence of the IED on the behavior of the rest of the system and the influence of this behavior on the IED again. Since it has feedback, this methodology is called *Closed Loop Testing* and allows the evaluation of more complex functions and protection schemes.

The main utilities of the basic grid use today, for closed loop tests, real-time simulation systems. However, the cost to acquire this equipment is very high, since signal amplifiers must be purchased, in addition to the simulation system, capable of faithfully reproducing the simulator's output values, since the real-time simulation systems reproduce low amplitude signals in their outputs.

In view of this, a tool was developed in Brazil that encompasses in a single software and in a single hardware, all the stages of the evaluation process of an IED or of a complete protection scheme in transitory conditions, allowing the performance of closed loop tests. The software enables, in addition to the modeling and simulation of complex systems, to make the direct connection to the hardware which is composed of the most advanced technological resources, capable of not only simultaneously injecting several analog current and voltage signals with high amplitudes per channel, but also carrying out tests on the universe in IEC 61850 through the process bus and station bus [5, 6].

In order to prove the efficiency of the differential line protection (87L) implemented with the process bus, a comparison was made between the installed protection using the conventional method (hard cabling) and in the environment of the IEC 61850 standard (Ethernet cable). The paper will present results of a closed loop test where, through the modeling of an extra-high voltage system, scenarios with different types of contingencies was simulated, considering variations such as: type of fault, location, evolutionary faults, fault resistance and communication failure.

The solution presented below allows, in addition to the creation of simulation routines and automatic evaluation of the results, direct communication with the universal testers, which reproduce the simulated signals in the IED and acquire the trip signals, which are used to interact with the software through iterative tests (closed-loop tests). In addition, the cost added to the complete system (hardware and software) is considerably lower when compared to real-time simulation systems, thus being accessible to the vast majority of companies and institutions.

It is also worth mentioning that the solution is portable, not limited to testing laboratories and with the same hardware it is possible to carry out both tests in the universe of IEC 61850, as well as with binary inputs / outputs and analog channels.

A. Developed Tool

The tool developed for closed loop testing reproduces the waveforms obtained from software simulations through a universal test set that injects the signals at secondary levels or Sampled Values into the protection devices and interfaces with them through the acquisition of binary signals or GOOSE messages. Figure 1 shows the procedures performed.

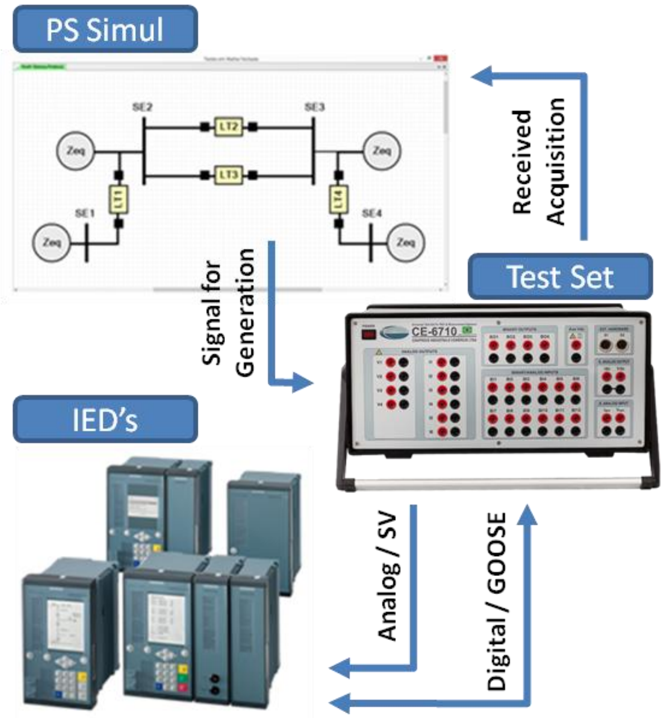

Fig. 1. Simulation of closed loop systems using the iterative method.

B. 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 version. This program, created with the main purpose of allowing the user to model complex power, control systems and to simulate electromagnetic and electromechanical transients, it works with a very friendly interface, with a series of resources that facilitate the obtaining and evaluation of results, data entry, error visualization, among others. In order to enable the creation of any power and/or control system, more than 400 models of system devices are available, including several of these not covered by any other transient simulation software. In addition to carrying out the simulations, the software will allow the reproduction / acquisition of the signals by the test set.

