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Current Status and Future Trends in Protection, Control and Communications Testing in Electrical Grids using Real-time Simulation

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Abstract

In recent times, real-time simulation has been used to validate the testing and design of protection, control, and communications systems prior to their commissioning in the field, which has improved the reliability and security of the commissioning processes for electrical systems. This paper reviews the state-of-the-art and future trends in protection, control, and communications testing of electrical grids using real-time simulation. In addition, a summary is presented in which all the works and technologies mentioned are listed with the purpose of identifying new challenges in the proposed topic. Finally, future trends related to the use of real-time simulation for evaluating protection, control, and communications schemes are presented. Real-time simulation is very useful due to the increasing complexity of modern electrical power systems, therefore, it is necessary to use this kind of tool to facilitate field testing, avoid unnecessary work, and reduce costs for clients.

Keywords: Real-time simulation hardware in the loop, software in the loop, protection relay, control test

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 is decreasing constantly, making them available and accessible to a great number of users for many applications [4, 5].

Real-time simulation is a process whose purpose is to reproduce, with the highest possible level of precision, the dynamics and response times of real systems through the use of computing hardware and software. This allows the evaluation of complete electrical systems with their respective protection, control, and communications schemes and makes it possible to observe their performance as though they were implemented in real systems [6].

Recent advances in computing have allowed the rapid development of real-time simulation in many applications, including the testing of protection, control, and communications equipment in electrical systems.

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On the other hand, the efficient operation of electrical grids is a great challenge for the electrical sector as they constitute highly complex systems. Such systems involve a large number of devices, where the integration of each one should maintain the equilibrium of the properly operating system [7, 8]. Thus, it is of great importance to carry out factory and on-site integral tests of different equipment and elements that make up an electrical grid in such a way that the correct operation of the system can be checked [9].

With the emergence of new fields of application, powerful real-time simulators, and novel procedures introduced by modern engineering, the optimization of traditional testing and commissioning processes of electrical schemes and equipment has been achieved [10]. Various reference institutions for the electrical sector have proposed to modernize, optimize, and include in the processes the participation of information and communication technologies as a means to integrate all system domains and a catalyst of the advantages that these technologies represent [11] in relation to reliability, quality, and efficiency improvements in the service. This has been evidenced in the works referenced below, where real-time simulators, information technologies, and telecommunications have been used to optimize the testing and commissioning processes [10], [12–21].

The incorporation of real-time technology prior to implementation provides relevant support to the protection and control tests of electrical grids. At the same time, it allows reducing the costs and maintenance time, avoiding unnecessary engineering, and increasing the reliability of the energy supply. The implementation of this technology will allow electricity companies to make fast and timely decisions at the time of carrying out any kind of reconfiguration of electrical schemes and power system equipment.

2 Protection, Control and Communications Testing Using Real-Time Simulation

2.1 Protection systems

In large transmission and distribution electrical grids, electrical substations are commonly monitored and controlled [22, 23]. However, when the start-up test of the different elements are performed, for example the ones corresponding to a substation, a group of inspections should be done at the time of manufacture, before energizing the elements and after putting them into service [24, 25].

Protection schemes vary from one electrical system to another, depending on the voltage levels, importance of the installation, and the energy company. Such schemes are classified according to the importance of the machines or equipment to be protected, such as generators, transformers, capacitor banks, buses, and lines [23, 26].

Advances in electrical grid protection have been considerable due to the recent integration with microprocessor technologies, which allows a single protection unit to include many different functions [27, 28]. Thus, the integration of functions is convenient when they complement each other to avoid power system faults.

Nowadays, technology allows to integrate both protection and control functions, where it is possible to have equal and redundant units for each output and that seems to have economic appeal based on the fact that the time and number of operation contacts are not compromised [6, 23, 28].

2.2 Control and communications systems

Currently, two control concepts prevail in electrical grids—traditional and automated—with the latter being the trend in modern electrical grids. The use of intelligent electronic devices (IEDs), which are autonomous apparatuses with integration and communication capacities, through standard protocols that make use of one or more microprocessors with the ability to send and receive information [6, 22, 27].

