Real time simulation with software relay models

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RESUMEN

Este artículo describe una variedad de modelos de software en plataformas corriendo a tiempo real, enfocados para obtener una simulación con la visualización de acciones automáticas durante condiciones de falla. Los modelos desarrollados pueden adquirir información en forma dinámica (voltaje y corriente) de un sistema de potencia virtual implementado. El voltaje y la corriente de fase se capturan como señales con forma de onda, y son accesibles para esquemas de protección integrados como modelos de software en software en un laso. Eso es, el uso de un código para representar algoritmos de relé a distancia y responder mientras la simulación en tiempo real tiene lugar.

PALABRAS CLAVE

Simulación en tiempo real, sistema de protección, prueba HIL, liberado de falla.

ABSTRACT

The article describes a variety of software models running in a real-time simulation platform, the focus is get a long time simulation with the visualization of automatic actions during a fault condition. The models developed can acquire dynamic information (voltage and current) from the virtual Power System implemented. The voltage and current three phase signals are captured as waveforms, and they are accessible to protection schemes integrated as software models into software in the loop process. It means the use of code for representing distance relays algorithms and responding while ongoing real-time simulation.

KEYWORDS

Real-time simulation, protection system, HIL test, fault clearance.

INTRODUCTION

Real-time simulators provide very useful data in the field of testing hardware, measurement units and protection systems. It would not only provide information in terms of optimal design and functionality of protection relays, also provide global information to develop Wide Area Monitoring Systems (WAMS) [1]. The WAMS is then essential data to execute remotely a logic designated to provoke automatic reconfiguration of the system topology. Anyway, each particular problem must be pre-evaluated in depth considering several transient scenarios.

In order to make use of long term simulations in a real-time platform, as first step, the user have to organize a multi-rate representation. Several factors are important to consider before getting a global model. Experts suggest organize by zones in order to manage for some elements equations with maximum detail and other treated as equivalent.[2]

The implementation is based in Matlab-Simulink® and RT- Lab® blocks prepared to manage a test power system. Those elements at remote areas would be a standard model for stability transient analysis. It will be noticed subsystems for representing generators, transformers, loads, etc. The simulation emphasizes in the use of waveforms passing through primary protection zone, and the transmission lines are planned as distributed parameter models without frequency dependence. An overview of OPAL-RT Simulator is presented in figure 1 and more information about it in.[3]

The event of fault clearance is present for less than one second. For that reason, the time of interest for testing software relays is in the order of 50 to 2000 ms. Within this period of time are detected the operation states showed in figure 2 and listed below:

1) Pre-fault condition,

2) Fault insertion,

3) Trip for one line terminal at closer substation,

4) Fault clearance at both terminals,

5) Breakers reclosing if it is possible, and

6) Stability response in post-fault condition.

The purpose of this work is to simulate local intelligence taking action to complete automatically the fault clearance. The output signal for controlling the trip on breakers is with software in the loop process since acquire the voltage and currents signals, processing they inside the relay and its algorithms and produce the output signal to local breaker.

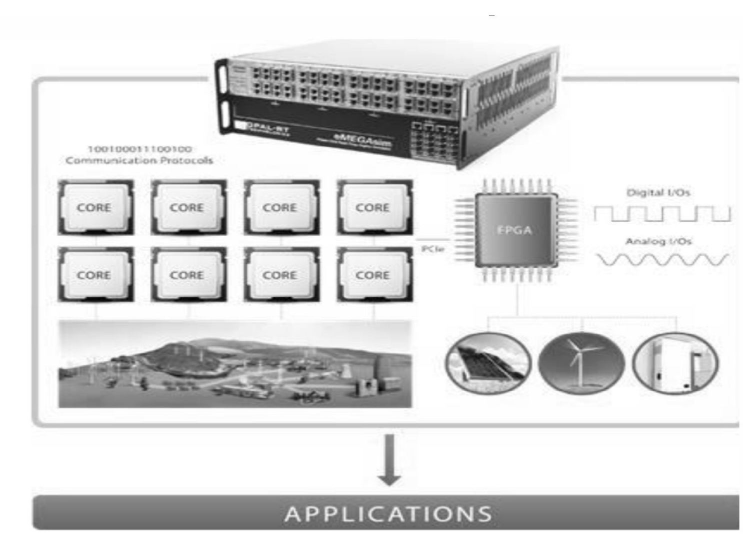

Fig. 1. Overview of real-time simulator OPAL-RT®.[4]

