

Emulation tool for research purposes in smart grids

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Abstract- In this work the implementation of a real-time emulator operating under the principle of Power Hardware in the Loop (PHIL) is presented. The system developed is a great tool for the study of electrical anomalies such as harmonics in smart grids. The general structure of the emulator, control scheme, sensors, instrumentation and amplification stages are described, which provides flexibility in terms of power ranges, topologies and control techniques. The algorithms of control and execution of the simulation models in real time are implemented in the platform dSPACE DS1103. The results of the real-time emulation with purely sinusoidal voltages and with harmonic content are presented, which show excellent performance and versatility to analyze study cases with diverse loads; besides, smart grids with different topologies and non-linear loads.

Index Terms- Power Hardware in the Loop, Real Time System, Smart grids, Power Amplification Stage.

I. INTRODUCTION

Tests for the study and analysis of electrical systems are diverse due to the multiple areas of knowledge that are involved in modern electric power systems. An alternative to analyze them is to build the system on real hardware, but it is usually expensive and requires long time to implement and perform the tests. Another option is to use simulation software, but it has the disadvantage that if the system is not properly modeled, it moves away from its real behavior. On the other hand, The simulation using Hardware in the Loop (HIL) is used for the development and testing of embedded systems in real time and constitutes an effective platform to include real behavior of hardware under test (HuT) interacting with models of simulation of complex systems [1]. For its part, PHIL systems are an extension of HIL, particularly in the field of electric power systems, because it allows real-time emulation in which the HuT can be subjected to higher voltage and current levels. This provides almost real test conditions, with a robust, flexible and reliable system [2]. Nowadays, different commercial platforms oriented to the analysis of power systems under the PHIL principle are commercialized. OPAL-RT platforms provides a real-time emulator with stability in simulations due to control and protection of HuT, with field of application in power systems [3]. National Instruments with its PXI units introduces a robust and high-performance platform for manufacturing, military, aerospace, machine monitoring, automotive and industrial testing applications [4]. The NOVACOR platform of RTDS Technologies allows to achieve powerful, accurate, accessible and scalable real-time simulations for control systems [5]. In the literature there are reported works in different areas where the PHIL technique is applied with commercial platforms. In [6], the optimized construction of models are developed for a crystalline photovoltaic panel that is analyzed with a real-time simulator to improve the accuracy of the dynamic model. Also in [7] a simulated energy network through a voltage source converter (VSC) is under test, to analyze stability in the control system, besides a method is proposed to improve some cases of instability. In [8] the implementation of a control for a micro grid is presented. The mentioned platforms allow to have a closed loop system with stability and control in the PHIL simulations, although some disadvantages are the high cost and the closed architecture. In this work the design and implementation of the power, instrumentation and control stages of an electric system emulator under the PHIL principle is carried out. The real-time processing and control algorithms are based on the DS1103 platform and the instrumentation and control stages are carried out, achieving a robust, precise, stable, flexible and low-cost emulator to analyze electrical systems under the PHIL principle.

II. PRINCIPLE OF PHIL OPERATION

Figure 1 shows some of the elements of a micro power grid, it can be seen that it is integrated by elements of distributed generation such as: photovoltaic panels and wind turbines; also some common loads as motors, inverters, linear and non-linear loads are presented. In order to construct a micro grid, it is necessary to have different elements that comprise it, such as measuring equipment, control and processing of information. This is a complex task that requires a great amount of time for its execution. However, the PHIL concept allows to mitigate aspects such as: the lack of infrastructure and execution time without losing accuracy and reproducibility. Figure 2 shows the PHIL concept, which can be divided into the virtual part and the experimental part. The experimental part corresponds to the HuT, which in this case is the photovoltaic system. The virtual part consists of the simulation model executed in real time of the micro grid, without considering the photovoltaic system. The connection between the virtual and experimental stage is made through sensors and actuators; the last one employs usually an amplification stage. In this sense, a power inverter is operated in closed loop to simulate the voltage applied to the HuT, which corresponds to the output voltage of the virtual simulation.