Some automatic maneuvering concepts in control systems are based fundamentally on available information inside the substation, where the action of the control devices may be sent or modified in a local or remote way. Some automated operations in electrical grids are relay automatic setup, automatic maneuvering of equipment, automatic reclosing, synchronized control of switches, transformer control, low-frequency automatic disconnection of load, automatic system restoration after a loss of power supply, sectionalization of the fault zone, automatic control of tap changers, and reactive power control as mentioned in [22, 23, 27, 28].

2.3 Protection, control, and communications test

In protection and control, each device and instrument must be completely assembled, set up, and tested in the factory, which is commonly known as Factory Acceptance Testing (FAT). Later, these devices must be subjected to tests to ensure reliable operation of all the components in the field, known as Site Acceptance Testing (SAT).

FAT guarantees the security and quality of the equipment, device, or instrument before its delivery or final installation. It is necessary to be sure that equipment is operating properly and without anomalies that can affect the in-field functionality and installation. With these tests, it is possible to check that all specifications and previously established requirements have been met [24, 25, 29, 30].

SAT makes it possible to determine the electrical, mechanical, operational, and environmental characteristics of each electrical component under real operating conditions, with the aim of guaranteeing the fulfillment of the design specifications. The results obtained through this test are able to establish parameters that make it possible to determine the degree of degradation and allow early detection of malfunctions in the system or equipment during their normal operation and lifetime in the electrical grid [23, 31].

Fig. 1(a) displays a scheme representing the current method of protection, control, and communications tests performed on electrical grids. Traditional FAT is applied to each individual component, which entails manual and disjointed work, that is, it does not involve the integration of all the equipment making up the system to evaluate the performance and interactions among them. To develop traditional FAT, three-phase injection equipment is used, which makes it possible to obtain current and voltage magnitudes and other magnitudes with high precision, however, this technique incurs high costs in terms of equipment and availability. In addition, when performance tests are carried out through simulations, they are performed in a decoupled manner and not in real time, i.e., offline. Thus, there is no mathematical, functional, or precise model representation of the power environment that the system is going to face as it does not represent a real plant.

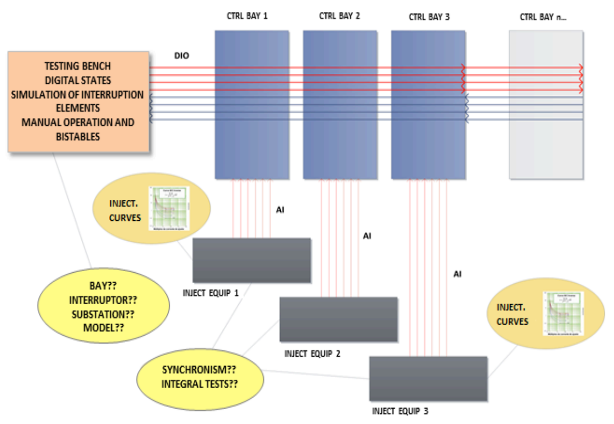
In Fig. 1(a), it can be observed that to test the protection, control, and communications schemes in n bays, the use of n injection devices is indispensable. This is not efficient from an operational, logistical, or economic point of view due to factors that carry weight at the time of test execution such as the necessary staff coordination, time, and availability of the testing equipment. When commissioning tests are carried out in the traditional manner, the following questions are posed: To which bay are the tests applied? To which breakers are the tests applied? What happens to the other protection, control, and communications devices in the substation? Is there a model of the system? Finally, is there synchronism in test execution?

The optimization of integral protection, control, and communications in electric grids using real-time simulation, information technologies, and telecommunications, as shown in Fig. 1(b), makes it possible to save time and achieve testing precision and optimal and efficient designs in view of demanding and modern power systems and electrical grids.