Among the various features of the software, we can highlight: resolution of the differential equations by hybrid method (Trapezoidal + Interpolation + Euler) that avoids the occurrence of numerical oscillations during switching; possibility of declaring global variables as constants that allow adjustments common to several blocks at a single point; feature of automated multiple tests, with the change of one or more system constants; application of faults without the need to divide the transmission line manually; short circuit between turns of the transformer through access to its windings; internal measurements of different magnitudes of the power blocks; automatic evaluation of results using logics parameterized by the user; files protected by password; easy data entry; creation of complete reports; among others.

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 made available: rectifier / inverter bridges; current control; wind sources (average, ramp, noise and gust); models of wind turbines and their pitch controllers; photovoltaic panels (equivalent circuit or catalog data); components that perform the MPPT (maximum power point tracking); DC-DC converters: boost, buck, buck-boost, cuk and sepic; among others.

For the interface with the hardware to be recognized by PS Simul, the binary input blocks, GOOSE input, analog output, binary output, GOOSE output and *Sampled Value* output are available in the software library. 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 channels of the test sets to be used in the software.

The input digital signals are used by the iterative process and this procedure is identified for any changes in logic levels or just for the rising or falling edges. With the iteration, 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 points of the circuits that involves boolean digital logic. This process of signal generation and acquisition occurs by automatic overlapping of stages with the feedback of the circuit, thus configuring a closed loop system in stages with excellent results. It is worth highlighting that this methodology is only possible due to the repeatability of the IED's actions that have great precision in the acquisition and processing of signals. In addition, the effectiveness of the iterative method for conducting closed-loop tests has already been compared with the methodology used by real-time simulation systems [7, 8], where it has been proven that the results for testing applications in protection devices are the same.

C. 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-6710 hardware has been chosen, which allows to perform both tests in the universe of IEC 61850, with 16 publishing and 44 subscribing GOOSE channels, in addition to 24 publishing and 24 subscribing *Sampled Values* channels, as well as with binary inputs / outputs and analog channels, with 6 current channels, with the generation capacity of 32 A RMS and 210 VA per channel, and 4 voltage channels with 300 V RMS and 100 VA of capacity each.

D. Iterative process

To exemplify the iterative process, it is assumed to test the instantaneous overcurrent protection of an IED set to 0s. For this, a circuit was modeled having a binary input with iteration on the rising edge, responsible for reproducing the trip signal acquired from the relay, connected to a circuit breaker. The two steps of the iterative process are shown in Figure 2.

First, the simulation is carried out without considering any command signal for the circuit breaker (Figure 2 - 1.1 and 1.2) and the intention is to obtain the waveform that will be generated. In the first generation, the relay response is acquired. After the first generation (Figure 2 - 1.3), the signal that was acquired from the relay (Figure 2 - 1.4) is inserted in the system modeling for a next simulation, in this way it is possible to modify the behavior of the simulated system through an external signal. As this signal is connected to the trip command of the circuit breaker, what is expected is that in the next simulation (Figure 2 - 2.1 and 2.2), the fault current will be extinguished after the breaker opening time, which represents the second stage of the iterative process. Then, the resimulated signal will be reproduced (Figure 2 - 2.3) and the relay is expected to exhibit the same behavior for its trip signal (Figure 2 - 2.4), according to a tolerance range chosen by the user, which can be defined both by percentage and absolute value.

