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Real-time Simulation with OPAL-RT Technologies and Applications for Control and Protection Schemes in Electrical Networks

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Abstract

In recent years, industrialized countries have begun to use real-time simulation (RTS) to validate designs prior to installation and operation. This process allows increasing reliability and security in the development and commissioning of electrical systems. This paper presents some concepts about real-time simulation and some implementations conducted in a real-time laboratory in Colombia using OPAL-RT technology for electrical engineering applications. The aim of this document is to present how this type of technology contributes to improving research and developing new technology, and examples of recent applications. The idea of the real-time laboratory is to provide support to companies in the electrical sector and academic institutes that intend to use this kind of technology for researching protection and control systems in electrical networks. This technology allows researchers to emulate possible real operating conditions that can be difficult to execute due to reliability and security problems. Finally, the impact and advantages of having a real-time laboratory and its applicability to validate and design future systems in electrical engineering are presented.

Keywords: Real time simulation (RTS), Model in the loop (MIL), Hardware in the loop (HIL), Power hardware in the loop (PHIL), protection and control tests

1. Introduction

Simulations have been used for many years for the planning and design of electrical networks [1], from the incorporation of transmission lines in power systems to the optimization of motor drives in the transportation sector. Simulations have performed a fundamental role in the development of a great many applications [2]. During the last decades, the evolution of simulation tools has been carried forward by the accelerated evolution of computational technologies. Because computational technologies have improved their performance, the capacity of the simulation tools for solving large and complex problems has also increased in a short time [3]. Additionally, the cost of digital simulators has been decreasing constantly, making them available and accessible to a great number of users for a great number of applications [4], [5].

The efficient operation of electrical networks is a challenge for companies in the electrical sector as they constitute an important and complex infrastructure in Colombia. These networks comprise a large number of devices, where the integration of each one should maintain correctly the power balance of the network [6], [7]. Therefore, it is important to perform integral tests during the manufacture and commissioning of electrical network equipment in order to verify its correct operation [8].

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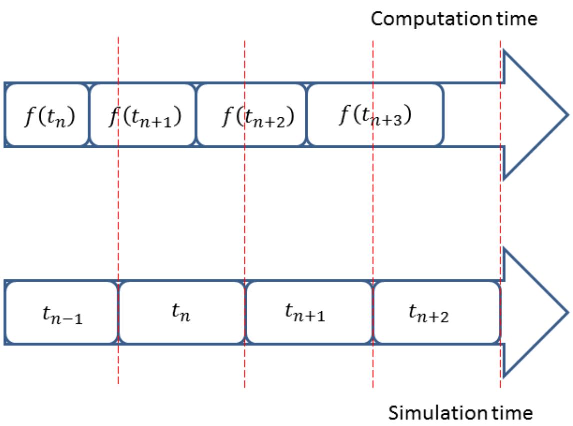
However, electrical companies in Colombia do not have the tools to evaluate the improvement of each scheme, process, and device in an integrated manner from the manufacturer to the final location in site. Currently, simulation processes in Colombia are performed off-line, without the possibility of emulating probable conditions and real contingencies that only are possible with the system operating on-line.

Several factors can lead to the collapse of a power system, e.g., a high demand for electrical energy, a large number of abnormal events, non-conventional connections of energy sources, and the devices that comprise the network. Consequently, there is a reduction in the reliability, security, and availability of the power system due to the poor state of electrical energy supply to the users, which is a big problem for the power system and network operators [9]. To lead a new perspective for solving this problem, a real-time laboratory using the OPAL-RT technology [10] was created in Colombia by Potencias y Tecnologías Incorporadas PTI S.A. This facility allows performing real-time simulations to analyze power systems, including solutions and technologies suitable for companies in the country's electrical sector [11].

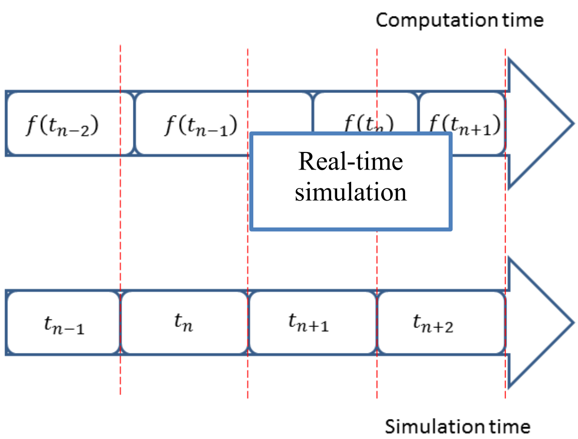
2. Real-time Simulation

To obtain the best result from real-time simulation, it is necessary to check the scenarios presented in the execution of progressive simulations or in the utilization of software. For example, when a simulation is performed, desynchronization between the simulated time and the real time calculation occurs [12]. Depending on the programming characteristics of the software solution techniques and the system complexity, desynchronization can be translated as a delay or an advance of the computation time with respect to the simulation time. The previous situation is shown in Fig. 1, where both scenarios correspond to the known off-line simulations [13], where the period of time in which results are obtained is not relevant. For practicing aspects, the objective of this type of simulation is to obtain results as soon as possible.

On the other hand, real-time simulation not only represents the true dynamics of the system but also emulates with high accuracy the response times of its physical parts. The time taken to generate simulated results should be approximately the same as that of the real system.



a) Rushing simulation



b) Dragging simulation

Fig. 1. Types of off-line simulations [1]

Fig. 2 shows that the computation times can be shorter than its respective step in the baseline for time, but never larger. Any superposition or overlapping between time clusters and computation is avoided. In this case, the simulation process is a one-to-one function, where for each time cluster there is only one computational cluster. This is different to accelerated simulations where the remnant time or time of inactivity is used for advancing the computations of the next time step and, therefore, overlapping occurs.