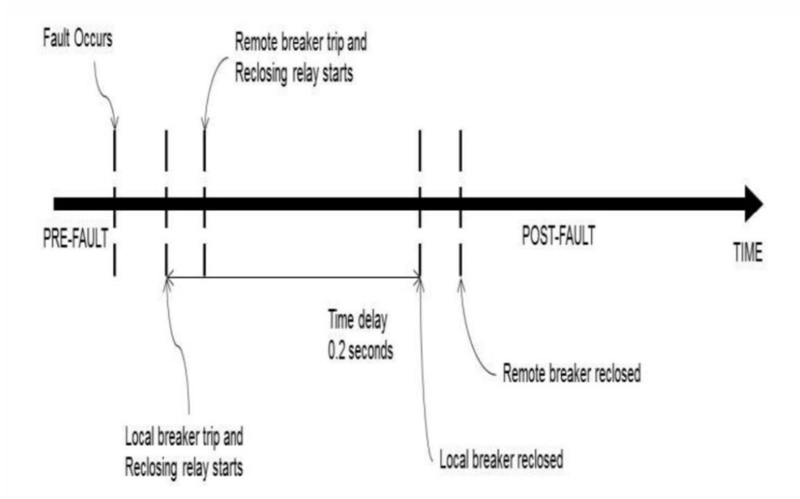

Fig. 2. Time scale with actions to fault clearance process in transmission lines.

Original software models for protection relays and phasor measurement units (PMU's) are programmed and tested within the real-time simulation platform, the last one with the goal to make long time registers. As mentioned above, the contribution is that the analyst does not program the different sequences, but only the beginning of the failure and its type. Technical challenges are presented in the process of adding the response action of the relay automatically by adding settings, given via software interface commands and prepare this interface to make acquisition data from analog signals in physical devices.

The Section 2 shows the models implemented in OPAL-RT® platform, continuous and discrete models. In Section 3, the process to make the fault clearance process is explained previous to propose the test case that is presented in Section 4. The last part is the conclusions, Section 5.

IMPLEMENTATION IN REAL-TIME PLATFORM

Real-time simulation is a modern way for the design and improvement of electrical apparatus to Power Systems. With the evolution of computing technologies have appeared simulation tools to produce simultaneously slow and fast dynamics transient phenomena.[5] Researchers beforehand complete the activity for a model validation and authentication of parameters. The enhanced models produce a formulation in the form:

$$\dot{x} = A_k x + Bu, \quad (1)$$

$$y = C_k x, \quad (2)$$

where A is a square matrix; x becomes the states, B is a matrix with parameters for altering u sources.

Real-time platforms choose the trapezoidal rule as solver since it allows to engineers deal with different time steps according to zones of observation. By this manner a multi-rate simulation improve the exploitation of distributed parallel computing. Nowadays real-time platforms can provide amplified signals to feed directly protection relays with analog outputs. In this work has been programmed all software models for representing the protection scheme and PMU's as well a software models. Thus software in the loop (SIL) simulation is performed into an OPALRT® platform. In general this tool assigns:

1) One master computation subsystem block,

2) N number of slaves subsystems, and

3) One console subsystem as interface with user.

In this work the center of attention is evaluate algorithms representing SIL process and the sceneries to use real signals for voltage and current and interact with physical breaker in a HIL simulation. By one hand are acting those enhanced models of Power System. While simulation is running, the topology suffers a modification by order of virtual relays programmed with the intention to create the signal for controlling breaker.

Figure 3 is presented to make understandable the strategy to manage oriented objects in Matlab-Simulink® environment. The test system is separated as hierarchical subsystems as mentioned before with one master and some slaves. These are declared with relationship to an interior time step (ΔT 1, ΔT 2, ΔT 3, ΔT 4 and ΔT 5).