III. IMPLEMENTED SYSTEM UNDER PHIL PRINCIPLE

The implemented system in this work is conformed of a single phase inverter that is controlled with the platform DS1103 using the unipolar PWM switching technique and considering dead times. The control is done with the Simulink / Matlab software and loaded on the DS1103. Also, the single-phase inverter module consists of 6 IGBT's with the flexibility to handle half bridge topologies, single-phase and three-phase complete bridge, it has a variety of protections against severe operating conditions, such as short circuit, overvoltage, overcurrent and overheating. In addition, the converter is powered by a four-quadrant power supply. The inverter output is connected to an LC filter to obtain an AC filtered voltage, which is applied in real time to an external resistor (in this case the HuT). A transformer is used as a voltage sensor for voltage measurement; and the current measurement uses a current probe, fluke i200s, both sensors are connected to ADC inputs of the DS1103 platform . The mentioned key elements of the implemented PHIL system are shown in Figure 3.

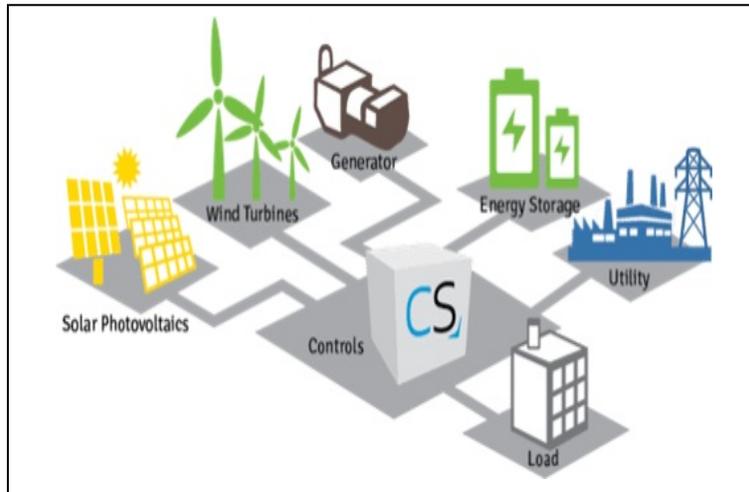


Fig. 1. General scheme of a micro grid.

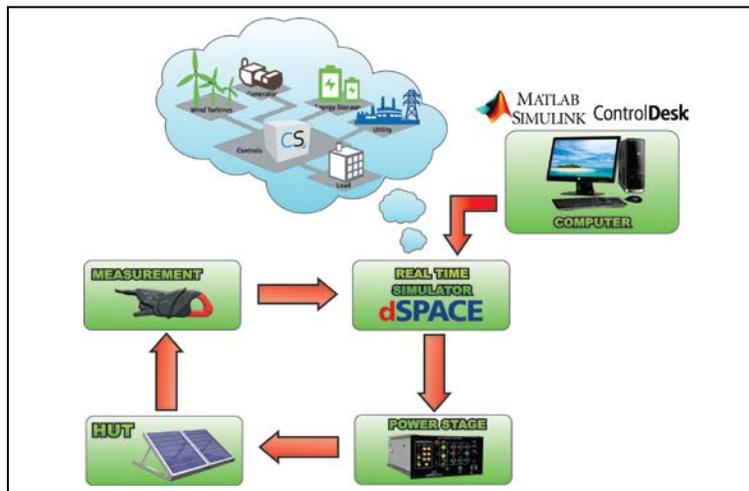


Fig. 2. Micro grid implemented with PHIL.