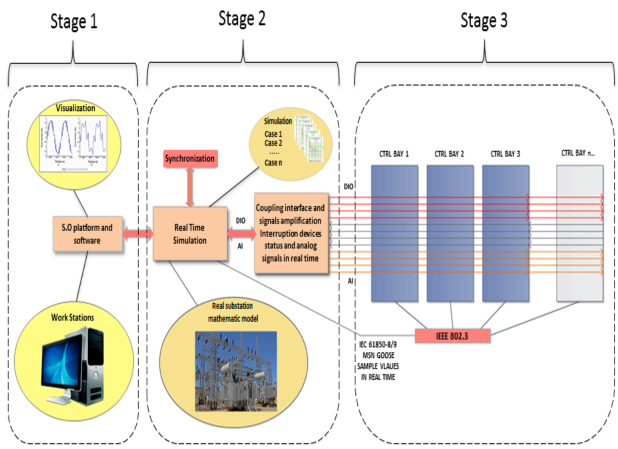
In Fig. 1(b), the process of implementation of the necessary technologies to simulate an electrical grid in real time—in this case, as an example, a substation and its protection equipment—has been divided into three stages:

- Stage 1: Base technologies for modeling and visualization.
- Stage 2: Processing, data flow, and communications.
- Stage 3: Integration schemes, signal acquisition, and performance monitoring.

The first stage refers to the selection of the software platform and technologies for modeling and performance visualization of the system under analysis. In the current market, there are several companies that offer interesting solutions in real time. The second stage of implementation encompasses the processing hardware components, data flow, and communications. In this stage, the necessary equipment and processing power to carry out the real-time computations, data flow to and from the simulation hardware, and finally the technologies and protocols of communications to connect the simulation workstations with external protection, control, and communications devices are established according to the test requirements.



(a)



(b)

Fig. 1 Protection, control, and communications testing: a) Traditional way and b) Using RTS

The third stage of implementation is related to the schemes and technologies that interact with the power equipment. This corresponds to signal amplification, data acquisition devices, monitoring technologies, and operation schemes to carry out a real-time simulation loop.

These implementation stages promote the development and use of real-time simulation, information technologies, and telecommunications. This makes it possible to integrate the real functionality of protection, control, and communications equipment with a precise simulation of the real power system through effective interfaces for the respective data exchange in a quick, secure, and reliable way.

2.4 Real-time simulation for protection, control, and communications schemes

Different schemes that use real-time simulation for the commissioning of protection, control, and communications systems in electrical grids have been developed, currently, there are four main representative schemes into which the different techniques and methodologies to carry out real-time electrical performance tests can be grouped. These schemes are software in the loop (SIL) or model in the loop (MIL), rapid control prototyping (RCP) or controllers in the loop (CIL), hardware in the loop (HIL), and finally power hardware in the loop (PHIL). These schemes are widely used for the representation and modeling of electrical systems and protection, control, and communications schemes with the aim of obtaining a preview of what the real system performance could be.

2.4.1 Software in the Loop (SIL) or model in the Loop (MIL)

In an SIL scheme, both the controller and plant may be simulated in real time (Fig. 2) [32]. This is very useful when it is difficult to access protection, control, and communications systems. However, all the devices must have the validated models to obtain accurate results [33].

Fig. 1. SIL scheme

2.4.2 Rapid Control Prototyping (RCP)

In an RCP scheme or CIL (controllers in the loop) scheme, the plant is real and the controller is simulated. The plant is connected through an input/output interface to the virtual controller. The control implemented through a real-time simulator has the advantages of being faster, more flexible, and easy to program [34]. Due to these characteristics, it is very useful in the optimization of algorithms for the control, validation, and detection of errors (Fig. 3).

2.4.3 Hardware in the Loop (HIL)

An HIL scheme involves the simulation of a virtual plant [35] in such a way that its implementation with the real controllers is possible through an input/output interface (Fig. 4). Some implementations based on this concept can be reviewed in [36–47]. Other references related to this scheme can be found in Table I.