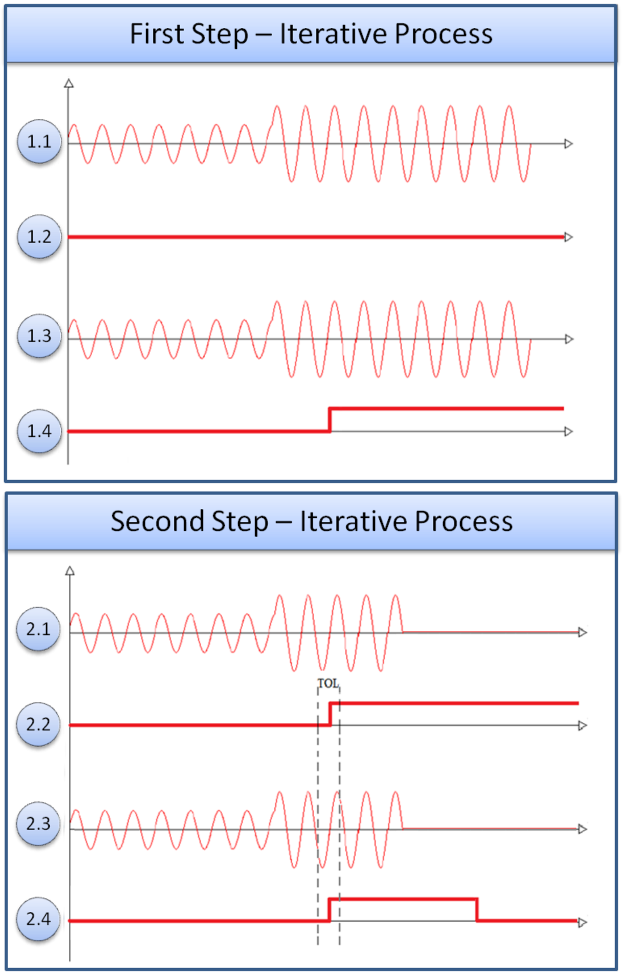

Fig. 2. Steps of the iterative process.

The final behavior of the IED related to the applied fault can be analyzed in Figure 2 - 2.4 and summarized as follows: when the fault is identified, the relay commands the trip signal to the circuit breaker that opens the circuit after three cycles and with the elimination of the fault, the relay stops sending the trip command after a few milliseconds. The simulation is only finalized when the actuation of the relay under analysis occurs within the same time interval defined by the parameterized tolerance, otherwise, the generation is repeated until the condition is satisfied. If new actions occur, the iterative process will be performed in a cascade.

In short, the iterative process operates due to the repeatability of the IED's actions when requested to the same fault. At each iterative step, the tool, through an intelligent algorithm, learns from the behavior of the IED and uses it later to interact with the power system, enabling a change in its response from this point on. All of this methodology combined with the repeatability of the relay allows the final behavior of the interaction between system and IED to be built in stages until all actions are mapped and revalidated within the time determined by the user.

III. Case study

In order to make the comparisons, tests were carried out with both methodologies (conventional method and IEC 61850 context), in the protection schemes implemented to a system that has characteristics similar to those of the Brazilian basic power system with respect to voltage levels, typical transmission line geometry and short circuit levels, focusing on differential line protection (87L). The modeled circuit includes two substations represented by their equivalent systems and between them, a transmission line (500 kV class) and the groups of instrument transformers were all modeled. The circuit breakers were externally controlled by SIEMENS relays (SIPROTEC 5 - 7SL) as showed in Figure 3.

In the conventional test, PS Simul performs the simulation of the modeled system, sending the analog and digital signals, directed to this purpose in the software environment, to the test set. Once this is done, the equipment will reproduce the signals (voltages, currents and binaries) and apply them to the 7SL relays. At the same time, IED's output binaries are acquired so that they are considered (when opening or closing breakers, for example) in the subsequent iteration. All connections between the test set and the relays are made, in this methodology, through hard cabling. Figure 4 illustrates the signal flow of this method.

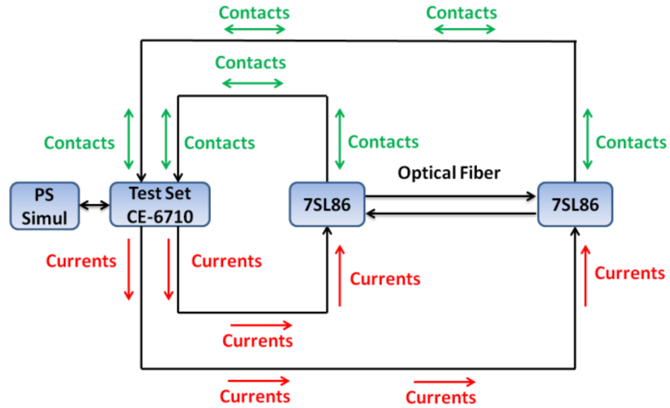

Fig. 4. Conventional methodology with analog signals and binary contacts.

In the environment of the IEC 61850 standard, the hard cabling is replaced by an Ethernet cable and the traditional analog and digital signals, replaced by GOOSE and *Sampled Values* messages. The signal flow occurs similarly to the conventional method, as shown in Figure 5.