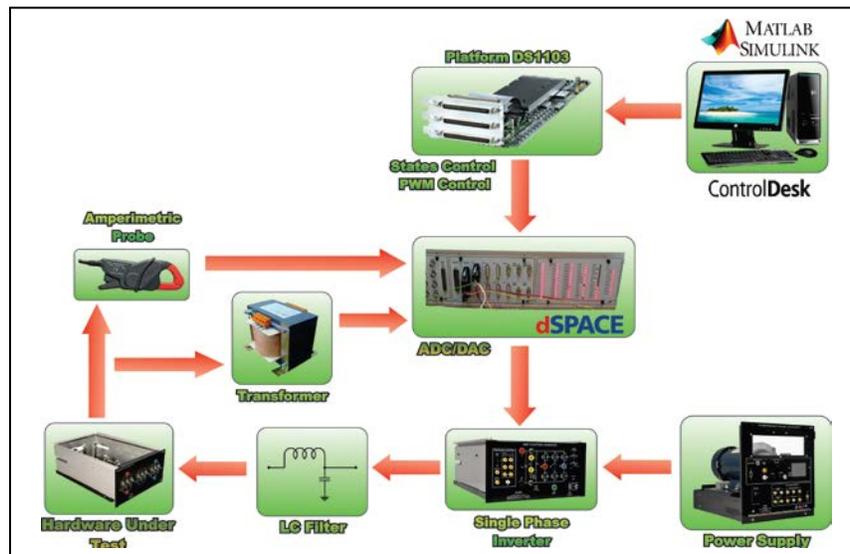


Fig. 3. General scheme of the system implemented under the PHIL principle.

IV. HuT VOLTAGE CONTROLLER

The voltage controller is one of the most importance part of the PHIL, it allows accuracy in the system performance, since the virtual voltage and the voltage applied to the HuT can have difference in open loop operation such as drop voltage, delays and harmonic distortions. The reference signal of the controller is the block "Sine Wave", which allows generating purely sinusoidal or non-linear references with the presence of up to five harmonics. The gains G_{ma1} and G_{trns0} are used to calibrate the current and voltage sensors respectively. The designed controller is a controller by feedback states, being the voltage in the capacitor and the current in the filter inductor the feedback signals. The gains G_{ma2} , G_{ma3} , G_{ma4} and G_{ma6} correspond to the controller's gains, which are tuned with Matlab software. The output of controller "A" is sent to the subsystem "INVERTER CONTROL" as shown in Figure 4. The subsystem contains the blocks needed to generate PWM signals with unipolar switching. These signals are sent to the amplification element providing a voltage to the HuT with equal amplitude, phase and waveform that the generate by the voltage control reference.

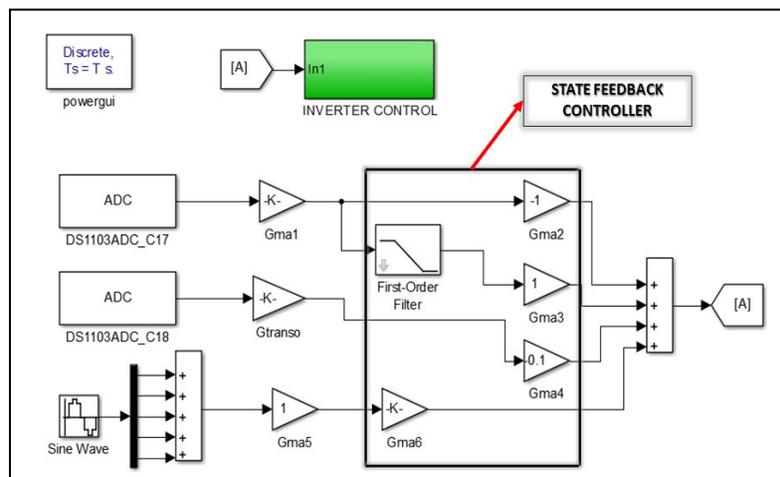


Fig. 4. Simulation model made in Simulink for voltage control of the HuT.

Using the ControlDesk software, the monitoring of the input and output signals of the DS1103 platform is carried out, in addition, it allows to control some parameters in real time of the simulation model. The signals of the simulation model and measured signals can be displayed graphically as it is shown in Figure 5. The bottom of the Figure 5 shows the variables to be displayed, as well as its magnitude. In order to have diverse conditions in the simulation, the values of the simulation model parameters are changed using the interface. It can be seen in the figure 5 that the controller's gains and sensor gains are modified individually, while the harmonic components of the reference signals are deployed in matrix form, it allows to modify the magnitude and frequency of each harmonic component. The options "STOP", "PAUSE" and "RUN" are added to control the execution in real time.