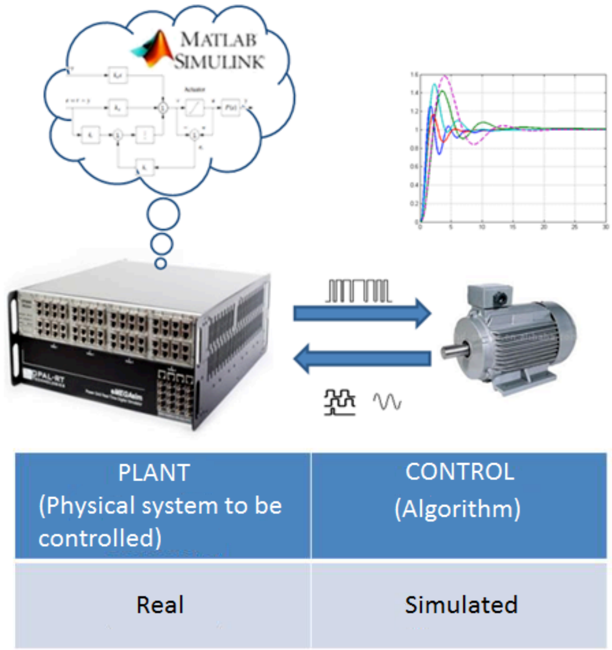


Fig. 2. RCP scheme

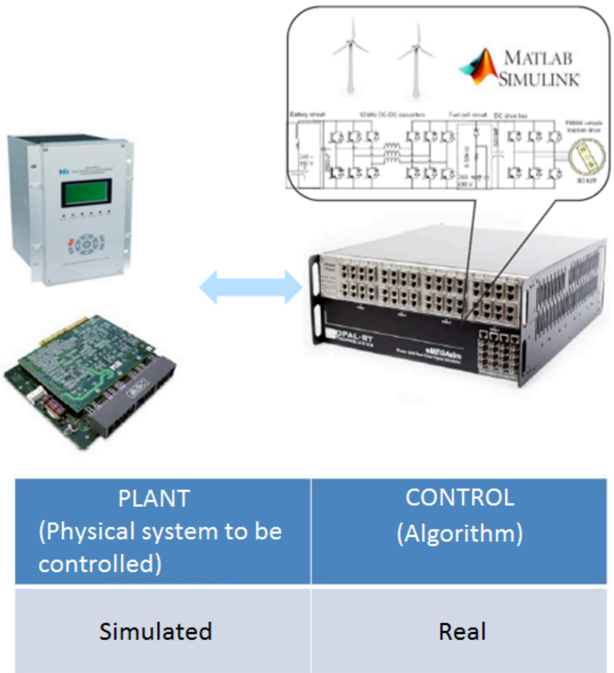


Fig. 3 HIL scheme

2.4.4 Power Hardware in the Loop (PHIL)

A PHIL scheme comprises a complete integration of a power system with its voltage and current signals equal to those in a real system (Fig. 5). The PHIL concept is essentially an extension of the HIL functionality and is based on the interaction of components or elements that require high power flows, and with an electric circuit or grid running on a simulator [48, 49]. Figs. 5 and 6 illustrate the operation and functionality of a PHIL scheme, where the conditions and topology of the grid, as well as the occurrence of faults, contingencies, and abnormal operation, are simulated through real-time simulation. The interface with the protection, control, and communications equipment, such as relays, is made through power amplifiers whose function is to amplify the small signals delivered by the real-time simulator to an adequate magnitude so that the relays can operate (secondary injection) as shown in [17, 19, 47, 49–53]. Schemes similar to PHIL can be reviewed in [17, 47, 49–51, 54], where their implementation and performance evaluation are described in great detail. Other references related to this scheme can be found in Table I.