Slave system to group generators

Evidently synchronous machines have a dynamic response slower in comparison with those for transformers and transmission lines. Thus based on this feature, it is organized slaves to manage zones A and C grouping generator models. The model includes a local control for each generator, figure 4 shows the implementation, by this manner the simulation can be extended with duration for several seconds. All required parameters are given by user through Simulink libraries.[6]

Line models on remote zones

In order to optimize cycle time, slaves are prepared to concentrate models for remote areas. Perceive that a normal grid is with several interconnections, however

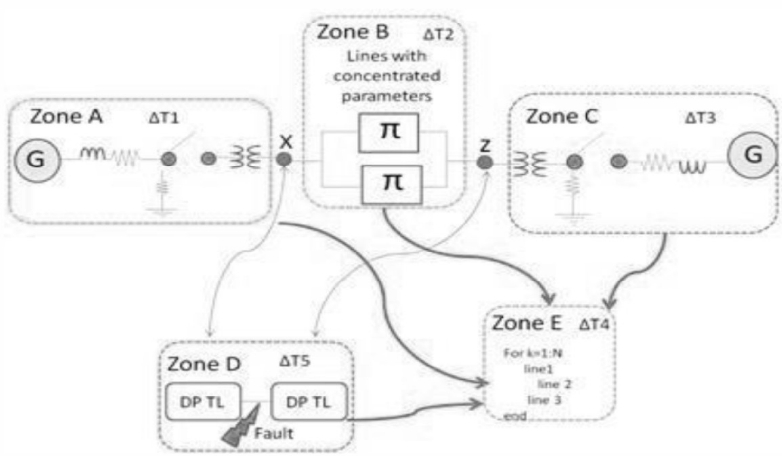

Fig. 3. Software separation for implementation in real-time platform.

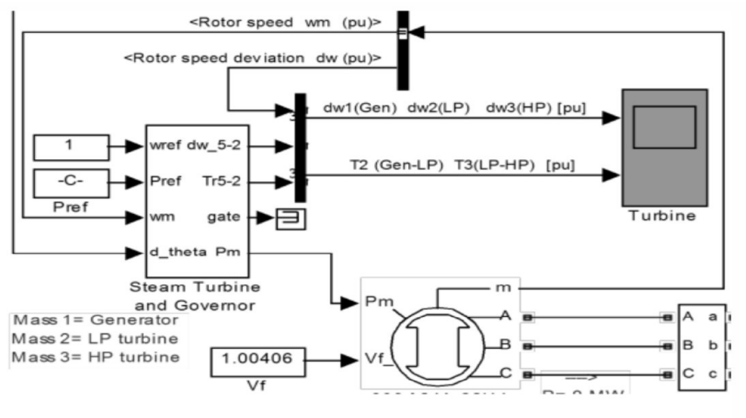

Fig. 4. Simulink model of synchronous machines.

some lines are where protection scheme do not respond. Since protection scheme programmed is based on distance relay logic, it still responds to faults over the adjacent transmission line, thus beyond that position it is a common practice to use a Π model for representing the transmission lines.

In other way, models as universal line model (ULM) in which it has distributed parameters and it can even analyze the frequency dependency between the same parameters. For this case a model is used of aerial line only of distributed parameters without including the detail of the frequency, taking as a base the formulation of aerial lines for electromagnetic transient simulations,[7] where:

$$\frac{\partial v(x,t)}{\partial x} + L_G \frac{\partial i(x,t)}{\partial t} + z'(t) \otimes i(x,t) = 0, \tag{3}$$

$$\frac{\partial i(x,t)}{\partial x} + C_G \frac{\partial v(x,t)}{\partial t} = 0, \tag{4}$$

where the convolution denoted by ⊗ can be expressed by:

$$z'(t) \otimes i(x,t) = \sum_{n=1}^{N} \psi_n(x,t) + r_k i(x,t). \tag{5}$$

Protection relay scheme

Become aware the need to declare a protection zone D, where relay should take action demand distributed parameter models for transmission lines. This zone considers an internal fault, so main transmission line in study is divided in two segments in order to insert a fault.[8]

The fault model is with a value given by the user as a resistance. Internally this slave (zone D) will be propagating waveforms with bandwidth by the order of 20 kHz, thus the internal time step is 50 µs.

In figure 3 is noticeable arrow connections among slaves. It is presented a relationship between the zone D and discrete devices. The simulated signals pass through current transducer models considering saturation. By this manner we add distinctive noise in the input of relay models.

The protection relay is the decision device; this decision is made by a logic process in three steps: fault distance (FD), zone discrimination (ZD) and fault classification (FC).

