Design and Implementation of a Power-Hardware-in - the-Loop Interface: a Non-Linear Load Case Study

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Abstract---Power-Hardware-In-the-Loop (PHIL) simulation enables the testing of an electrical load virtually exchanging power with a real-time simulator. PHIL extends the applicability of the traditional Hardware-in-the-Loop (HIL) simulation, which involves only signal exchange. The main challenge of this power exchange is the requirement for a highly dynamic power electronics interface. In this paper, PHIL simulation is used to test a non-linear load to analyze its impact on existing electrical systems. A multi-agent platform is also used to monitor the behavior of the system under study: the monitoring system is used to validate on-line the PHIL, verifying that the interface does not significantly affect the system behavior. Significant industrial applications of the procedure are also discussed.

I. Introduction

Virtual Prototyping is widely used in the design, development and testing of new systems. It uses the software-based model of a product, system, or component to explore, test, demonstrate and/or validate the design and design alternatives. One of the most used techniques in virtual prototyping is Hardware-in-the-loop (HIL), in which simulation based on mathematical models replaces part of the real systems or components, and interacts with real hardware. Generally, HIL techniques are limited to control applications [1], i.e. there is only signal coupling between the hardware and the virtual system.

Virtual prototyping with natural coupling connections can be achieved through the use of a novel methodology called Power-Hardware-In-the-Loop (PHIL) [1][6]. In PHIL simulation, the interface point involves conservation of energy so that real power is virtually exchanged between the simulation software and the actual hardware. This methodology significantly extends the applicability of HIL to any electrical or mechanical device or system. In previous work [1], PHIL experiments have been successfully implemented for a first-order system based on the simulation software Virtual Test Bed (VTB) and Real-Time VTB (VTB-RT) [4][5].

In this study, PHIL simulation is used to analyze the impact of a non-linear load on an electrical plant. In particular, a DC electrical drive with an AC interface is chosen as the new equipment under test, and a single resistive-inductive load as the existing system. Also, a monitoring system based on a multi-agent platform is added in parallel to the PHIL experiment to verify the effectiveness of the proposed system [2].

II. PHIL Simulation System

Figure 1 shows the structure of the PHIL simulation system. The original system is split into two subsystems: one is the simulation model in VTB-RT, and the other is the real hardware. These two subsystems interact with each other through the simulation/hardware interface. At each simulation step, the current in the hardware is sampled and sent to VTB-RT through the analog-to-digital converter (ADC) devices. Based on this current value, VTB-RT feeds back the load voltage based on a simplified model of the external device. The voltage value is actuated through an FPGA-based digital control of an H-Bridge inverter.

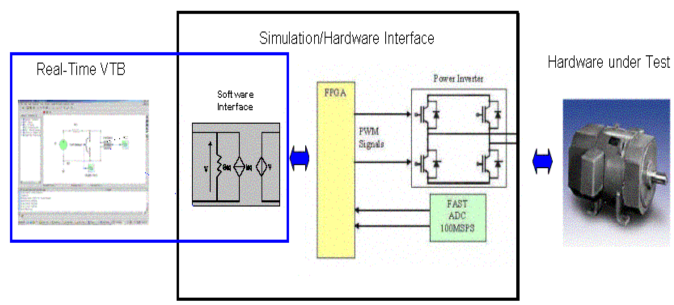


Figure 1 General scheme of the PHIL simulation system

A. *Implementation of the Simulation/Hardware Interface*

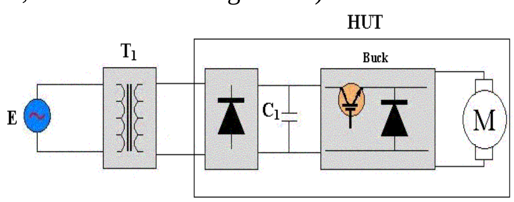
The simulation/hardware interface comprises the software model and the hardware component. The software interface model runs in VTB-RT to approximate the time-domain behavior of the hardware under test (HUT) using the current feedback. The hardware part of the interface consists of a silicon H-Bridge inverter, which is controlled by an FPGA. In order to meet the bandwidth requirements the platform is mostly digital and includes a minimal analog section composed of a fast ADC and a signal conditioning stage. The latter is based on high-speed operational amplifiers. A Compact PCI (PXI) embedded controller is used for interfacing and monitoring. Data acquisition and a fast control loop are implemented with the FPGA. A detailed description of the simulation/hardware interface can be found in [1] and [3].