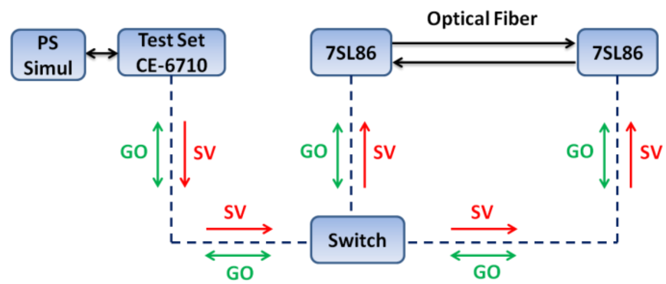

Fig. 5. Process Bus with GOOSE and *Sampled Values*.

The two 7SL devices were time-synchronized with one another via the Protection Interface [9]. One of the devices functions as the timing master and synchronizes the clock of the other device. As all Sampled Value voltages and currents are created by the same equipment (CE-6710), that is, the signals are already in the same time base, the equipment does not need to be synchronized with the devices under test. For this reason, a common reference was not used for synchronize the test set and the relays.

The elaborated system was submitted to a total of 260 test scenarios, where several fault conditions were simulated with variation of the type of fault, angle of incidence and location, in order to prove the correct functioning of the protection system. Table I briefly describes the scenarios evaluated.

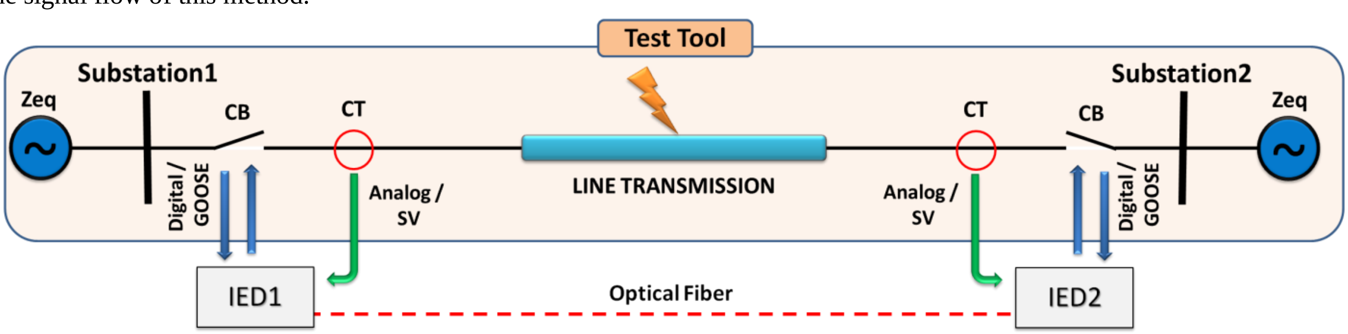

Fig. 3. System representation.

TABLE I
DESCRIPTION OF TESTS PERFORMED

Cases	Description
50	Internal faults with an incidence angle of 0º and 90º. Three-pole reclosing with and without success. Faults at: 0%, 25%, 50%, 75% and 100% of SE1-SE2.
50	Evolutionary internal faults with an incidence angle of 0º and 90º. Three-pole reclosing with and without success. Faults at: 0%, 25%, 50%, 75% and 100% of SE1-SE2. Evolution after 1 cycle from the beginning of the fault.
30	Internal faults with fault resistance variation, in the middle of the line. Fault incidence angle of 0º and 90º, adjusting the fault resistance with values from 5Ω to 200Ω. Three-pole reclosing with success.
10	External faults at the inputs of SE1 and SE2, with incidence angles of 0° and 90°. For these cases, the 87L function must not be checked.
40	External faults at the inputs of SE1 and SE2, with saturation and with incidence angles of 0° and 90°. For these cases, the 87L function must not be checked. In each substation different types of faults will be simulated, for different values of burden resistance, aiming to cause light and heavy saturations.
10	External faults followed by internal faults, with incidence angles of 0° and 90°. For these cases, three-pole reclosing should be checked without success. The internal fault will starting after 6 cycles of the beginning of the external fault.
40	External faults with saturation followed by internal faults, with incidence angles of 0° and 90°. For these cases, three-pole reclosing should be checked without success. The internal fault will starting after 6 cycles of the beginning of the external fault. Light and heavy saturation will be caused by varying the load resistance.
12	Internal faults in the "switch on to fault" condition. For these cases, the SOTF function must be checked after attempting to energize the line. The conditions tested: SOTF with SE1 terminal Open: 0% and 100% SE1 SOTF with SE2 terminal Open: 0% and 100% SE1
10	Check the response of the relay for under and over frequencies (57 Hz and 72 Hz). Apply faults of different types to 50% with a fault incidence angle of 0º and 90º. For this case, three-pole reclosing in unsuccessful mode should be checked.
8	Faults without communication, internal in positions 0% and 100%, in addition to external faults. Apply faults with angle of incidence of 0º and 90º. For this case, the action of overcurrent protection (emergency) and reclosing in unsuccessful mode should be checked.