Currently, there are complex power systems that require study of their current phenomena and contingencies as they can cause faults or serious damage. For this reason, different scenarios are obtained to evaluate their behavior for probable anomalies. The real-time simulation allows interaction with real systems and physical components, and allows the testing of many scenarios with high fidelity and without any risk. Real-time simulation offers the possibility of modeling the network with plants, controllers, and other equipment, replacing physical parts in the study with problems in availability, location, cost, or security.

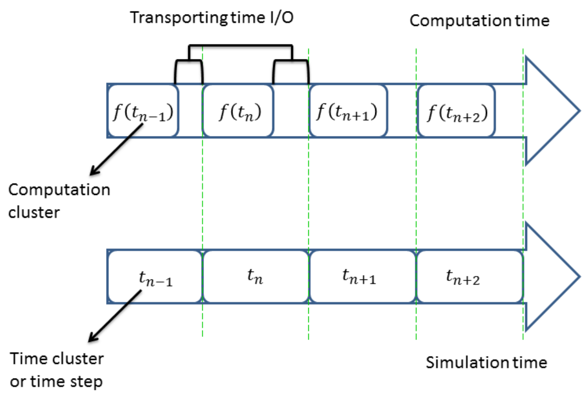


Fig. 2. Real-time simulation [1]

Until now, the first advances with this technology have been possible for electrical networks, power electronics, and the aeronautic, automotive, and academic sectors. Real-time simulation allows different configurations according to the part of the system that the user would like to simulate and depending on the application as shown in Fig. 3. Simulations can be identified in the following categories: model in the loop (MIL), rapid control prototyping (RCP), hardware in the loop (HIL), and power hardware in the loop (PHL).

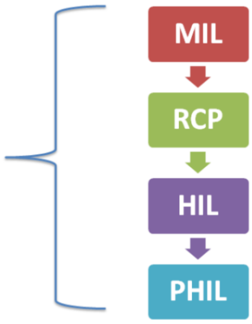


Fig. 3. Schemes in a real-time simulation [1]

2.1 Model in the loop
In an MIL, also known as "software in the loop" (SIL), with enough computation capability, both the controller and the plant can be simulated in real time [14] as shown in Fig. 4. This application is done in order to establish a test of concept, finish preliminary studies, and detect early mistakes [15].

2.2 Rapid control prototyping
In rapid control prototyping (RCP), the plant is real and the controller is simulated. The plant is connected through an input/output (I/O) interface. The implemented control through a real-time simulator has the advantages of being faster, more flexible, and easier to program than the physical part [16]. Because of its characteristics, this tool can be used to apply optimization, control algorithms, validate equipment, and detect errors as presented in **Error! Reference source not found.**.

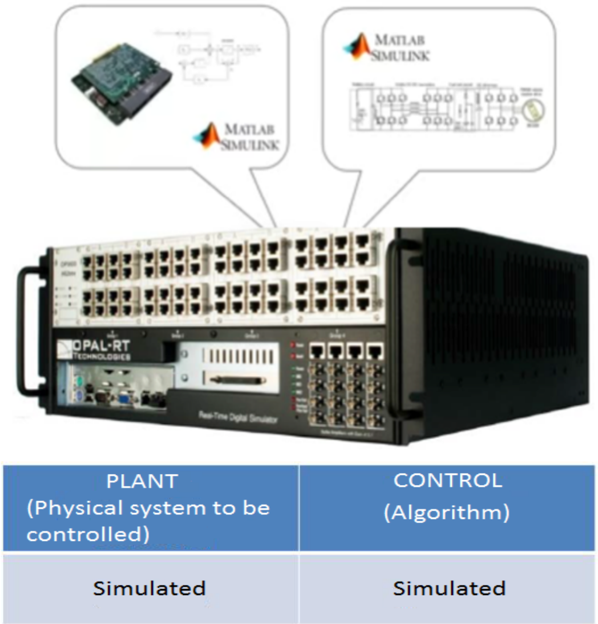


Fig. 4. MIL representation [1]

2.3 Hardware in the loop
HIL is based on simulating a virtual plant [17] where it can be implemented with the physical controllers through an I/O interface as shown in Fig. 5. As part of the advantages that the implementation of this type of scheme offers, is the possibility to perform a fast and early test for the control devices when the access to physical plants are difficult [18].

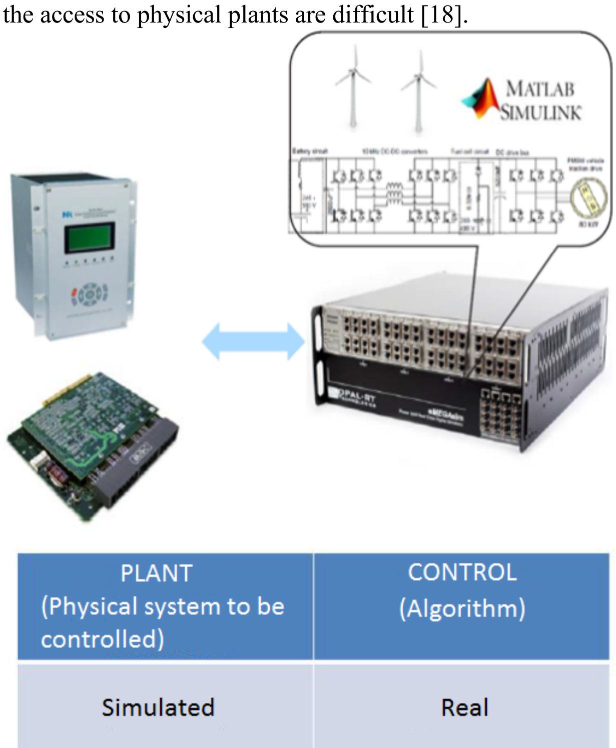


Fig. 5. HIL representation [1]