B. Real-Time Simulation Environment

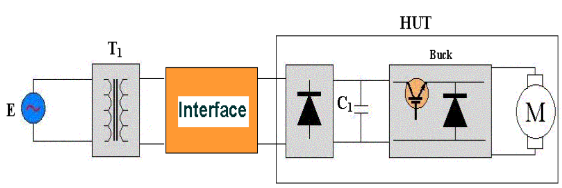
The VTB and VTB-RT are simulation software developed for the design, analysis, and virtual prototyping of large-scale multi-technical systems. In this study, they are used to establish the desired hard real-time simulation environment for the PHIL experiments. Different from the commercial real-time systems, VTB-RT is implemented entirely with public domain software. With VTB-RT, the PHIL experiment can be implemented using standard PC and off-the-shelf data acquisition devices. In this paper, VTB-RT is hosted in a National Instruments VXI-872Bpc controller. A detailed description of the VTB and VTB-RT can be found in [4] and [5].

III. APPLICATION EXAMPLE

The testing of a DC electrical drive system is used as an application example. Here, the HUT is a DC motor and its AC interface, while a power supply and a transformer are the rest of the system, as shown in Figure 2 a). The whole system is first simulated in VTB. When satisfying results are reached, the system is ready to be tested with PHIL experiments. To perform PHIL simulation, the rest of the system in Figure 2 a) is transplanted from VTB into VTB-RT, while the HUT is replaced by real hardware. The virtual and the real system interact with each other through the simulation/hardware interface, as illustrated in Figure 2 b).



a) The original DC electrical drive system



b) The PHIL experiment of the DC electrical drive system
Figure 2. Structure of the DC electrical drive system

The next step for this PHIL experiment is to test how the HUT would influence the performance of the existing system. Here, the existing system is represented by a resistive-inductive load, which is connected in parallel with the new hardware to the power supply. Through this experiment, we define a platform that is able to identify the harmonic impact of a new load in an existing system.

The experiment is monitored through a distributed monitoring system based on LabVIEW. The measurement section is inserted after the simulation/hardware interface. The transducers are a DC active current probe and a differential voltage probe. The two probes are connected to a Tektronix oscilloscope equipped with GPIB interface connected to a PC that hosts LabVIEW and the LabVIEW VI that acquires the measurements. The LabVIEW VI acquires a buffer of data from the channel of the GPIB port and makes it available for the other agents in the network. The simulation agent runs remotely in parallel to the real system, receiving the same input as the real system; the results of the simulation are compared with the experimental data by the monitoring system to identify incorrect behavior of the interface.

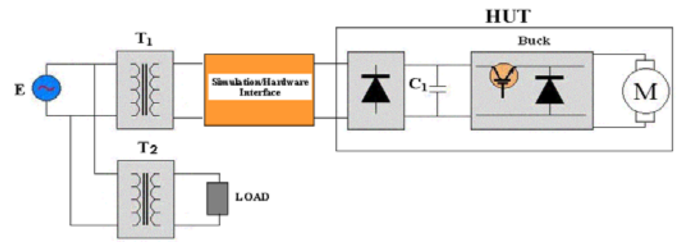


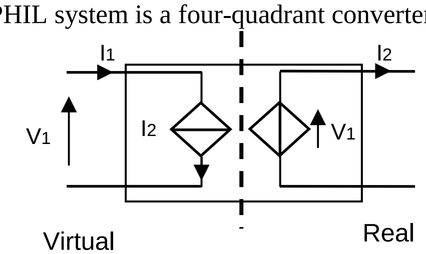
Figure 3. The PHIL experiment of a DC electrical drive system with the existing system

IV. THEORETICAL ANALYSIS AND SIMULATION RESULTS

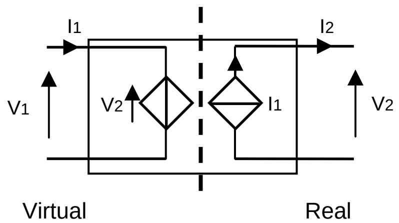
To choose an appropriate simulation/hardware interface for the PHIL experiment, different interfacing schemes are considered. These simulation/hardware interfaces are introduced in detail as following:

A. The Traditional Simulation/Hardware Interface

From the software standpoint, in the literature, two configurations are usually proposed to implement the PHIL interface. Both configuration can be described as an ideal transformer but in one case the virtual side of the interface behaves as a voltage-controlled current source as shown in **Error! Reference source not found.**4 (a), and in the other as a current-controlled voltage source as shown in Figure 4 (b). From the hardware standpoint, the interface must be able to deliver and absorb power. For this reason, the key component of the PHIL system is a four-quadrant converter.



a) First option for simulation/hardware connection



b) Second option for simulation/hardware connection
Figure 4. The traditional simulation/hardware interface

B. The Simulation/Hardware Interface Using a First-Order Dynamic Estimator [1]

This interfacing scheme approximates the dynamics of the hardware under test with a time-variant first-order system. In the simulation/hardware interface, the real hardware system is described as:

$$\frac{di_2}{dt} = ai_2 + bv_1 \tag{1}$$

Equation 1 can be discretized and written in the form of:

$$i_2(k) = R_{eq}(k)v_1 + I_{eq}(k) \tag{2}$$

Where Req(k) and Ieq(k) are equivalent resistance and current source, which approximate the time-variant HUT at time step k. Figure 5 shows the schematic of this new simulation/hardware interface. Detailed information on this interface can be found in [1].

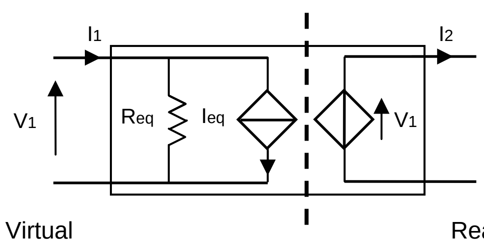


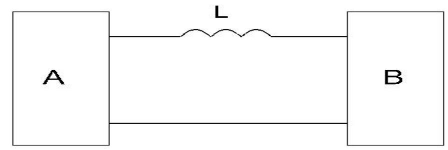
Figure 5. The novel simulation/hardware interface

C. The Simulation/Hardware Interface Based On Transmission- Line Links [7]

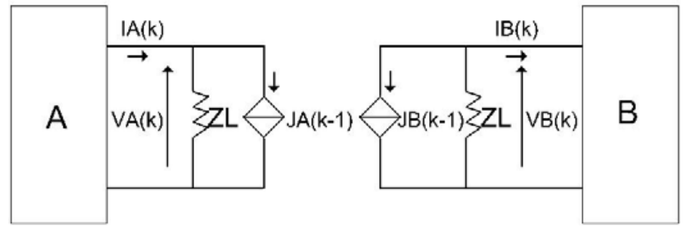
The Transmission-Line Modeling (TLM) technique models the discrete reactive components as transmission-line sections, know as links. For an inductor L (DC choke), the characteristic impedance of the TLM inductive link is:

$$Z_L = \frac{L}{T} \tag{3}$$

where T is the simulation time step. The mechanism of the TLM inductive link is illustrated in Figure 3, where Figure 6(a) shows the original system: subsystem A and B linked by the inductor L, while Figure 6(b) shows the decoupled system using TLM inductive link. Notice that here the inductor is actually replaced by the interface, while in the previous two cases, the inductive load remains in the decoupled system.



(a) The original system



(b) The decoupled system
Figure 6. The simulation/hardware interface based on TLM inductive link

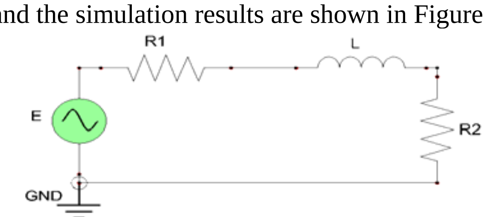
In Figure 6(b), the controller current sources in the simulation/hardware interface can be calculated as following:

$$J_A(k-1) = -\frac{v_B(k-1)}{Z_L} + i_B(k-1) \tag{5}$$

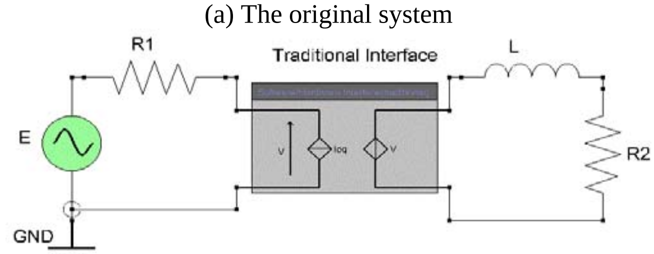
$$J_B(k-1) = -\frac{v_A(k-1)}{Z_L} - i_A(k-1) \tag{6}$$

D. Decoupled Simulation of a First-Order System

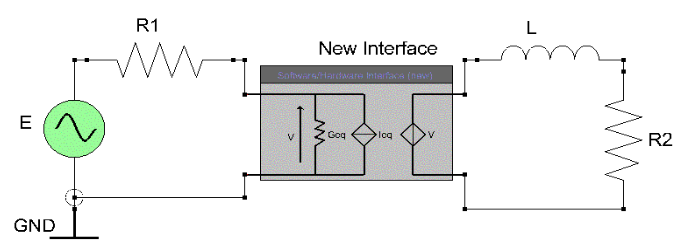
To choose most suitable simulation/hardware interface for the PHIL experiment, the above three interfacing structures are compared using a first-order inductive-load system, as shown in Figure 7. The parameters of this system are listed in Table1, and the simulation results are shown in Figure 8.



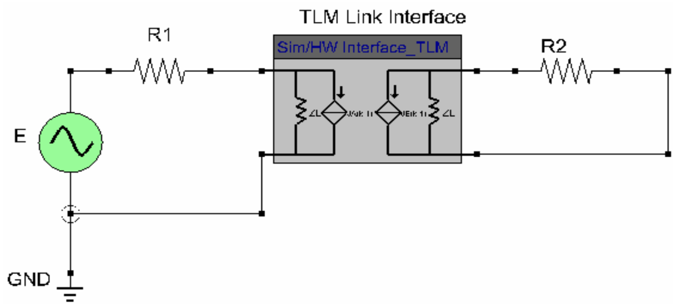
(a) The original system



(b) The decoupled system with the traditional interface



(c) The decoupled system with the interface based on the first-order dynamic estimator



(d) The decoupled system with the interface based on the TLM inductive link

Figure 7. The decoupled simulation of the first-order system with different interfaces

TABLE I
PARAMETERS FOR THE FIRST-ORDER SYSTEM

Component	Variable	Value
voltage source E (sinusoidal)	amplitude frequency resistance (R_1)	1V 6Hz 1hm
load	Resistance (R_2) Inductance (L)	51ohm 1mH

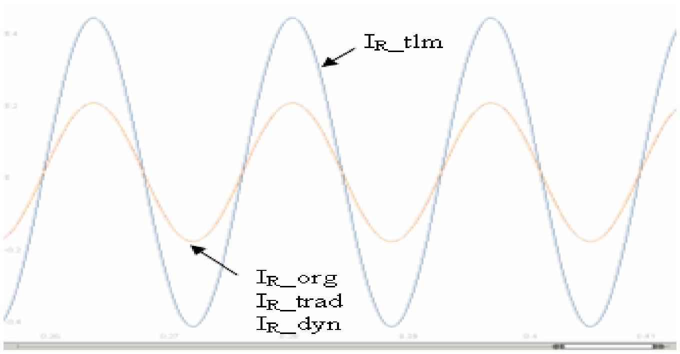


Figure 8. Simulation results of the decoupled first-order system

In Figure 8, I_R_org stands for the load current in the original system, while I_R_trad, I_R_dyn, and I_R_tlm stand for that in the decoupled system with the traditional interface, the interface based on the first-order dynamic estimator and the interface based on the TLM inductive link, respectively. As it can be seen that the decoupled systems with the first two interfaces give the same performance as the original system, while the system with the TLM inductive link yields a steady state error. Hence for the more complex DC motor system, the possible candidates for the simulation/hardware interface are the traditional interface and the interface based on the first-order dynamic estimator.