IV. COMPARISONS

For the purpose of exemplifying the comparisons made, the results obtained in the case of an AN fault at 0% of the transmission line, with an incidence angle of 0º, simulating an unsuccessful reclosing, were used. In this case, the IED's identify the internal fault and both command the trip signal (eB1-7SL86_1-TRIP and eB2-7SL86_2-TRIP). After the operation of the substation circuit breakers, the fault is eliminated and, exceeding the dead time of the reclosing (1s), both IED's control the reclosing of the circuit breakers (eB1-7SL86_1-REC_79 and eB2-7SL86_2-REC_79). After the reclosure, as the fault still remains in the system (unsuccessful reclosure), both IEDs (7SL86_1 and 7SL86_2) operate by the SOTF (eB1-7SL86_1-SOTF and eB2-7SL86_2-SOTF) and by the differential (eB1-7SL86_1- DIF_87 and eB2-7SL86_2-DIF_87).

Figure 6 show the modeled circuit on PS Simul an Figure 7 illustrates the waveforms obtained for the explained case using the IEC 61850 environment testing methodology, equivalent to the result obtained with the conventional methodology. The figure shows the currents measured in the secondary of the CT's of substations 1 and 2, as well as all the protection functions monitored in each relay.

Table II shows a comparison between the two methodologies, through the results obtained in the performance of repeatability tests (20 repetitions), with regard to the operation times of the relays protection functions, proving the equivalence of both results in this regard. With the analysis of the table, it can be seen that the differences in the average times of the actions that occur before reclosing do not exceed the time of 0.9 milliseconds, which, considering the repeatability of the IED, is a time that can be disregarded. After reclosing, the maximum difference observed was 2.79 milliseconds in the performances. Such increase is justified by the lower precision of the IED for counting the reclosing time, which, despite resulting in small time differences, will result in different reclosing moments, generating different re-energizing transients, that is, other levels of transient currents will be read by the IED, resulting in different performance times.

TABLE II
COMPARISONS TIMES IN MILLISECONDS OF IEDS PROTECTION FUNCTIONS

SIGNAL \ SYSTEM		ANALOG Tavg.	IEC 61850 Tavg.	ΔTavg.
TRIP (7SL86_1)	BR	14.182	13.707	0.475
	AR	16.480	14.885	1.595
DIF_87 (7SL86_1)	BR	14.307	13.700	0.607
	AR	17.135	16.037	1.098
SOTF (7SL86_1)	BR	-	-	-
	AR	20.100	17.310	2.790
OC_50/51 (7SL86_1)	BR	-	-	-
	AR	-	-	-
REC_79 (7SL86_1)		1035.6	1033.1	2.500
TRIP (7SL86_2)	BR	14.540	13.707	0.833
	AR	17.157	15.960	1.197
DIF_87 (7SL86_2)	BR	14.190	13.837	0.353
	AR	17.122	16.345	0.777
SOTF (7SL86_2)	BR	-	-	-
	AR	22.950	20.605	2.345
OC_50/51 (7SL86_2)	BR	-	-	-
	AR	-	-	-
REC_79 (7SL86_2)		1033.1	1031.7	1.400

Tavg. → Average signal activation times between all repetitions;
ΔTavg. → Difference between the averages obtained in the analog test and in the environment of IEC 61850 standard;
BR → Occurring before reclosing;
AR → Occurring after reclosing;