2.4 Power hardware in the loop
PHIL completely integrates a power system, with voltage and current signals equal to a physical network as shown in Fig. 6. The PHIL concept is essentially an extension of HIL functionality and is based on the interaction of components or elements that require high load flows and with an electrical circuit or network that is running in a simulator [19], [20]. PHIL, therefore, is an innovative and powerful tool for testing power converters, generators, protections, and FACTS (flexible alternating current transmission systems) besides other components that comprise a power system. The use of RTS is required due to the increasing need to evaluate the operation and performance of electrical systems for both normal operation and for contingencies [20].

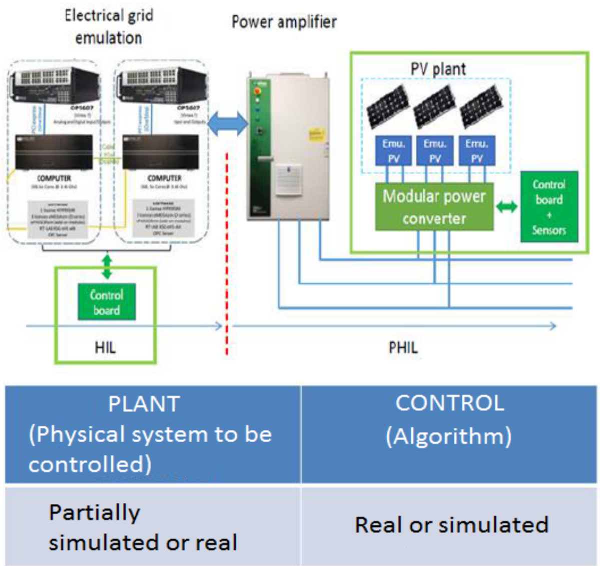


Fig. 6. PHIL representation [1]

With the advances in this technology, the accuracy gap between the dynamics and occurrence times of a real and simulate phenomenon becomes smaller each time.

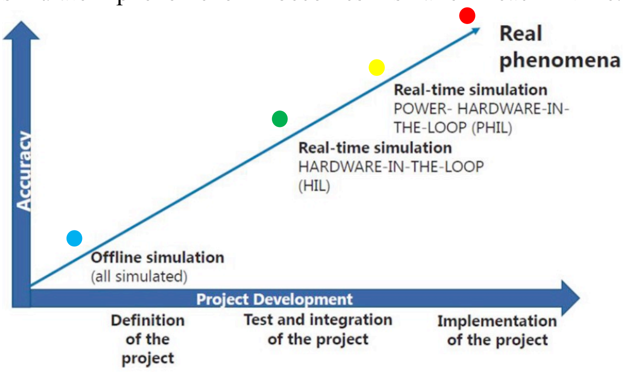


Fig. 7 shows how the main objective of this technology is to approach the real phenomenon and with tools such as HIL and PHIL, this is possible.

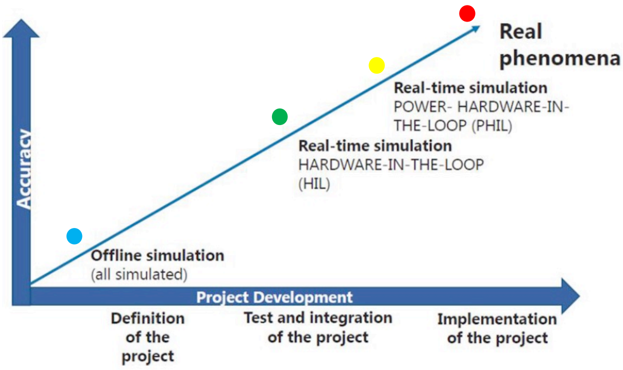


Fig. 7. Approach to the real phenomenon [1]

Real-time simulations have great potential as tools to evaluate the performance of machinery and electrical equipment. The main advantage is the capability to test a large number of electrical schemes with respect to control and protection. Therefore, it is possible to anticipate and prevent faults, determine susceptibility to external factors, evaluate resilience, and check the safety level of systems when contingencies or abnormal operation conditions occur.

Therefore, OPAL-RT technologies allow the integration and conjunction operation of different electrical components as shown in Fig. 9. In addition, it provides the possibility to simulate electrical circuits and power networks, and different operating conditions, faults, and contingencies with high accuracy.

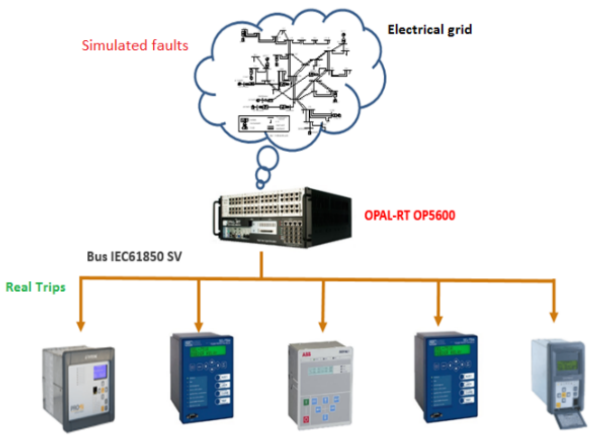


Fig. 8. Integration and conjunction operation through OPAL-RT

3. Real-time Laboratory with OPAL-RT Technologies

3.1 Control and protection scheme with PHIL integration and communication protocol IEC61850 Standard

It is required that the systems components of electrical networks operate with a high degree of reliability. Protection devices cannot avoid their operation and should operate correctly during a fault event. Thus, it is necessary that each protection device runs correctly and in proper cooperation with other protection devices in the power system. In this case, a real-time simulation with OPAL-RT technologies was performed with the aim of testing overcurrent protection relays in which the response time and coordination were evaluated according to the criteria used in a common protection coordination study.