E. Decoupled Simulation of the DC Motor System

The traditional interface and the interface based on the first-order dynamic estimator are then applied for the decoupled simulation of the DC motor system. The VTB schematic for the original system is shown in Figure 9. Parameters of the system are listed in Table 2.

TABLE II
PARAMETERS FOR THE DC MOTOR SYSTEM

Component	Variable	Value
voltage source (sinusoidal)	amplitude frequency	120V 60Hz
transformer	ratio leakage inductance	24 1mH
	capacitor (C)	10mF
	Duty ratio for the buck converter	0.5
DC motor	rated voltage Rated Speed armature resistance armature inductance	24V 550rad/s 2.0ohm 270uF
	rotor inertia	6.39e-6 $k_g \cdot m^2$
	drag coefficient mechanical load	3e-6Nms/rad 1.0Nms/rad

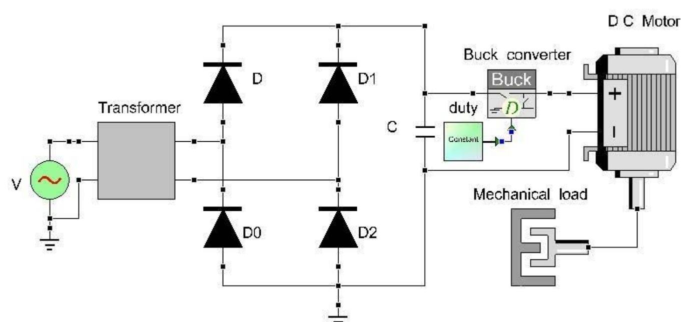


Figure 9. The DC motor system

The simulation/hardware interface is inserted between the transformer and the diode bridge, as shown in Figure 10. The decoupled system with the traditional interface gives satisfying results which are consistent to those of the original system, as shown in Figure 11, while the system with the interface based on the first-order dynamic estimator becomes instable. Therefore, the traditional interface is adopted for the PHIL experiment of the DC motor system.

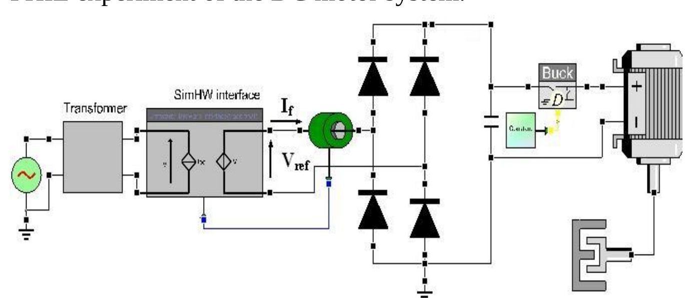


Figure 10. VTB schematic for the DC motor system with the traditional interface

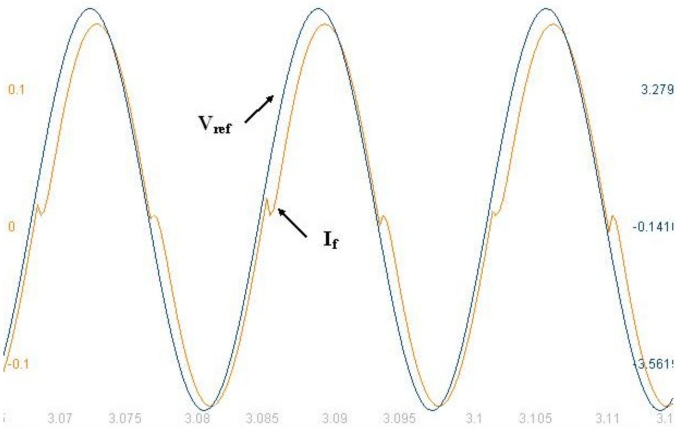


Figure 11. Simulation results of the DC motor system (I_f-current feedback from the hardware, V_{ref}-voltage output from the simulation/hardware interface)

V. EXPERIMENTAL RESULTS

A. *PHIL Experiment*

PHIL experiment is conducted for the DC motor system shown in Figure 10. The system is separated into two parts: the voltage-source and the transformer, which are implemented in VTB-RT, and the rest of the system is implemented by real hardware. The experimental results are shown in Figure 12 , where I_f is the input current of the diode bridge and the voltage reference sent out by VTB-RT (Vref). The current measurement is done through an LEM HAW sensor. The experimental results are consistent with the simulation results shown in Figure11; notice that the stair steps in the waveforms are due to the zero-order-hold effect of the data acquisition devices.

