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Connecting in Real-time Power System Labs: an Italian Test-case

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***Abstract*—Sharing of hardware and software facilities together with knowledge and expertise among laboratories is a key point in research. In the power systems field this is possible even remotely by coupling real-time simulators located in different laboratories. In this paper an experimental test-bed is described. It consists of the remote interconnection of the real-time simulators, located at Politecnico di Torino and Politecnico di Bari respectively, in order to perform Remote Power Hardware-in-the-Loop experiments. The possibilities and limitations of this type of co-simulation are described and a case study is presented.**

Keywords— Real time simulation, Remote Hardware-in-the-loop, Co-simulation, Microgrid, Research infrastructure sharing

I. Introduction and Motivation

The installation of non-controllable power plants exploiting Renewable Energy Sources (RES) introduced new challenges in the planning and in the operation of the electricity system. Currently, the future development of the electricity system is described by using two opposite approaches, based on the supergrid implementation [1], and microgrid implementation [2], respectively. In the first approach the system will be reinforced with the expansion of the transmission system, while the latter case it will be based on the wider and wider use of autonomous communities. Both cases require the use of new devices that need to be tested before their installation to verify their compliance with the standards in different grid conditions. The reiteration of particular tests, deriving from defined network conditions, can be really though, especially in case of complex phenomena applied to different devices under test. All the above issues pushed different European institutions to share their knowledge and their research infrastructures, by implementing the "laboratories in the network" framework [3][4]. The pursuing of this goal takes advantage from one quite recent tool called Real Time Co-Simulation, which has the following advantages [5]:

- soft sharing of hardware and software facilities within a federation;
- set-up of a multi-site simulation platform;
- testing of devices by integrating (power) hardware in the loop and remote software-in-the-loop;
- enhancing simulation capabilities for large systems;
- keeping confidential any susceptible data/model/algorithm

An example of this kind of infrastructure is the ERIC-Lab [6], making possible co-simulation among laboratories in Politecnico di Torino (Italy), RWTH Aachen University (Germany), JRC Petten (The Netherlands) and JRC Ispra (Italy). Another successful application is the RT-Superlab, which allowed to connect together Research Institutes widespread between Europe and US [7].

This paper describes the implementation of an experimental test-bed in which two technical universities in Italy, namely Politecnico di Bari (PoliBa) and Politecnico di Torino (PoliTo), interconnect their physical laboratories through internet communication.

The availability of a real microgrid interfaced to a Power Hardware-in-the-Loop (PHIL) facility at PoliBa, together with the high computation capability proper of the simulator of PoliTo, open the possibility to exploit these two features to simulate large systems (decoupled between the two real time simulators), with a real microgrid connected, implementing the so called Remote PHIL (RPHIL). The application requires to exchange electrical variables between the two laboratories through internet. This is done resorting to a Virtual Private Network (VPN) and adopting UDP protocol for communication. A non-linear power amplifier is used to replicate the network conditions simulated at PoliTo on the real microgrid in PoliBa, while the load conditions in the real microgrid in PoliBa impact the network simulation in PoliTo.

The rest of the paper is organized as follows: Section II describes the infrastructure parts (i.e., microgrid, the simulation facilities and the communication), Section III-A shows why it is not possible to exchange electric variables using the instantaneous values but more wise approach is necessary, Section III-B presents the case studies, whereas the final section provides the concluding remarks.

II. Co-simulation Power Hardware-In-The-Loop Architecture

The paper presents the results of the setting up of a power-hardware-in-the-loop platform, based on remote real time co-simulation. The two laboratories that are interconnected are located respectively in Bari (Southern Italy) and Turin (Northern Italy) at an air distance of about 1,000 km.

A. Politecnico di Bari - LabZERO

The power-hardware-in-the-loop (PHIL) test facility at the Politecnico di Bari (PoliBa) is located in the public research laboratory LabZERO [8][9]. The facility is composed of a real time digital simulator (OPAL RT5600) that communicates bi-directionally via optical fiber with a 16 kVA 4-quadrants programmable power source (Triphase PM15A30F60). The power source has a 6-channel power output that is currently configured for a 4-wire AC connection.