Figure 4 shows the scheme or distance relay implemented. If these three algorithms find a fault condition in the protected element then the trip signal is sent to a CB, this device is the actuator that can perform the opening and/or reclosing. The detail in distance relay algorithms can be reviewed in.[8]

Digital filter and phasor calculation inside the protection relay

A sinusoidal waveform can be characterized by a complex number know as phasor. Consider a pure sinusoidal signal given by:

$$x(t) = X_m \sin(\omega t + \varphi). \tag{6}$$

The phasor illustration of (6) is set as:

$$\begin{aligned} X &\equiv \frac{X_m}{\sqrt{2}} e^{j\varphi} \\ &= \frac{X_m}{\sqrt{2}} \left(\cos\varphi + j\sin\varphi\right). \end{aligned} \tag{7}$$

Note that the signal frequency (ω) is not explicitly stated in the phasor representation. The magnitude of the phasor is the rms value $\left(\frac{X_m}{\sqrt{2}}\right)$, and its phase is φ. This representation implies that the signal remains stationary at all times, the magnitude, frequency and phase do not change. The most common technique for determining the phasor of an input signal is to use data samples taken from the waveform and apply the discrete Fourier transform (DFT) or the fast Fourier transform (FFT), since sampled data are used to represent the input signal, it is essential that antialiasing filters be applied.[7]

If x_k, $k = 0, 1, \ldots, N-1$ are the N samples of the input signal taken over one period of the waveform input signal, and the phasor is given by

$$X = \frac{\sqrt{2}}{N} \sum_{k=0}^{N-1} x_k e^{\frac{-2\pi j k}{N}}, \tag{8}$$

the peak value of the fundamental frecuency thus obtained is then convert to rms value by dividing by $\sqrt{2}$.. The phase angle of the phasor is the angle between the time when the first sample is taken and the peak of the input but nonharmonic components and any other noise leads an error in estimation of the phasor, this error of estimation due to these effects has been discussed in the literature.

Figure 5 represents the interconnection between current and voltage transducer (CT and VT, respectively) with the transmission line, bus and protection relay, in this case the output of relay go to the breaker (52, ANSI nomenclature).

Synchrophasor

The term synchrophasor is used to describe a phasor which has been estimated at a specific instant time known as time tag. In order to obtain simultaneous measurements in a Wide Area of power system, it is necessary to synchronize these time tags.[10] The synchronization is achieved by using a sampling clock signal provided by a GPS receiver.

The connection diagram to have a PMU is similar to figure 5 to protection relay; the difference is that PMU have an extra input with the GPS data and the output go thought optical fiber channel until the concentrator in a Electrical

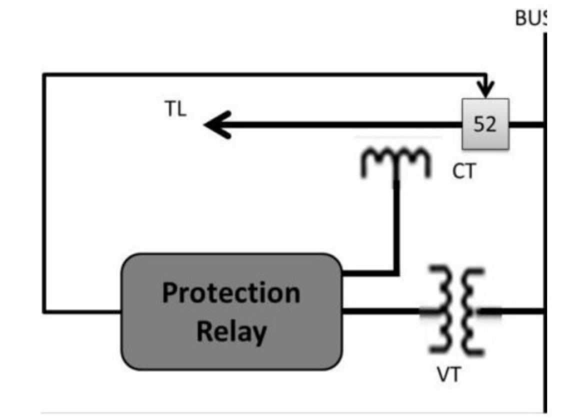

Fig. 5. Structural diagram block connection diagram of PMU.

Control Center or someplace like that.

The phasor data concentrator (PDC) receives and time-synchronizes phasor data from multiple PMUs to produce a real-time, time-aligned output data stream. APDC can exchange phasor data with PDCs at other locations. Through use of multiple PDCs, multiple lavers of concentration can be implemented within an individual synchrophasor data system.[11]

Implementation of PMUs

The implementation is performing in OPAL-RT® platform with the RT-Labv11.05® and Matlab®.

The implementation consist in a FAA filter, this is emulate as a Butterworth function of Fifth order with a 480 Hz as a cutting frequency.

The A/D converter is used to transfer the analog signal to digital samples, it uses a sampler with the capacity of 64 samples by cycle of fundamental frequency of input signal, in this case 60 Hz. The digital filter is used to remove all the harmonic component over the fundamental frequency, after it, the phasor is calculated as was show in the section before in this article. The Peak determination block is used to identify the peak of the input signal and recorded the tag time in this moment. The tag time in this case is getting by the Microsoft Windows® clock, which is synchronized through the internet to global time.