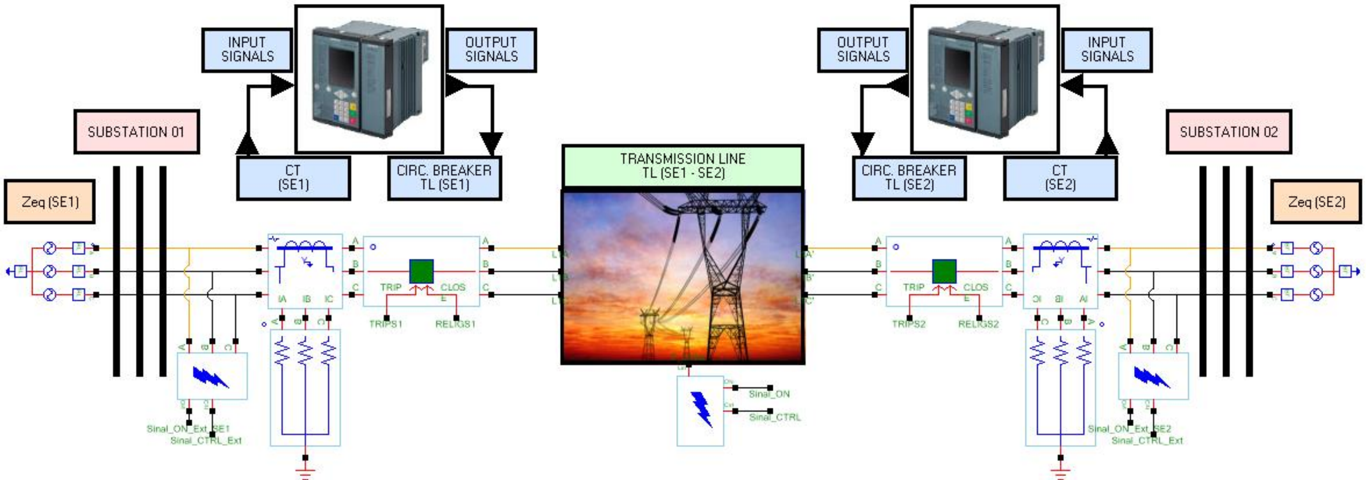

Fig. 6. Power circuit modeled on PS Simul.