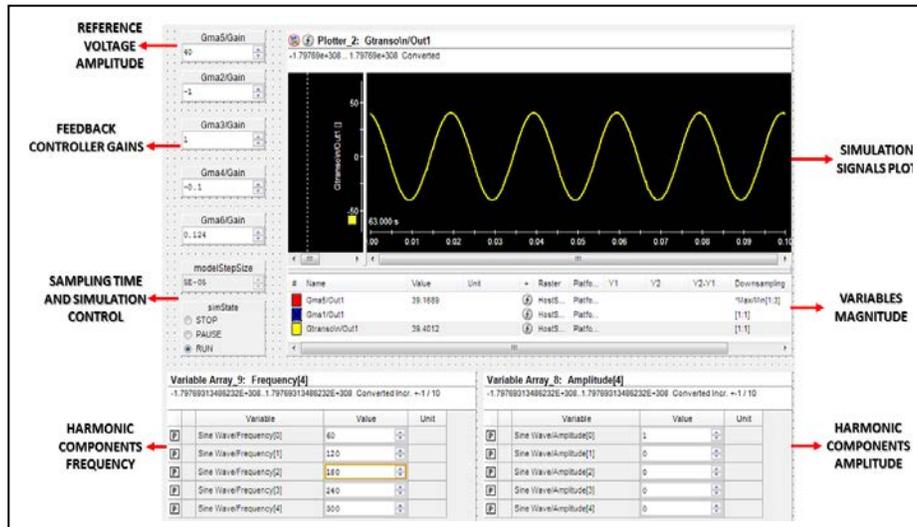


Fig. 5. ControlDesk software interface for control of simulation in real time.

V. RESULTS

Three case studies are presented, these allow observing the performance of the emulator with pure sinewave and harmonic reference voltages. The period of time in the simulation is $5e-5$ s. A single-phase full-bridge inverter is used, which is powered by a DC voltage of 50V, also a LC filter is used at the output of inverter, where the inductor L is 2mH and the capacitor C is 15 μ F; the cutoff filter is 919 Hz. In this study case an external resistance of 56 Ω is used as the HuT.

Figures 6 and 7 show the voltage applied to the HuT with and without control. The reference signal is purely sinusoidal with a frequency of 60 Hz and a peak amplitude of 40 V. It can be clearly seen in Figure 6 that the voltage applied to the HuT and the reference voltage are different in magnitude, phase and waveform, which is due to the attenuation applied by the filter, dead times and variations in the CD voltage source. In Figure 7 the same case study is shown, but now with the control system operating. It can be seen the excellent performance of the controller since practically the reference and the voltage applied to the HuT are practically the same in magnitude, phase and frequency, which makes it possible for the emulator to be used with great accuracy in PHIL systems with linear loads.

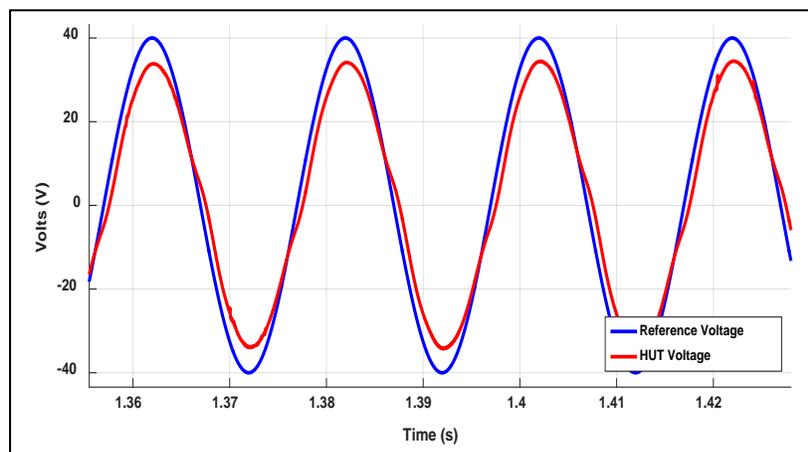


Fig. 6. PHIL simulation applying purely sinusoidal voltage without control phase.