To run the simulation, it was necessary to implement the power hardware in the loop model (PHIL) to integrate the physical protection devices. Fig. 9 shows the connection diagram of this model with the associated equipment. The reference OP5600 is used for the real-time simulation of the electrical power system [10]. ISA DRTS33 equipment is used to amplify the signals to real power system values. Finally, three IEDs are connected simultaneously to the simulation to validate the overcurrent protection functions. In this application, the tripping signals from the IEDs are obtained using the IEC61850-8 standard.

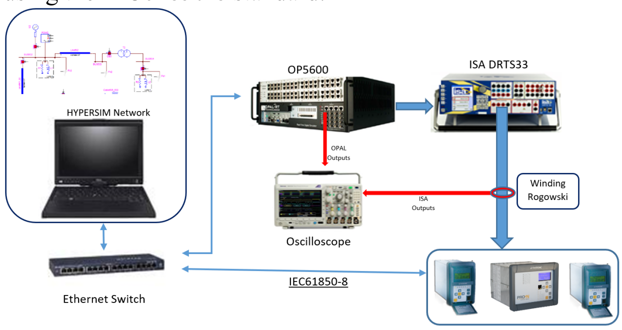


Fig. 9. PHIL model for integration of protection devices and IEC61850-8

This PHIL model has been implemented to validate the operation of the overcurrent relays according to the protection coordination study performed. In this case, the IEEE 13-node test feeder was implemented in ETAP software to determine the selectivity diagram and settings for a specific feeder of the network.

1) ETAP for coordination of protections

In the ETAP software, the IEEE 13-node test feeder was implemented as diagrammed in Fig. 11.

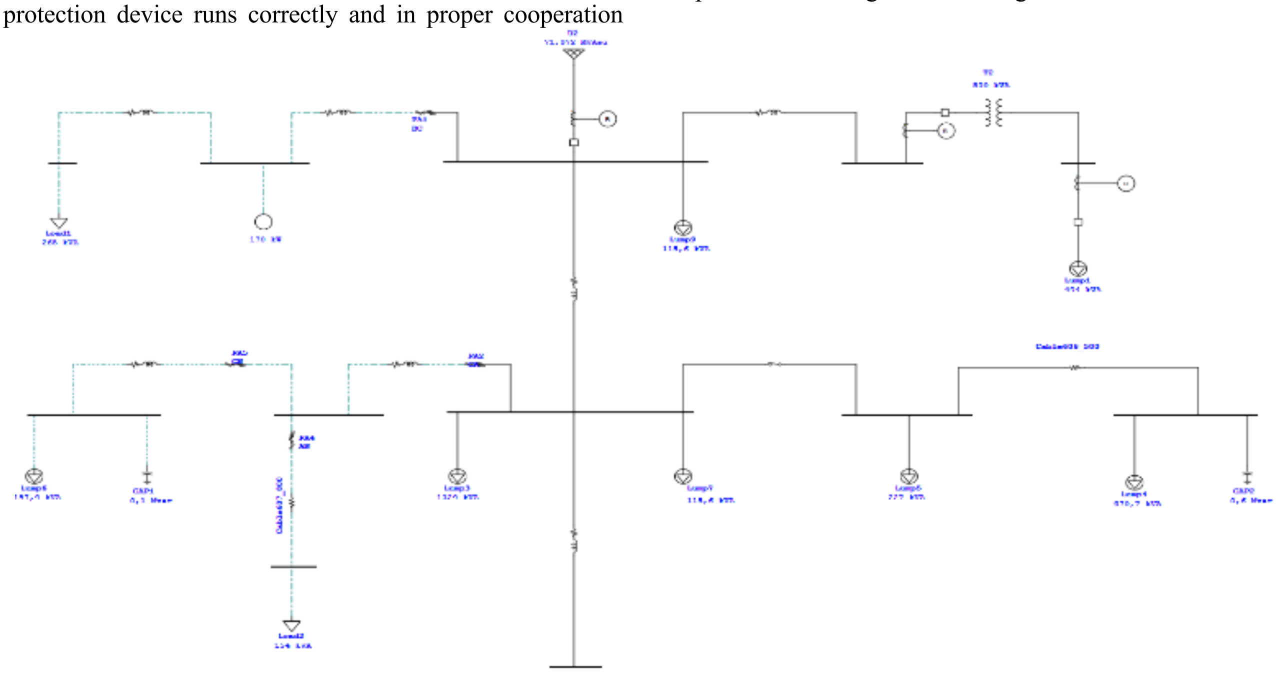


Fig. 10. ETAP – IEEE 13-node test feeder

On this network, the branches used for studying the coordination of three overcurrent relays are presented in Fig. 12.