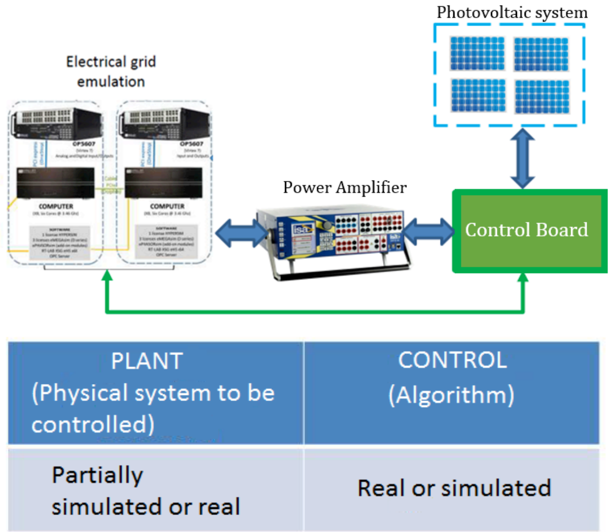


Fig. 4. PHIL scheme

In relation to hardware and real-time simulation computing power, companies like OPAL-RT Technologies, RTDS, DSpace, Speedgoat, and National Instruments have an important place on the market due to the interesting range of solutions they offer. However, just a few of them have dedicated lines and technologies focused on real-time simulations of power systems or, importantly, on the implementation of solutions that allow the testing of system and protection devices through HIL and PHIL integration schemes.

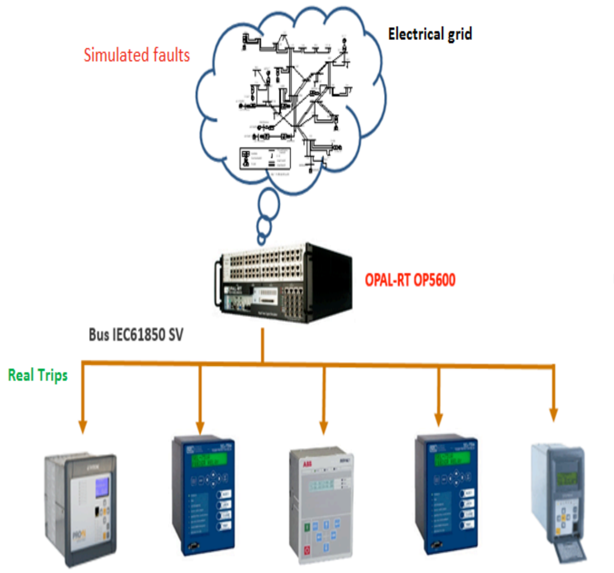


Fig. 5 Real-time simulation integration with real protection equipment (PHIL)

In this way, OPAL-RT Technologies and RTDS are companies that currently lead the market in real-time simulators, offering hardware and software solutions to carry out modeling, simulation, and visualization of real-time performance of an electrical grid, following any of the previous real-time schemes mentioned.

On the other hand, Mathwork´s flagship software, MATLAB, does not fall behind in the incorporation of toolboxes and software solutions for real-time simulation in what is named MATLAB Real-Time Workshop. Experiences of using OPAL-RT Technologies can be reviewed in considerable detail in [41–47, 55, 56] while RTDS can be reviewed in [19, 53, 57–66] and MATLAB Real-Time Workshop can be reviewed in [37, 40, 59, 67, 68]. Other references related to this scheme can be found in Table I.

Advances in ICT are playing a key role in the development of real-time simulation technologies. With the incorporation of standards and protocols of communication, data management, and control, such as IEC 61850 [17, 19, 36, 49, 51, 69, 70], IEC 61970 [69, 71], and DNP3 [17, 38, 47, 49, 60, 72, 73], applications that previously needed equipment and devices to be close to each other due to connectivity and data acquisition requirements are no longer subject to this limitation. Using Ethernet and WLAN networks through the protocols as mentioned, it is possible to integrate, simulate, and monitor in real time the performance and behavior of protection, control, and communications equipment and devices that comprise the real electrical grid. In this way, it is possible to obtain a precise reproduction of the system and to test it over different operating conditions established by engineers and all from centralized or unified workstations, called "WAMPAC" [36, 37, 40, 41, 49, 69] or "CPCS" [70, 74–76].