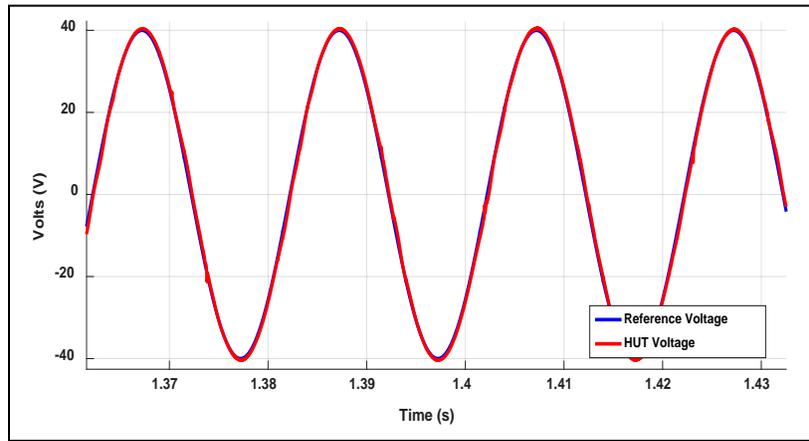


Fig. 7. PHIL simulation applying purely sinusoidal voltage with control stage.

The second study case consists in voltage with odd harmonics, the same parameters are used as the previous study case. The output results is similar to a square wave. The magnitude of the voltages is given with respect to the magnitude of the fundamental component (40 V_{peak} and a frequency of 60 Hz). The harmonic magnitudes corresponds to: $V_1=1$, $V_3=1/3$ y $V_5=1/5$. Figures 8 and 9 show the results without control and with control, respectively. It can be seen that without control applied in HuT vary greatly, nevertheless, Figure 8 clearly shows the controller's performance and the excellent response to changes in the reference signal.

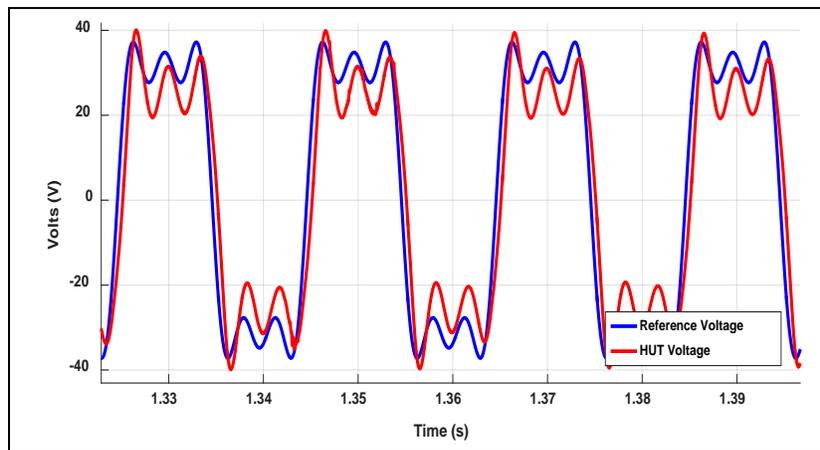


Fig. 8. PHIL simulation applying voltage with odd harmonics without control stage.

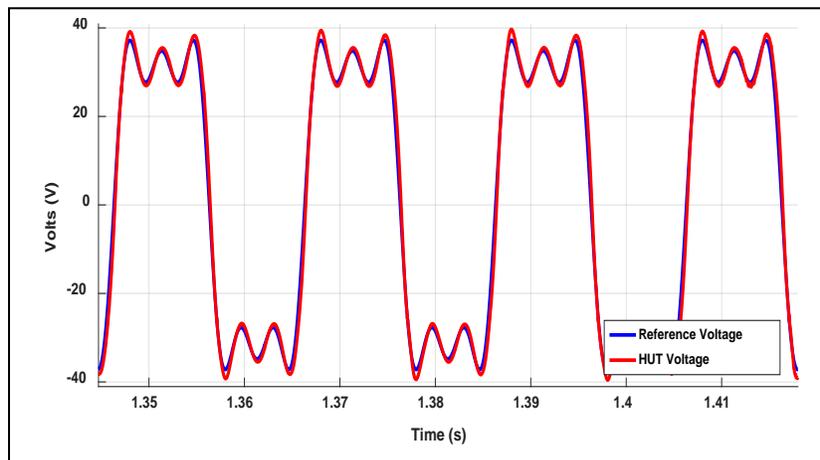


Fig. 9. PHIL Simulation applying voltage with odd harmonics with control stage.