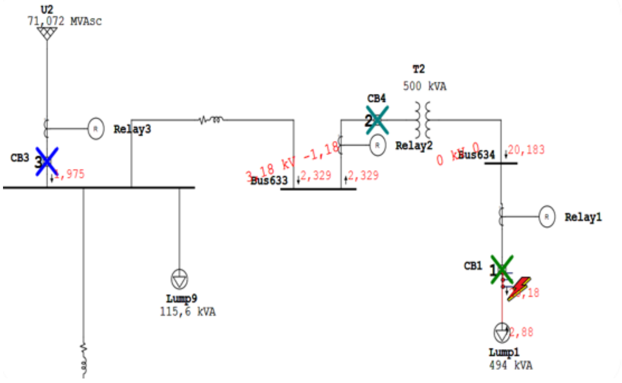


Fig. 11. Sequence of operation of protection devices

This protection scheme has been determined according to the technical specifications of the relays and the selectivity diagram created in ETAP. Table 1 shows the settings of the relays according to the study. The first relay is a Thytonic NA80, the second relay is a Thytonic NVA100X, and the third relay is a Thytonic NT10.

Table 1. Settings of the Overcurrent Relays

Relay	CT	Inverse Time Curve				
		Curve	Pickup	Dial	Pickup	Dial
1	2000/1	ANSI/IEEE EI	0.375	1.22	6	0.03 s
2	300/1	ANSI/IEEE EI	0.35	6.08	14.7	0.03 s
3	500/1	ANSI/IEEE EI	1.56	2.17	13	0.03 s

Fig. 13 contains the selectivity diagram where the settings were obtained graphically for an optimal sequence of operation and time delays according to IEEE Standard 242-2001.

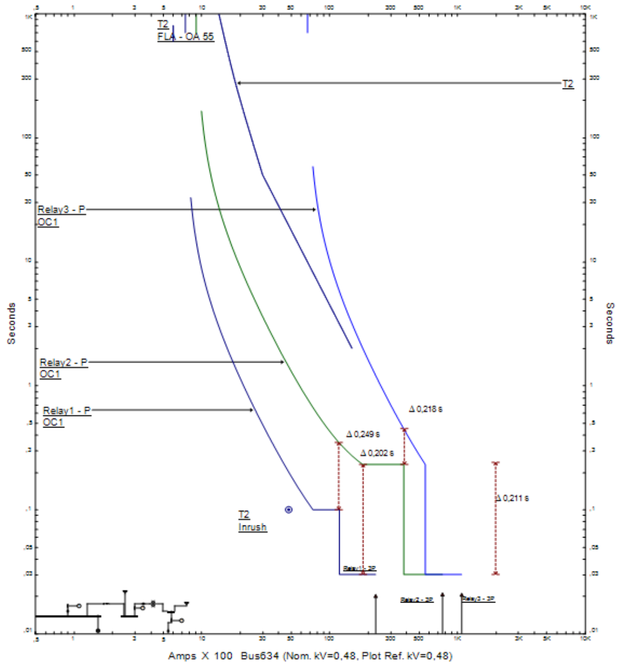


Fig. 12. Selectivity diagram of overcurrent protections

2) Modeling the power system in HYPERSIM

HYPERSIM is one of the software programs used for real-time simulation provided by OPAL-RT technologies. This software allows EMT simulations and the use of analog signals in the time domain to study the system. For modeling in HYPERSIM (Fig. 14), it is necessary to know the input parameters of each type of element of the network (e.g., line impedances, transformers, loads, etc.). A database that includes all the element network included in the ETAP software was used to obtain ng an equivalent model, estimating other parameter not available in the main information. For some models, the source code of HYPERSIM is compatible with EMTP-RV for opening the model directly; thus, this software allows an interface for importing some elements from ETAP.

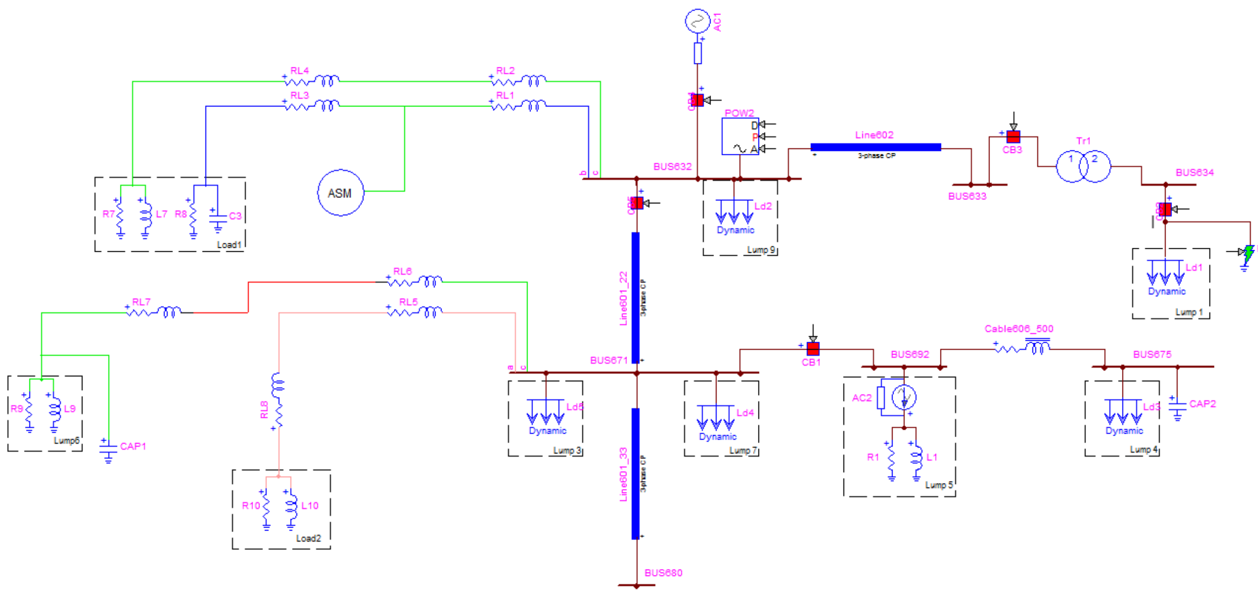


Fig. 13. IEEE 13-node test feeder implemented in HYPERSIM

Because simulations in HYPERSIM are obtained in time domain, a comparison of the results can be performed by using the ETAP software. The RMS values of the analog signals are obtained by using a mathematical function available in HYPERSIM.