The development of measurement and monitoring devices such as Phasor Measurement Units (PMUs) and intelligent electronic devices (IEDs) for control and management, which essentially allow the monitoring, control, and management of electrical grids, provides a step toward the goal of achieving real electrical systems behavior. Significant work is being conducted in regard to the functionality of these devices when integrated with real-time simulation with the aim of sampling and reproducing the performance of an electrical grid. Reports on development projects using these kinds of devices are available in [17, 43, 47, 60, 77] and [19, 28, 36, 49, 69, 70, 72] in relation to PMUs and IEDs, respectively.

Table I presents references related to real-time simulation implementation stages for protection, control, and communications testing. Additional references to journals and papers where the reader can find detailed information about the mentioned technologies are also cited in this table [55].

3 Real-time Simulation Challenges and New Trends for Protection, Control, And Communications Testing

Computing technologies have improved dramatically in recent years in terms of execution and cost and time savings. Usually, offline simulations are insufficient to reproduce the behavior of closed-loop systems with the integrated control software and real hardware to reach the required precision, thus, there is a need for real-time simulation.

Real-time simulation is the key to managing the complexity of modern electrical systems, as it allows to compensate the limitations of offline testing, while reproducing the complexity of protection, control, and communications schemes. This solution allows advantages such as flexibility, fast commissioning, easy data depuration, and wide range of tests.

In relation to the electrical grid´s communications systems, there is substation automation based on the IEC61850 standard, which is in the process of being accepted around the world for the implementation of intelligent grids in energy transmission and distribution systems. The optimal design for the integration of primary and secondary systems undoubtedly improves the control performance of substations and reduces wiring and maintenance.

Real-time simulation is used for closed loop testing of protection, control, and communications solutions. When conducting closed-loop testing, the simulator acts as the power system and interfaces to the test objects. For closed-loop operation protective relay testing, the simulator must provide real time data to the relay and sense trip and reclose status from the relay. Because the power system is being simulated, various faults can easily be applied under different network conditions to evaluate the performance of the protection, control, and communications. If the protection detects a fault, the trip signal will be sensed and the breaker in the simulation opened. On the other hand, with the real time simulation it is possible to try the interoperability between many different IEDs.

In the fields of processing and computing, numeric instability is one of the challenges when simulations involve the modeling of elements that requires a high degree of synchronism, using discrete time steps, especially in interconnected multi-machine systems. The development and implementation methods and techniques to solve systems are of essential interest for the simultaneous progress of software and hardware for multi-core and parallel processing.

Future trends include the development of interface models to deal with data loss and delay issues. The delay among simulators can be reduced through the implementation of a communications fitting model. Algorithms could also be developed for the optimization of computation times. Future works include the improvement of synchronization among workstations and the solution of issues related to an effective communication interface among simulators. In that way, the use of HIL and PHIL integration schemes is currently an option with high potential to carry out the necessary integration for protection and execution of control testing.

On the other hand, the structuring of co-simulation schemes, where electrical and communications schemes are simulated simultaneously in real time, is another challenge in the field of simulation. This will provide the capability to preview the behavior of the system against not only electrical contingencies but also informatics such as cyber-attacks, saturation, and communications collapse. Approaches to the overall performance of electrical and communications systems are currently under development. Much study remains to be done to validate this kind of simulation and its field application.

Challenges to overcome involve the modeling and implementation of unconventional equipment and instruments for measurement, protection, and control as well the search for the necessary means for their effective integration in real-time simulations. Fig 7 shows the stages of a project where the mistakes must be detected and corrected, being so important the design stage. Fig 8 shows that the less work leads to an increase of the cost, because correcting the mistakes at later stages could double the initial budget.