The controllable power output can be used either to locally feed a bank of resistors, inductors and capacitors, or to exchange power with a microgrid. The LabZERO microgrid, located about 120 m from the lab, is composed of several distributed energy resources such a PV generator, a wind micro-turbine, a 4-quadrants battery energy system, a 11 kW-charging station for electric vehicle and a small scale biomass combined cycle generator. The microgrid can be either connected to the main grid or work in isolated mode. When it is operated in isolated mode, the programmable power source can be controlled with a grid-forming scheme, providing voltage and frequency reference for the entire system.

All microgrid energy resources are monitored and controlled by a SCADA system via Modbus TCP/IP. However, due to the time delays introduced by Modbus communication (around 100 ms for each master-slave polling) and the time resolution of the energy meters (1 s), power measurements at SCADA will not be employed at this stage in the co-simulation platform.

B. Politecnico di Torino - G-RTSLab

G-RTS Lab, at Politecnico di Torino, is an internationally interconnected lab for real-time simulation. It is active in studying the role of electricity in energy transition, as well as new smart grids and super grids for electricity. The activities of the G-RTS Lab are integrated into the Energy Center Lab (EC-Lab), where interdisciplinary studies related to different energy sectors (e.g., electricity, gas and heat) can be studied entirely.

The facility is composed by a real time digital simulator (OPAL RT5600) with 7 activated cores and the possibility to perform simulations with the eMEGASIM and ePHASORSIM platforms. The first platform allows to performs EMT simulations with networks composed of 300 three-phase nodes, whereas the second one employs the phasor domains and accept networks up to 30,000 nodes.

C. Remote PHIL co-simulation architecture

The co-simulation architecture was designed in order to integrate the dynamic response of the PoliBa microgrid in the simulation of a larger electrical power system.

The design of the platform considered some relevant aspects of the existing communication link established between the two real-time simulators in Bari and in Turin. The two machines have been connected establishing a VPN tunnel and employing an IPsec encryption key to achieve communication security. The two machines exchange data using asynchronous messaging and UDP protocol.

As it will be shown in the next paragraphs, although the assessed communication performances are impressive (about 12 ms for each one-way transmission), the unavoidable delays due to the distance between the two remote locations do not permit to exchange electrical variables in the form of 50 Hz sinusoidal waveforms instantaneous values. The adoption of asynchronous messaging and a real-time transport layer protocol (UDP) that does not guarantee the proper message delivery is a relevant aspect to be considered, since incomplete or distorted voltage waveforms cannot be fed directly to the programmable power source for obvious security reasons. The adoption of UDP protocol yields some limitations but also certain advantages. For example, in the case of communication interruption, it ensures that missing and delayed packets are ignored and only most updated data are used [10]. According to our tests, the communication of electrical variables via UDP at slower rates (i.e. one packet at every cycle) seems secure enough in the established communication channel.

The proposed architecture assumes that each real-time machine (including the Target PC that controls the programmable power source) simulates a power system layer characterized by short-circuit powers significantly lower than the layer above. If this assumption holds, it is reasonable to assume that the layer below can be controlled using V, f reference signals, whereas its response is fed back in the form of P, Q signals.

This is for example how the PHIL architecture in Fig. 1 is organized. The real-time simulation generates voltage and frequency references to be fed to the programmable power source. The programmable source operates in grid-forming scheme, by imposing such references on the microgrid and the other connected devices. The real-time response of these devices is measured and fed back, in the form of voltage and current waveforms, to the Target PC, which controls the programmable source. These waveforms are analysed in real-time by a custom measurement block, so that exchanged active and reactive power is known with sufficient precision at every cycle.

The architecture in Fig. 1 can be slightly modified, as in Fig. 2, to include the co-simulation of the network. This second architecture represents the co-simulation RPHIL platform established between PoliTo and PoliBa. The two real-time digital simulators are each responsible for the simulation of a portion of the grid. The simulator that solves the network portion on a lower layer (or voltage level) receives voltage and frequency references from the simulator above and gives back the exchanged active and reactive power at the point of common coupling between the two network portions.

This configuration can be used to exploit the computation capabilities of both real-time simulators, but also suggests the possibility to develop new forms of collaboration in research and testing, where hardware equipment can be shared remotely without the necessity of physically moving it. This means that if, for instance, PoliTo needs to include in its simulations the dynamic behaviour of one or more of the devices that are employed at PoliBa (or viceversa), a remote PHIL communication can be established, allowing a physical share of power equipment.