Tables 2, 3, and 4 compare the load flow and 3-phase short circuit results obtained in HYPERSIM and ETAP.

Table 2. Comparison of Line Currents

Bus	ETAP (A)	HYPERSIM (A)
Line 602	68.3	69.3
Line 601_22	371.0	389.3
Line 601_33	0.0	0.0
Line 603_BC500 (phase b)	64.9	65.3
Line 603_BC500 (phase c)	64.9	65.3
Line 603_BC300 (phase b)	64.9	65.3
Line 603_BC300 (phase c)	64.9	65.3
Line 604_ACN300 (phase a)	63.5	62.0
Line 604_ACN300 (phase c)	71.3	73.4
Line 605_CN300 (phase c)	71.3	73.4
Cable607_800	63.5	62.0
Cable606_500	118.2	118.5

Table 3. Comparison of Load Flow Results Obtained with HYPERSIM and ETAP

Bus	Element	HYPERSIM			ETAP		
		V (%)	P (MW)	Q(MVAR)	V (%)	P (MW)	Q(MVAR)
632	Lump 9	103.00	0.10	0.06	102.67	0.10	0.06
671	Lump 3	101.00	1.16	0.66	100.55	1.15	0.66
671	Lump 7	101.00	0.10	0.06	100.55	0.10	0.06
675	CAP2	101.00	0.00	-0.61	100.36	0.00	-0.60
675	Lump 4	101.00	0.85	0.47	100.36	0.84	0.46
692	Lump 5	101.00	0.17	0.15	100.55	0.17	0.15
634	Lump 1	102.00	0.41	0.30	100.39	0.40	0.29
652 (phase a)	Load2	97.00	0.12	0.08	99.03	0.13	0.08
611 (phase c)	CAP1	101.00	0.00	-0.10	100.24	0.00	-0.10
611 (phase c)	Lump 6	101.00	0.17	0.08	100.24	0.17	0.08
646 (phase b)	Load1 (b)	103.00	0.16	0.00	102.13	0.16	0.00
646 (phase c)	Load1 (c)	103.00	0.08	0.14	101.92	0.08	0.14

Table 4. Three-phase Short Circuit Results

Bus	ETAP	HYPERSIM
Bus 632	12221	12265
Bus 633	8891	8892
Bus 634	23817	23800
Bus 671	7610	7619
Bus 675	6825	6834
Bus 692	7610	7616

3) Setting of relays and IEC61850-8 configuration

Settings of relays were configured such as CT inputs, Instantaneous, temporized tripping time, and pickup values. Fig. 15 shows the configuration of one relay using Thysetter software (software for configuring Thytronic relays).

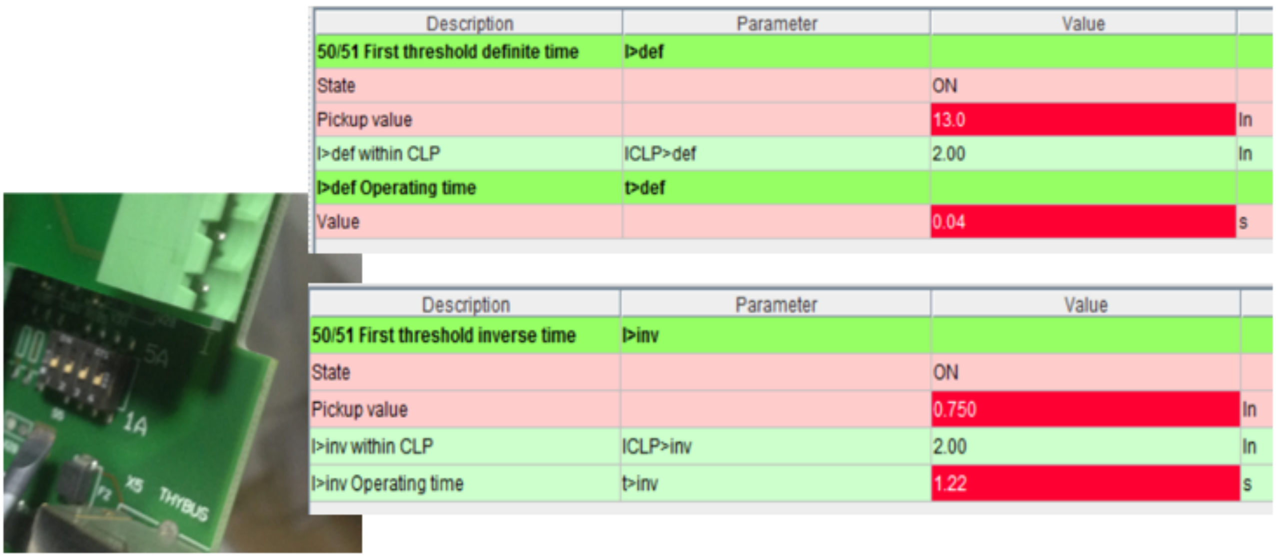


Fig. 14. Relay settings

Recent technologies for IEDs allow the application of communication protocols where some of them are able to use IEC61850. Additionally, depending of the driver, it is possible to use GOOSE (IEC61850-8) and Sample Values (IEC61850-9). The present simulation uses the GOOSE application for obtaining the trip signal of the overcurrent protections. By using this protocol, the IED constantly publishes the signals defined by the user and another IED is able to subscribe to the signals. IEC61850 uses the concept of logical nodes, where PTOC is used for overcurrent protection (PTOC for temporized unit and PIOC for instantaneous). This logical node is added for the binary signal of the tripping; then, the OP5600 will subscribe to the signal using a control scheme (Fig. 16).