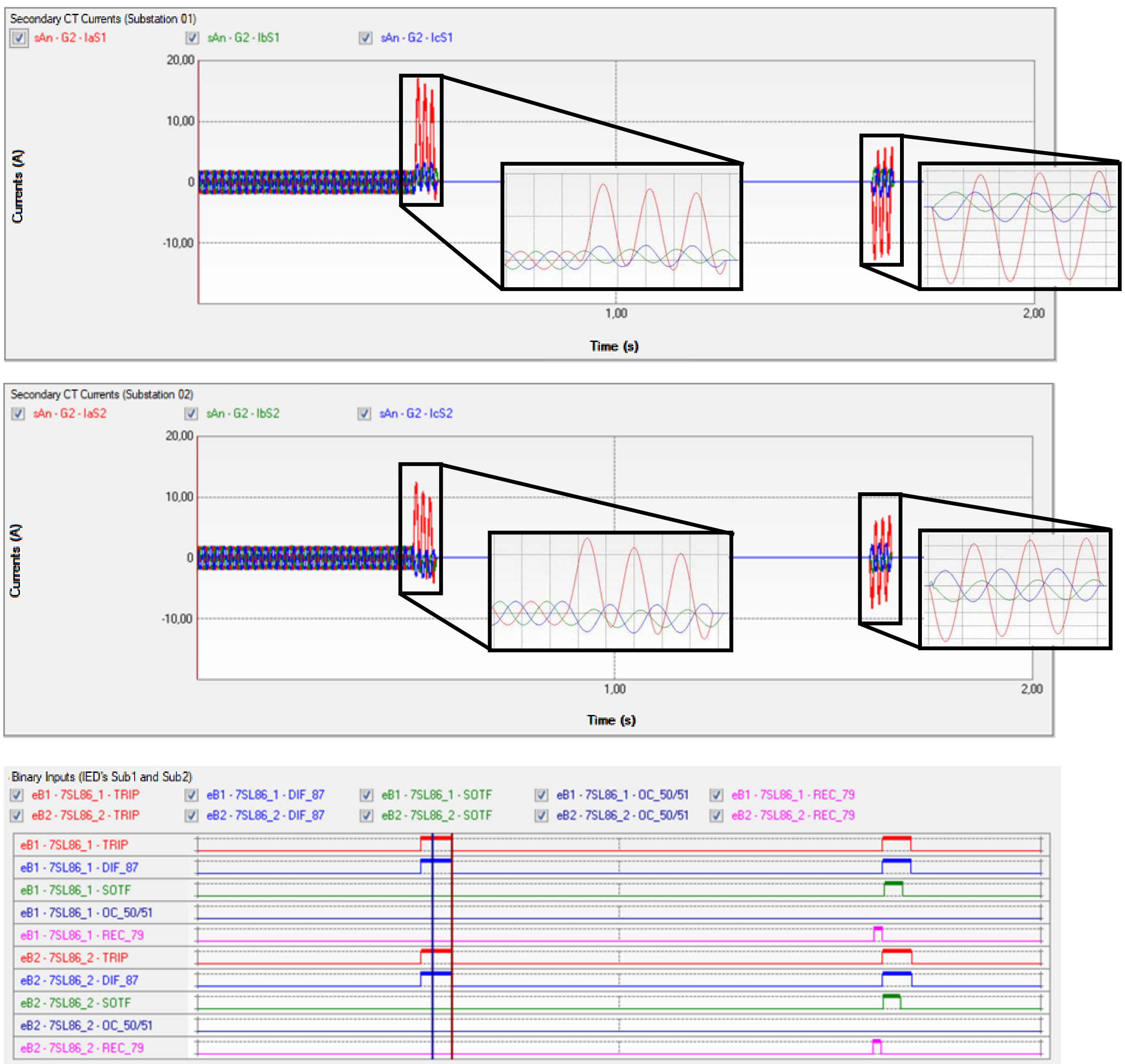

Fig. 7. Waveforms obtained in the PS Simul software for one of the simulated cases.

Figures 8(a) and 8(b) shows the systems used to perform the tests, with the conventional methodology (a) and in the environment of the IEC 61850 standard (b). These figures show the portability of the developed tool, which makes it possible to carry out field tests.

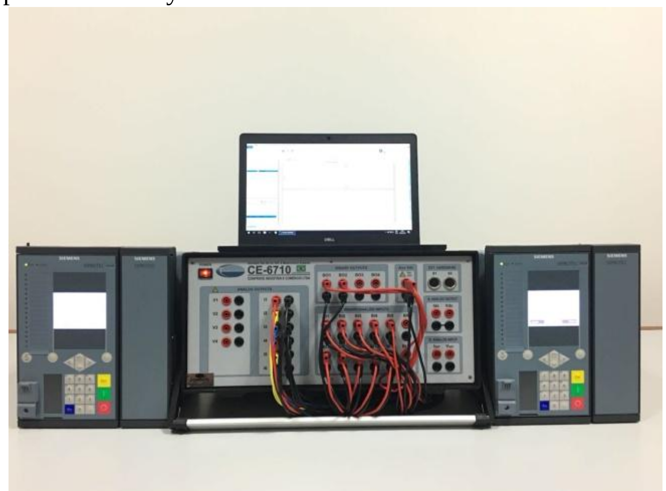

Fig. 8(a). Conventional Methodology.

Fig. 8(b). Environment of the IEC 61850 standard.

V. Conclusions

The study presented the results of the commercial IED's tests through the simulation of 260 contingency scenarios, aiming to prove the correct functioning of these when inserted into a transmission line protection scheme.

The concept of digital substation was used, working with the process bus through SV and GOOSE messages. In addition, the same system was tested using conventional methodology, where the Ethernet cable that transmits the messages in the IEC 61850 standard environment was replaced by hard cabling for sending the analog and binary signals.

By comparing the results obtained with both methodologies, with respect to the observed operating times, it can be concluded that the variations were minimal, which highlights that the implementation of line differential protection (87L) with process bus obtained performance equivalent to that of traditional hard cabling.

Finally, in addition to demonstrate the use of an extremely efficient portable tool for closed-loop testing, at a low cost compared to real-time simulation systems, the article showed the correct behavior of IED's when tested under the conditions of IEC 61850.

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