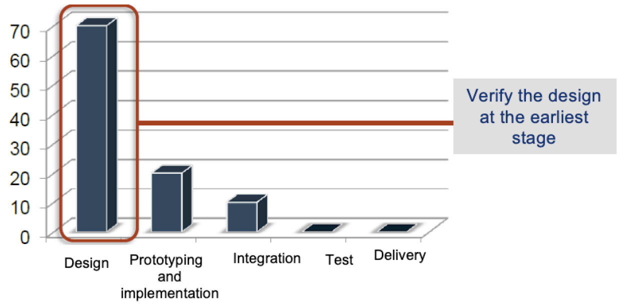


Fig. 7 Stages of the project and mistakes in percent [1].

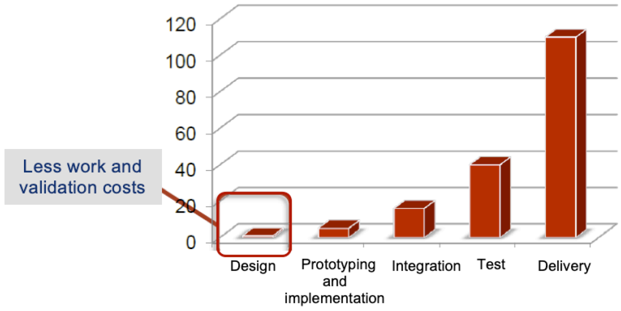


Fig. 8 Stages of the project and costs in percent [1].

Table 1. Classification of Technologies Sorted by Implementation Stages of Real-Time Simulation for Protection, control, and communications Applications and Testing.

Real-time simulation implementation stages for protection, control, and communications testing			**References**
Stage 1	**Stage 2**	**Stage 3**	
OPAL-RT technologies based on FPGA along with Matlab Simulink Toolboxes			[36], [38], [39], [42]–[47], [49]–[52], [56], [69], [70], [72], [77]–[84]
QNX RT operating systems			[45], [50]–[52], [54], [77], [79], [83]
GNU/Linux and open-source-based real-time simulation environments and software			[37], [44], [52]–[54], [67], [77], [85]–[89]
State Space Nodal (SSN) solver			[18], [36], [38], [46], [49], [59], [60], [73], [90]
	Use of parallel and multi-core computing for high simulation performance and precision through OPAL-RT Technologies and others.		[38], [40], [44], [45], [49], [50], [52], [59], [60], [73], [74], [77], [87], [90]–[96]
	Data exchange through high-speed I/O modules and cards.		[41], [45], [46], [61]–[64], [67], [73], [75], [79], [85], [89], [97]
	Use of high-performance and speed network Internet2 for data transfer among simulators.		[66]
	Real-time communications through Giga Transceiver Network Communication Card (GTNET)		[19],[40],[52],[54],[88],[57], [58], [65], [66], [98]
	Interconnection of simulators using the Ethernet TCP/IP characteristic and inter-rack communications (IRC)		[3], [40],[52],[60], [57], [65], [66]
		Hardware in the loop (HIL) scheme using OPAL-RT technologies, RTDS, and others.	[36]–[39], [43]–[46], [51]–[53], [56], [62], [63], [66], [69], [70], [72], [73], [78], [83]–[85], [87]–[89], [99], [100]–[116]
		Use of power hardware in the loop (PHIL) scheme	[17],[49],[36],[81],[52],[67],[91],[112], [114],[117]–[120]
		Use of Intelligent Electronic Devices (IEDs) for measurement, monitoring, and control.	[19],[28],[49],[42],[43],[84],[54],[88],[61], [75], [97],[98],[101],[71], [121]–[123]
		Use of power amplifiers to simulate power signals	[17],[19],[49],[36],[81],[52],[89],[60],[75], [97],[65],[57],[100],[117],[124]
		Time-synchronized injection tests using IEEE 1588 precision protocols	[17],[61],[112],[125]
Real-time distributed and non-distributed simulation using RTDS technology			[19],[40], [41],[52],[54],[88],[85],[60],[90],[93],[75], [97],[62]–[64], [65],[57], [58], [66],[98], [100], [101],[111],[112],[121], [126]–[135]
Wide Area Monitoring, Protection, and Control systems			[36], [37], [40], [41], [49], [69],[115],[71], [122],[124],[136],[137]
HVDC protection, control, and communications systems through			[93]