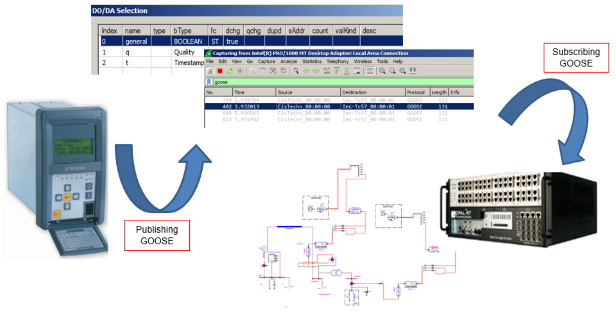


Fig. 15. IEC61850-8 application

4) Power hardware in the loop scheme - PHIL

The OP5600 simulator has a Xilinx FPGA, which allows generating analog and digital signals to use through the I/O cards. Therefore, the IEDs receive analog signals from the simulation: in this case, secondary currents coming from the TCs at each circuit breaker (Fig. 17).

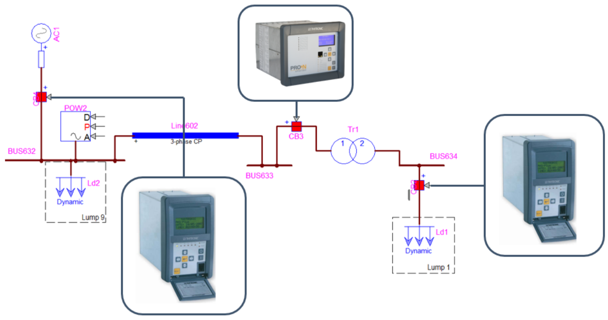


Fig. 16. Receiving analog signals from the simulation

From the OP5600, it is possible to obtain signals +/−15 V. The ISA DRT33 amplifier is used to obtain the same signal in current units. Fig. 18 shows the conversion of the signal (phase a) in one of the circuit breakers.

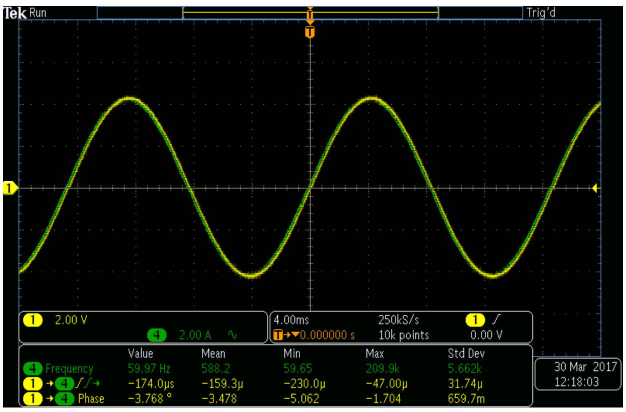


Fig. 17. Signal amplification

Moreover, ISA DRTS33 has three current outputs. The IEDs accept connections from one- to three-phase; however, for this study, only one phase was used (Fig. 19).

Fig. 18. Measurements from IEDs

5) Control using IEC61850-8 in HYPERSIM

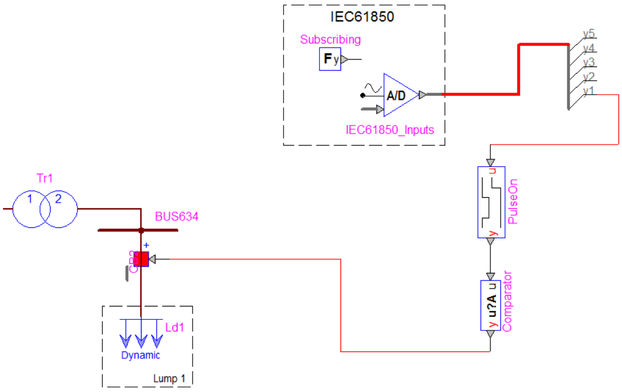


Fig. 19. Control in HYPERSIM with IEC61850-8

The block "Subscribing" was used for specification of the subscription to the IED and the block "IEC61850_Inputs" was used to obtain the inputs. In this case, it was configured for subscribing of the overcurrent trip signal, and then the input is a binary signal. The "PulseOn" element allows the conversion of the pulse to a constant signal and the "Comparator" allows opening the three phases when it receives the trip signal (Fig. 20).

6) Execution of a 3-phase short circuit

A three-phase short circuit has been defined in secondary of the transformer (Fig. 21).