Enabling and simplifying the sharing of equipment among public research laboratories is an important achievement that can allow to co-simulate and test complex systems, reinforce national and international research collaboration, enlarge the chances to exploit research equipment, and accelerate the return of investments on pricy technologies.

III. Experimental Results

A. Communication tests

The main communication challenge between two real-time systems is to guarantee data acquisition in order to provide reliable information to the connected actual power systems. A fundamental issue in co-simulation and RPHIL is the data transmission delay (or latency), as it impacts the co-

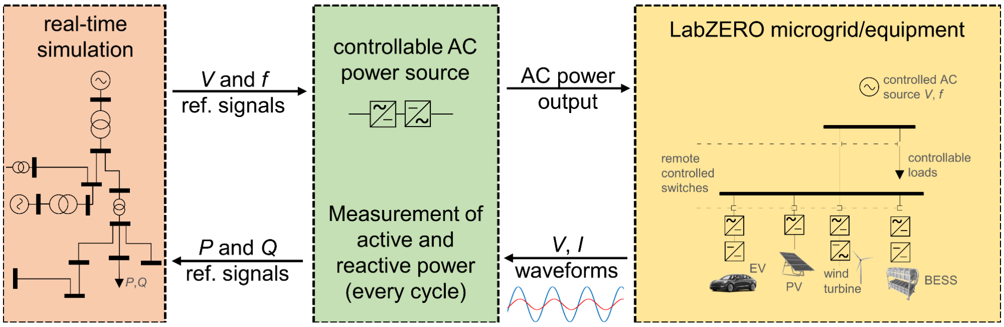

Fig. 1. PHIL architecture scheme

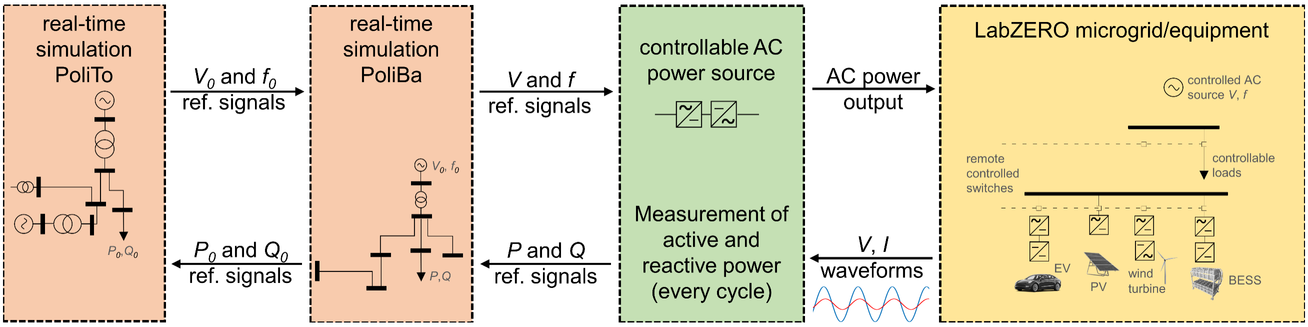

Fig. 2. Remote PHIL (RPHIL) architecture with network co-simulation

simulation stability. In order to assess the amount of lost packages and the quality of the data transmission, an initial loop-back communication test was carried out.

In a first test, a sine wave signal was generated by the simulator at PoliTo and sent to PoliBa using a 500 µs sample time. This same signal was then sent back to PoliTo as soon as received. Using "hardware synchronization mode", the generated signal and the one received at PoliTo were reproduced simultaneously as analog outputs of the digital simulator. These outputs were measured with an oscilloscope, as in Fig. 3. The blue signal is the original generated sine wave, whereas the teal signal represents instead the data received back at PoliTo. Thanks to the property of UDP protocol, which permits to use always the most recent available data, the two sine forms are distanced by a constant delay even when few packets are lost.