The output of data in the common format that is presented in the IEEE C37.118.1-2011 Standard.[10] In this case the output is showed as a display but it will be send by a fiber optic communication channel to its assigned PDC.

Fault clearance process by protection relays in real-time simulation platform

The protection system has the responsibility of detecting, classifying, locating and isolating faults in any element of power system; in this case the transmission line is the device to protect.

The protection systems consist in three devices: transductors for voltage and current measurements (TP and TC), protection relays and circuit breakers (CB). As primary protection 1 (PP1) one distance relay at each end of the line is installed, without the communication channel between these two relays.

In figure 6, the arrangement that is applied for the tests where the voltage meter and the current that feed the distance relays are presented, the relay emits the error signal to the switch which has the capacity to realize monopolar openings, finally a single-phase fault, 50% of the line and the transient character.

The protection relay is the device in charge of performing the conversion process from analog signal of the transducers to digital signals in phasor format, can also deliver synchrophasor if the relay is added to the input of a GPS. The distance relay implemented has a decision time of 1.5 cycles and the CB of 5 cycles to perform the opening, the time is considering conditions of the fundamental frequency in 60 Hz for the tested case.

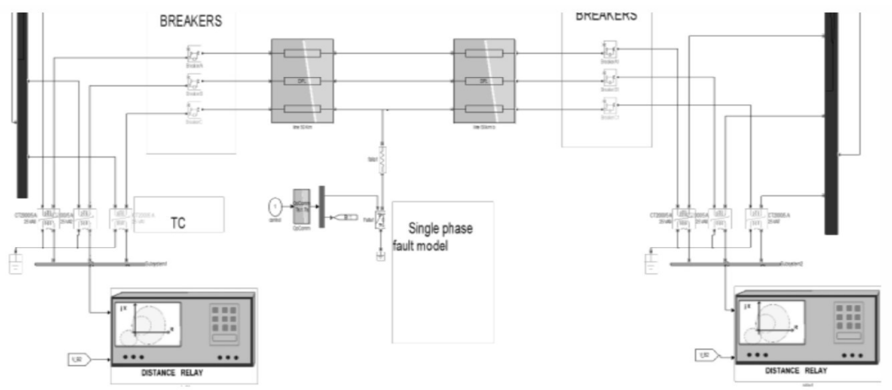

Fig. 6. Scheme of primary protection system in the transmission line.

Figure 7 shows the diagram for the real-time simulation platform implementation of the test case. In the master system, the generators, some transmission lines, circuit breakers; in one slave subsystem exits loads, transmission lines, buses and measurements are included; the second slave subsystem processed of signals measured for protection purposes in the distance relay and for synchrophasor recording and analyzing within the PDC, the distance relay has the ability to send signal to open the switches in case of failure. The Console subsystem is used as a monitoring space for raw and/or processed signals from the various nodes. The detail in the subsystem separation for any implementation in real-time platform OPAL-RT® can be consulted in.[4]

Test case

To show the raised tools and the solutions obtained is proposed to use as a test system the Kundur model which is presented in figure 8. It is proposed to perform a single-phase ground fault in phase A between bus 1 and bus 2 in the double circuit that joins the two generation areas. The fault is located at 49% of the line from B1 to B2, the fault resistance is 10 Ω.

The protection system consists of two distance relays, each at one terminal of the transmission line, a circuit breaker is associated with each relay and it has the ability to perform single-pole openings.

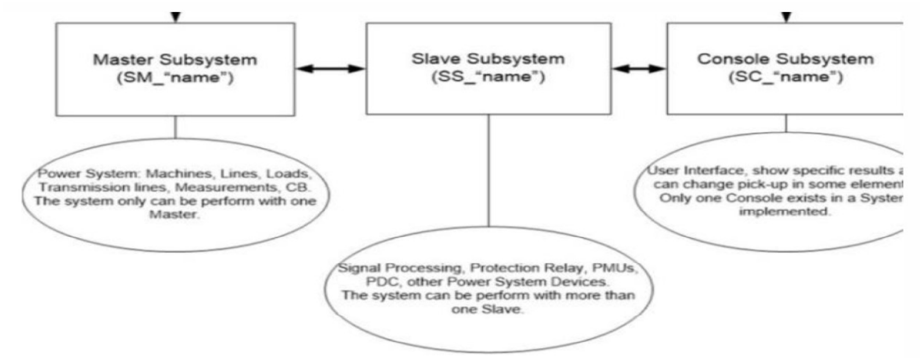

Fig. 7. Scheme of RT- implementation by subsystems.