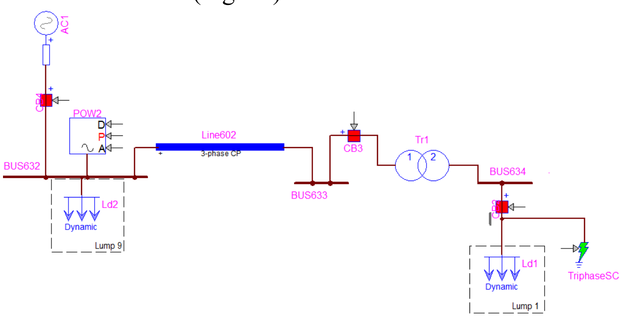


Fig. 20. Short circuit location

This event is simulated in real time and detected by the IEDs in the PHIL application. For obtaining the trip signals of all relays, the controls of two circuit breakers were disabled and the fault opened by the last trip signal. This means that the temporization was completed by the three relays in real-time. Fig. 22 presents the current signals during the event, where the first graphic has the current simulated and the second graphic has the real event measured by the Rogowski windings.

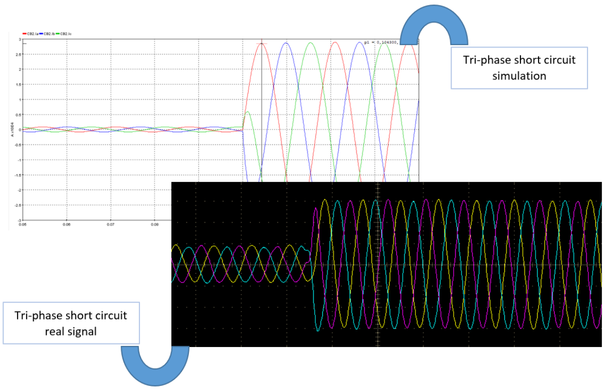


Fig. 21. Three-phase short circuit event

Because the IEDs are integrated to the simulation, it is possible to obtain their behavior during the event. Fig. 23 shows the result of the real-time simulation, where the following four states are identified:

1. **No event:** The system is running in steady-state conditions
2. **Short circuit:** The current increases because a 3-phase fault has occurred
3. **GOOSE signals:** The binary signals are received from the IEDs through IEC61850-8
4. **Opening fault:** The fault is opened because the control system of the last circuit breaker has changed the state

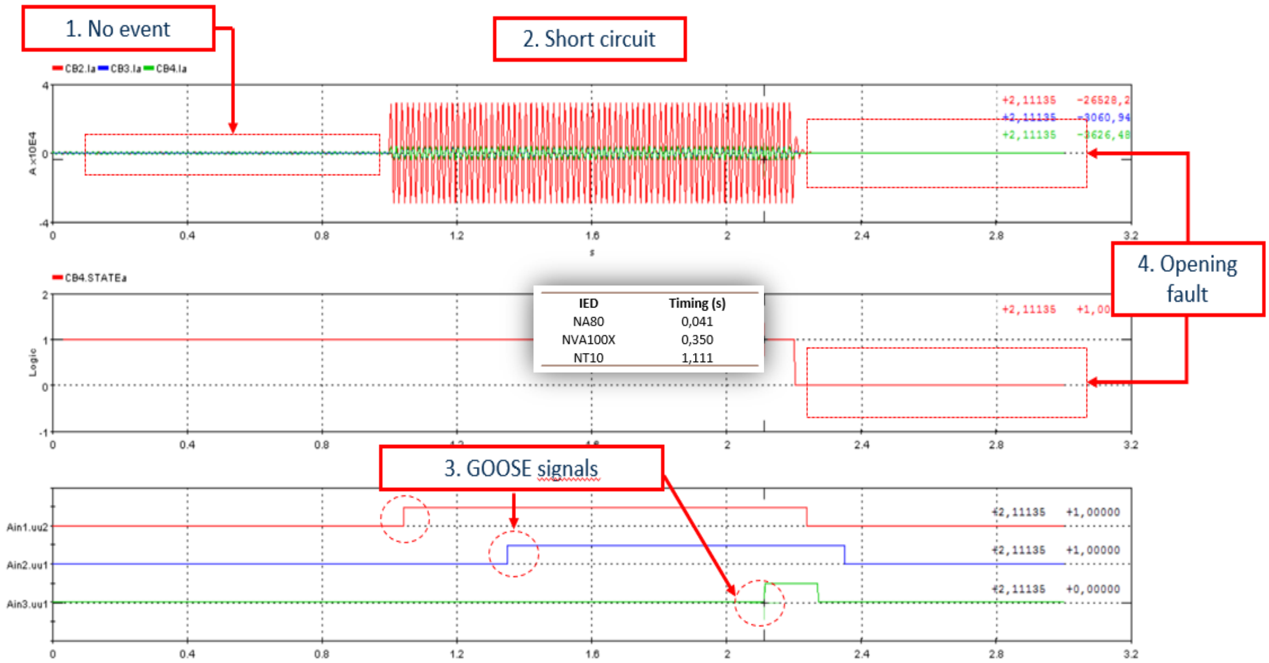


Fig. 22. Real-time simulation with PHIL

Fig. 23 presents the real operation sequence of the IEDs for the power system, considering the settings obtained in the coordination study of the relays.

4. Conclusion

The intention of the real-time laboratory with OPAL-RT technologies for real-time simulation is to focus on new challenges in delivering high-quality services and innovation for customers. With this type of application, the main challenges of the productive sector include appropriating scientific personnel, mainly from the private sector. There is a need to test new technologies, products, and processes with the high possibility of progressing toward higher levels of productivity and competitiveness in the regions and the country. Real-time simulations allow supervising and optimizing process performance before commissioning. The real-time laboratory offers electrical companies many alternatives to validate new elements in the power system and, especially, for testing protection and control systems. Real-time technologies reproduce with high accuracy the dynamics with both hardware and software. and performance of real systems and offers reliability in the obtained results, which is necessary for proper and opportune analysis. In the case of protection and control, real-time technology allows supporting the expansion of future electrical networks and the coupling of new technologies.

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