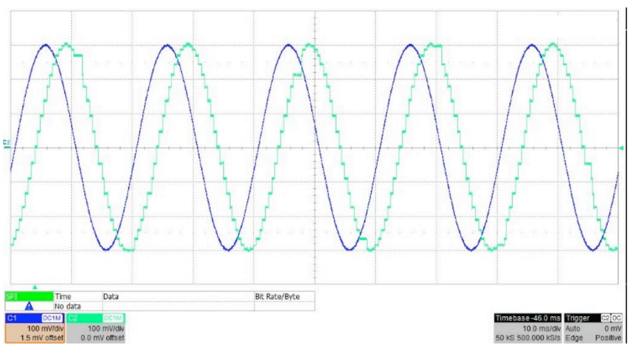

Fig. 3. Oscilloscope measurement of generated and received waveforms.

The next step was to calculate the delay between the two waveforms. For this purpose, a disturbance (an offset step-change) was applied to the generated sine wave. The detection of this same disturbance in the received signal permits to measure the time needed to move data from PoliTo to PoliBa and back. Fig. 4 shows the sent and received signals as recorded by the real-time simulator at PoliTo. The blue waveform is the discretized signal sent by PoliTo whereas the red plot shows the data received from PoliBa. It can be noticed that the delay is larger than one period (i.e. 20 ms at 50 Hz) and that some data packets were lost.

In order to evaluate the quality of the transmission in terms of data loss and delay, the Total Harmonic Distortion (THD) of both signals and delay were averaged along a 24 cycles (see Table I). It can be observed that the THD of the sent signal is much lower than the received signal, because of data packets lost in the transmission.

TABLE I. DELAY AND THD OF THE COMMUNICATION TEST

Description	Value
THD Sent Signal	0.11 %
THD Received Signal	15.71 %
Average Delay	25 ms

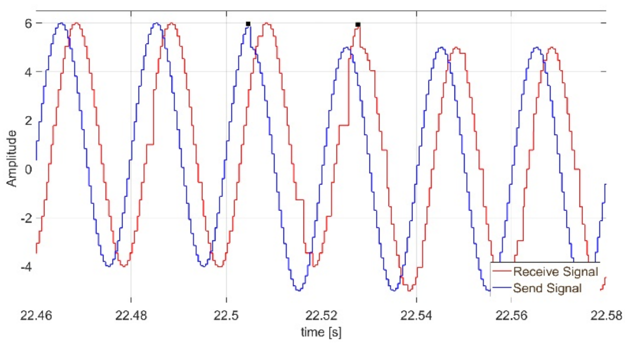

Fig. 4. Sinusoidal waveform sent and received.

Assuming that the transmission delay does not change with the direction of the transmission, the delay associated with a single transmission is estimated in about 12.5 ms. This is an excellent result considering the distance of the two locations (about 1,000 km). On the other hand, the high distortion levels in the received waveforms suggest that sine-waves cannot be used directly to operate remotely a power device. Therefore, a different manner of sending data is required; for instance through phasors or other electrical variables, so that the information content is guaranteed with transmission.

B. *Local and Remote Power Hardware-in-the-Loop tests*

These experimental tests were carried out in order to compare the performance of the proposed RPHIL architecture (Fig. 2, where the network is decoupled) with respect to the local one (Fig. 1, where the network simulation is not decoupled). In the *Local PHIL test*, the grid simulation is just carried out by the PoliBa digital simulator. On the other hand, the *Remote PHIL test* employs the PoliTo digital simulator for grid simulation, whereas the PoliBa one is used to i) pass on the voltage and frequency (V, f) references to the programmable power source and ii) provide the active and reactive power (P, Q) measurements back to the grid simulation at PoliTo.

The programmable power source controls its output in grid-forming mode, according to the voltage and frequency references received from the digital simulator at PoliBa. The output is used to feed power to a resistive-inductive (R-L) adjustable load bank. The tests simulate the transients following several load step changes. Each step change is obtained by switching on/off the R-L load.

In order to allow for a comparison in terms of time response, the load switching is obtained through the control of a contactor by means of a programmable smart relay. The programmable smart relay activates/deactivates the contactor's coil according to a digital signal received by the digital simulator at PoliBa. The digital simulator operates in hardware synchronized mode, so that it can provide the digital signal to the programmable logic relay at a specific instant. All trajectories are recorded using this signal for synchronization of the local machines.