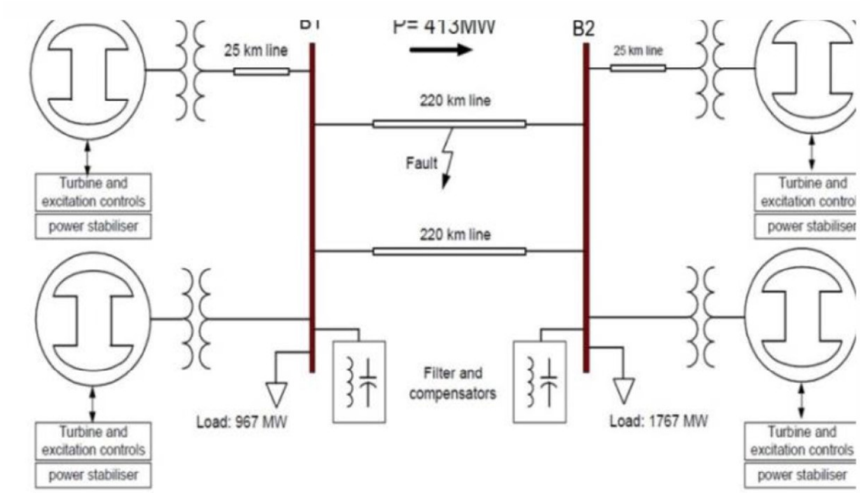

Fig. 8. Kundur System implemented as test case.

The registers are of magnitudes voltages and currents coming from PMUs, also the registers of phase sinusoidal signals of both voltages and currents are included; all measurements are seen from the bus 1. The PMU implemented has the ability to transmit voltages and currents in phase components as magnitude and phase, in this case only the magnitudes are shown from the bus 1.

The PMU implemented has the ability to transmit voltages and currents in phase components as magnitude and phase, in this case only the magnitudes are shown.

Figure 9 represents the magnitude of voltages in phase components, the register begin before the insertion the fault and stop three seconds after the CB finish their own operations. In the same way figure 10 displays the magnitude current phasor in ABC components; all those are digital values processed inside the PMU and delivered to a cup of 30 samples per second and for a better appreciation we proceeded to present in a graphical format instead of tabular.

Figure 11 and figure 12 are the voltages and currents as sinusoidal signals before the signal processing as syncrophasor, in these signals is not possible in a clear form recognize the changes occurring in the magnitudes during the captured record, specifically in the voltage register.

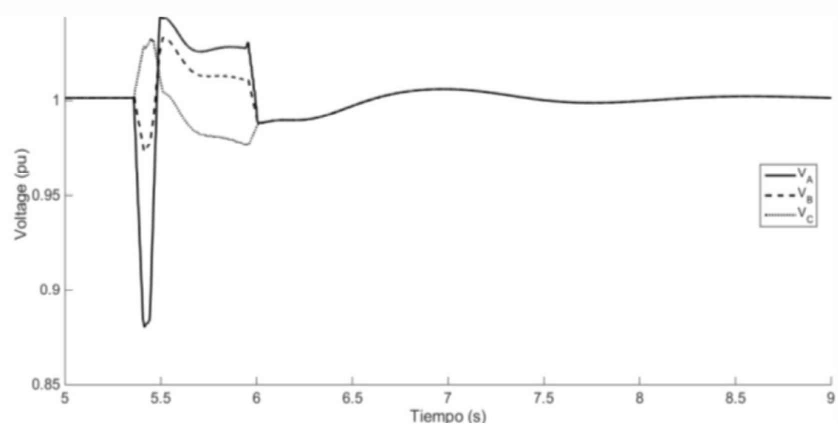

Fig. 9. Three phasor voltage signals.