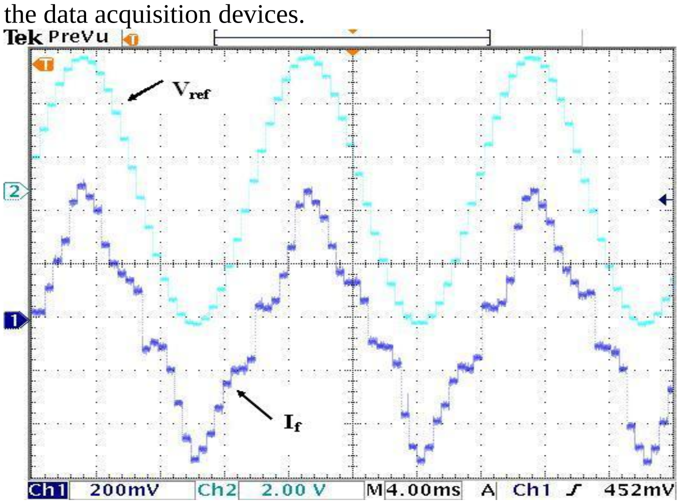


Figure 12. Experimental results

B. *Agent-Based System Monitoring*

As discussed in previous paragraph the PHIL experiment can introduce significant errors in the experimental scenario. For this reason it is really important to perform both an a-priori and an on-line validation of the procedure.

In few words we want to be sure that once we substitute the virtual model with the real equipment the interface is not affecting the waveforms of the system.

This requirement calls for a two-stage validation process:

1. validation of the model of the system through hardware comparison
2. on-line comparison between virtual and real experiment.

At the University of South Carolina we recently developed a distributed monitoring platform able to integrate simulation data and experimental results. The approach is based on agent-based monitoring procedure.

The use of agent-based systems for monitoring of complex systems has been proposed in literature, among which [8], [9] and [10]. In [11] and [12] is the simulation agent is introduced within the framework of agent based monitoring.

The simulation agent opens the way to a variety of applications:

- in steady state conditions it can be used to generate virtual data to be compared with the real data to perform diagnostic actions.
- in real-time it can be used to generate virtual measurements of non accessible measuring points.
- out of the monitoring loop it can be used for training purpose [11].
- in support of a decision making system it can perform a set of “what-if” simulation scenarios.

The simulation agent requires the availability of a very flexible simulation platform capable of easily interface with data acquisition systems. The following requirements can be considered critical to be able to accomplish each and every of the previously listed tasks:

- easy interface to a network based system
- high level of flexibility and possibility of run time changes
- easy interface to data acquisition systems
- real-time capability

The Virtual Test Bed (VTB) is chosen as ideal simulation platform. VTB is capable of interfacing with LabVIEW. Depending on the specific application of monitoring we consider the communication with the simulation agent can be performed with two different protocols: single point and buffered.

The single point communication is adopted whenever the simulation agent has to interact in real time with the rest of the system. The buffered communication is the preferred choice when there are no real-time constrained in the simulation tasks.

The structure of the monitoring and simulation system proposed here is very simple and it involved only two agents: one performing data acquisition, the other one performing simulation.

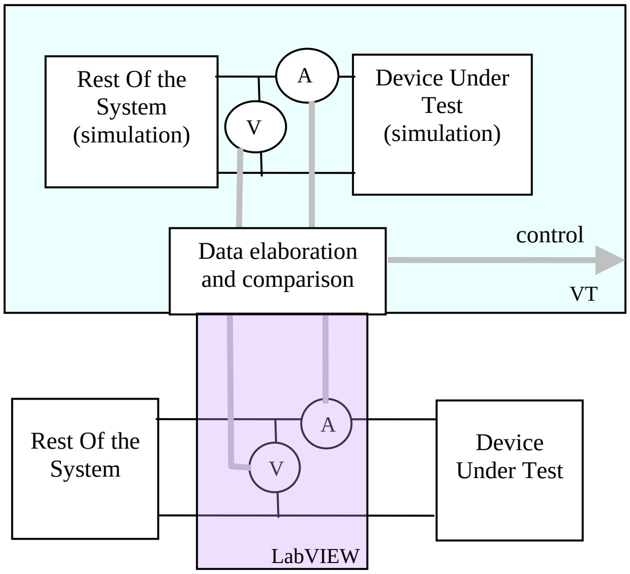


Figure 12. The decoupled simulation of the first-order system with different interfaces

The simulation agent receives data from the measurement section for comparison with simulated variables. The proposed structure has been tested, without the Power Hardware in the loop interface, on the target system to validate the VTB simulation model and the VTB-LabVIEW interface.