The third case study consist in five harmonics, it results in a waveform similar to a sawtooth with a negative slope. The magnitudes of the fundamental and the harmonics in per unit are shown below: $V_1=1$, $V_2=1/2$, $V_3=1/3$, $V_4=1/4$, $V_5=1/5$. Figures 10 and 11 show the voltage in HuT and the reference without control and control respectively. It can be seen that the voltage applied to the HuT with control works properly with even and odd harmonics, also it shows great accuracy. This shows that the emulator is capable of working in PHIL systems that contain non-linear elements.

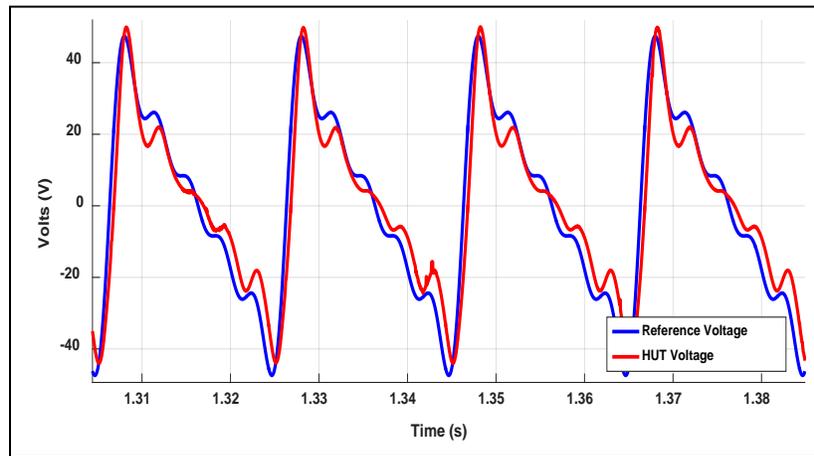


Fig. 10. PHIL simulation applying voltage with harmonics from 1 to 5 without control stage.

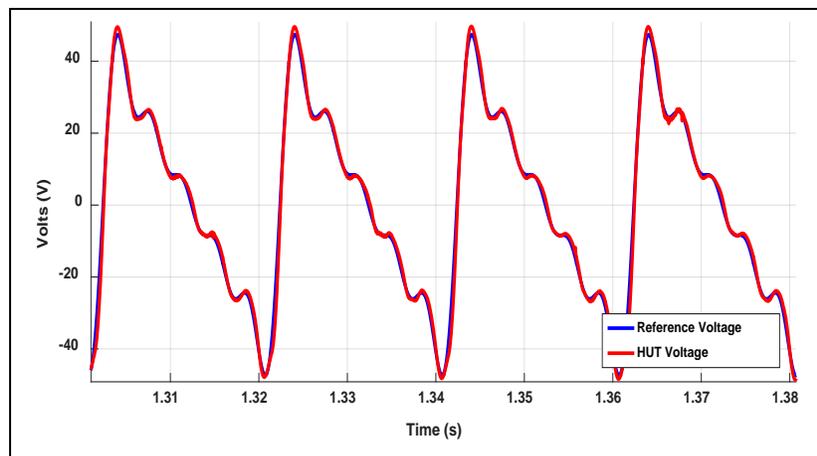


Fig. 11. PHIL simulation applying voltage with harmonics from 1 to 5 with control stage.

VI. CONCLUSION

In this work the implementation and operation of an electrical systems emulator under the PHIL principle was presented. The general structure of the emulator and the different its elements are described, as well as its performance under different case studies. The results allow to determine that the emulator works with great accuracy with voltages of pure sinusoidal references and with the presence of harmonics, which makes it suitable to emulate PHIL systems that have linear and non-linear loads with the control developed. Another aspect to highlight is the flexibility to handle HuT of different powers. Also, since the system is an open architecture, it can be used with different elements.

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