Real-time simulation implementation stages for protection, control, and communications testing			References
Stage 1	**Stage 2**	**Stage 3**	
SYMADYN and NewLinkC platforms.			
		Implementation of adaptive protection schemes.	[49],[41],[43],[82],[101],[124],[138]
		Use of National Instruments technologies, modules, and accessories for signal acquisition and processing.	[45],[79],[87],[90],[109],[113]
Central Protection, control, and communications Systems (CPCS)			[54],[75],[97],[76]
	Real-time co-simulations to simulate the interaction between ICT and power systems		[49],[58],[71],[122]
	Communications under protocol IEC 61850 GOOSE and sample values		[17],[19],[49],[36],[42],[43],[52],[54],[88], [75],[97],[65],[57],[98],[71],[121],[123]
	Interface unit (IU) for measurement and control		[75],[97]
DSpace technologies			[79],[52],[54],[67],[53],[110],[113]
	IEC 61970 standard application for specification of automated testing.		[42],[71]
	Standards related to modeling, connectivity, control, automation, measurement, and management of interconnected power sources.		[139]–[150]
		PMU and Synchrophasor Vector Processors (SVPs)	[17], [36],[40],[61],[69], [71], [72], [115], [136],[137]
		SIL	[38]
		CIL-CHIL	[42],[81],[41]
Power systems and ICT simulation environment (EPOCHS)			[49],[71]
Real-Time Hybrid simulator			[124],[128],[151]
Matlab Real-Time Workshop			[44],[45],[59],[90],[68]
Real-Time extension of the Virtual Test Bed (VTB-RT)			[52],[67],[113],[114],[105]
Speedgoat technology			[151]
		Network monitoring and control based on real-time wavelet transform.	[47]
	Time division multi-access (TDMA) for precision in simulation of power converters.		[38]
	Communications using high-level data connection (HDLC) Gigabyte Ethernet and Aurora protocol.		[46],[38],[78]
	Use of distributed network protocol 3 (DNP3)		[17],[49],[36],[40],[50],[84], [91],[61],[66], [58],[122]

7. Conclusion

This paper has conducted a review and analysis of the state-of-the-art and future trends of electrical grid protection, control, and communications testing using real-time simulation. The progress of technology in this matter and future implementations in the field of protection were presented to provide a better method to validate FAT–SAT commissioning for the protection, control, and communications of electrical substations.

A consolidation of different technologies and concepts related to the implementation stages of real-time protection, control, and communications testing is presented, with contributions from different authors that will allow future implementations and developments in this proposed matter.

This work presents a consolidated database with different solutions that allow the electrical grid protection, control, and communications testing to be optimized with the aim of reducing maintenance costs, unforeseen failures, inadequate coordination, incorrect designs, and demanding delivery times.

These are reduced using real-time simulation because it is a tool that makes it possible to test IEDs, control equipment, and pilot plants with the modeled system, offering a high guarantee in its subsequent field execution without inconvenience.

Because unconventional renewable energy sources are increasingly being inserted in electrical power systems, protection coordination and system control are becoming more complex. Hence, it is necessary to use real-time simulation tools to analyze the performance of system components prior to their implementation in electrical grids. Therefore, this review work suggests that in modern electrical systems, real-time validation should always be done before field implementation with the aim of avoiding high costs due to inadequate planning.

Simulation and validation tests in real-time simulation laboratories are recommended, as these allow to implement models, systems and technological solutions for protection, control, and communications. These procedures are implemented to have reliable, safe, and accurate results, adding value to the traditional procedures required for taking early decisions and improving the operation of the power system. Besides, real-time simulation is recommended for designing, planning, testing, and validation of new protection, control, and communications strategies that are difficult to perform in the field.

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