The input voltage AC of the physical system has been acquired and fed to the VTB simulation as input of the model. The line current of the physical system has been acquired and compared to the simulated current. The VTB-LabVIEW interface is bi-directional, so that not only VTB can receive data from LabVIEW, but also VTB can send data to LabVIEW. In Figure 13 the input voltage, measured by LabVIEW in the physical system is used and input by VTB, is plotted in Visual Extension Engine (VXE), the visualization tool of VTB. In Figure 14, the simulated current from VTB is visualized together with the measured current in LabVIEW.

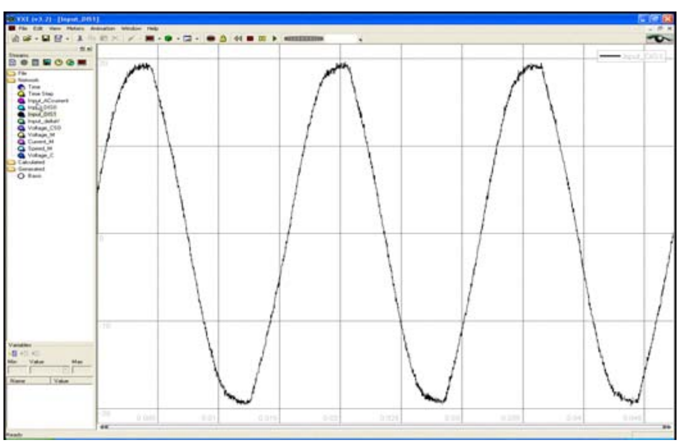


Figure 13. Input AC voltage as it appears in the VTB environment

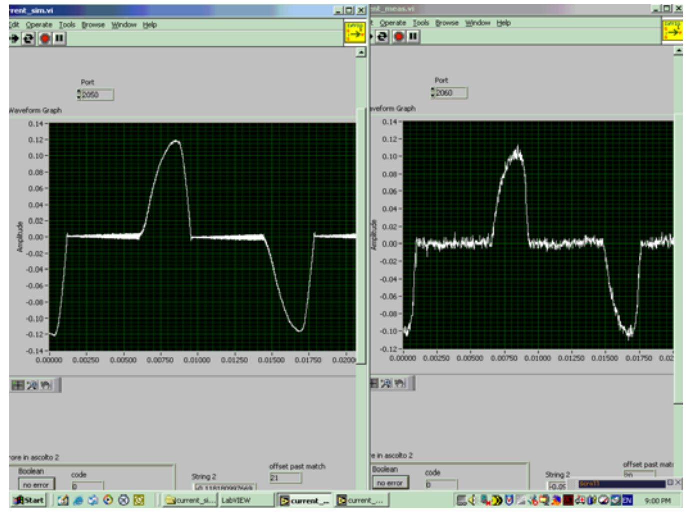


Figure 14. Simulated current (left) and measured current as visualized in LabVIEW

VI. Conclusions

In this study, the PHIL experiment for a DC motor system is performed, and the experimental results match well with those obtained from simulation. The main goal of this paper was to extend the PHIL analysis to highly non-linear loads. At this stage, the simplest solution that describes the interface as an ideal transformer gives the best experimental results, but more research is needed to come to a standard approach for the design of the experiment. However, the experimental results show that it is possible to keep the simulation stable also under non-linear conditions. Considering the criticality of the process and the possibility of significant deviation from the correct results, an agent-based monitoring system is also implemented to supervise the experiment and compare with validated date. The combination of the monitoring system and of the HW/SW interface provides a low-cost and efficient way for device prototyping and system integration.

Acknowledgment

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