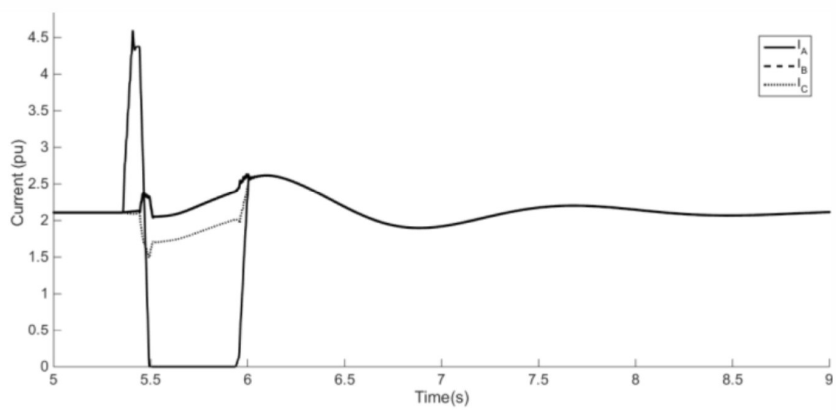

Fig. 10. Three phasor currents signals.

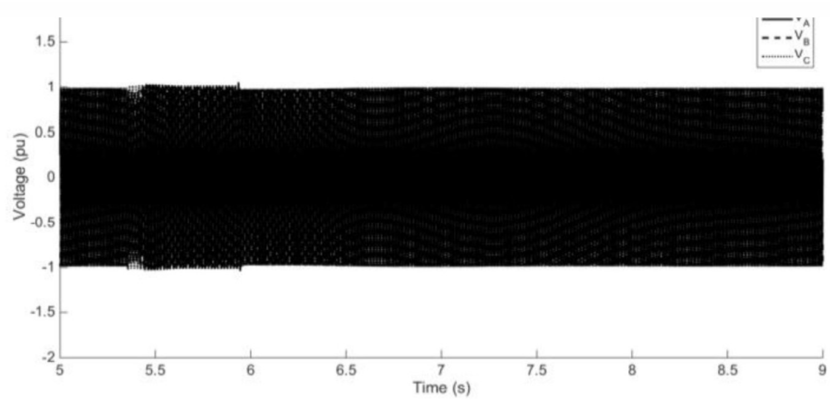

Fig. 11. Three phase voltage signal in time.

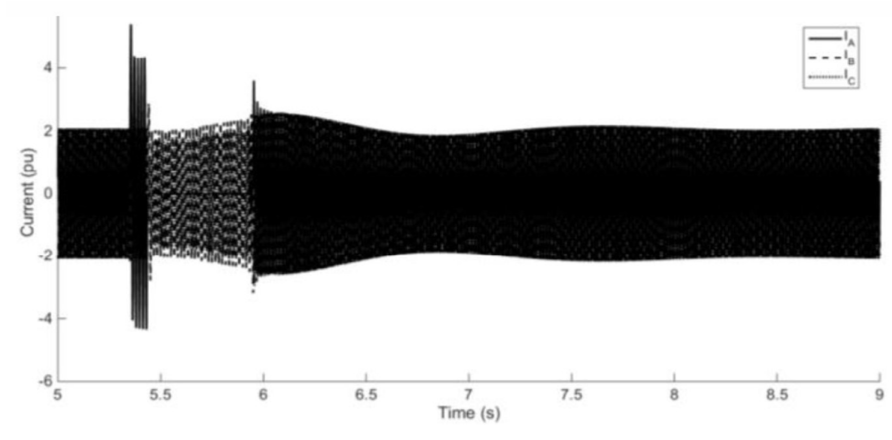

Fig. 12. Three phase current signal in time.

CONCLUSION

In this article is presented the process performed for fault clearance in a real-time Simulation platform; the work presents long-term records for voltage and current processing signals.

The fault identification and the output opening or reclosing of breakers are due to the implementation of distance relays with the ability to respond when contingencies scenarios occurs in its primary protection zone.

In this work has been obtained records of voltage and current signals by processing data in synchrophasor format, following the protocol presented by the IEEE Standard. The register is made in abc phase components instead of being only positive sequence; this is for voltage and current signals. Taking advantage of the recording capacity of the OPAL-RT® simulation platform, the sinusoidal voltage and current signals were stored and these are presented.

In addition the acquisition system to protection relays and PMU has the ability to receive not only virtual signals from simulation, also with enable the analog channels in the real-time simulator can receive analog signals and processing them in the same form that the virtual.

ACKNOWLEDGMENT

Authors want to thank the National Science Foundation of Mexico (CONACYT) for the support of this project.

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