In our tests, a base nominal load of 192.9 W and 64.3 var (inductive) is always on, whereas the contactor allows to switch on/off an additional load of 450.0 W and 128.6 var (inductive). Since this load variation cannot realistically cause appreciable voltage deviations on the simulated grid, the measured active and reactive power load is multiplied by a scale factor (x100) and then applied to the simulated grid.

The electrical grid implemented in the simulator is based on a portion of a medium-voltage grid topology of Turin. This network has one feeder derived from a 22-kV busbar of a 220/22 kV primary substation. The system operates at f=50 Hz. The studied feeder connects eight MV/LV substations; the MV/LV transformer and the real hardware are connected to the last substation of the feeder.

The loads of the simulated network are modelled as equivalent loads directly connected to the MV distribution system, except in one node where the MV/LV transformer and a portion of the LV network are represented in detail. In the RPHIL test the system is decoupled in correspondence of this MV/LV transformer: the MV distribution network is simulated at PoliTo, whereas the LV feeder at PoliBa.

Numerous tests were carried by switching the additional load on and off using both local and remote PHIL implementation. In all tests, not shown here for the sake of brevity, the voltage response was stable. Local and remote PHIL tests showed comparable voltage time responses and same steady-state values. Although the voltage transient events cannot be fully replicated in the local and remote PHIL tests, similar transient responses have been studied in the followings. The transients reproduce the PHIL and RPHIL response in the case of upward and downward step load variations.

Fig. 5 shows the voltage time response together with the active power measured at the programmable source, in the case of a downward load step-change variation. The first load step change is usually experienced within about 3 cycles from the sending of the switching signal (t=0). The power measurements are communicated as soon as a new estimation is available (i.e. at every cycle). The voltage response in the *Local PHIL test* (up) is very close to the one in the *Remote PHIL test* (bottom), although the second one is delayed. It can be noticed that, in the *Local PHIL test*, the voltage transient starts as soon as a P, Q variation is communicated to the digital simulator. In the *Remote PHIL test*, the first voltage response is delayed by about 25 ms from the moment of the first P, Q variation. This is the cumulative time needed to send the power measurements to the PoliTo simulator and send the first voltage response back to PoliBa. In the remote test the voltage plot has a lower time resolution because of the sample time used for transmission of the V, f signal from PoliTo. Same results and behaviour can be observed comparing the responses to an upward load step variation (see. Fig. 6).

This result is consistent with the communication time delay assessed in the previous tests (Section III-A) and is also confirmed by the recordings of voltage and power at both locations (PoliBa and PoliTo).

As represented in both Fig. 7 and Fig. 8, the power measurement step change is received at PoliTo with a delay of about 12.5 ms. The subsequent voltage transient is then communicated to PoliBa with an equivalent delay. The figures also permit to appreciate the difference between the simulated voltage trajectory and the one received (with delay) at PoliBa. Considering that the transmission from PoliTo is asynchronous, and that the sampling rate for the transmission was set at one sample every 3 ms, the two voltage trajectories appear sufficiently similar.

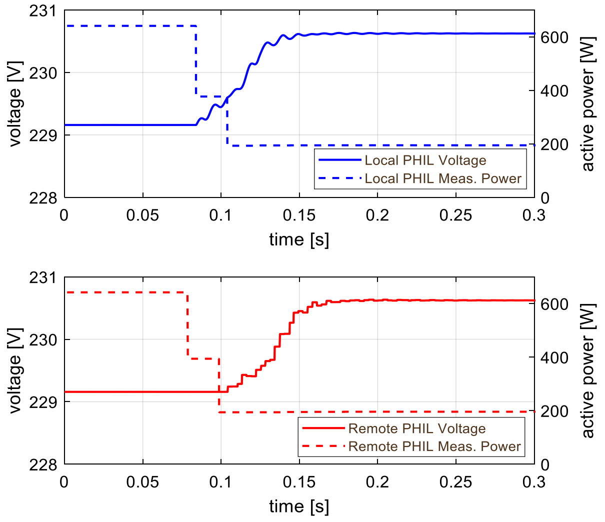

Fig. 5. Voltage and active power trajectories recorded at PoliBa for a downward load step variation: *Local PHIL test* (up) and *Remote PHIL test* (bottom)

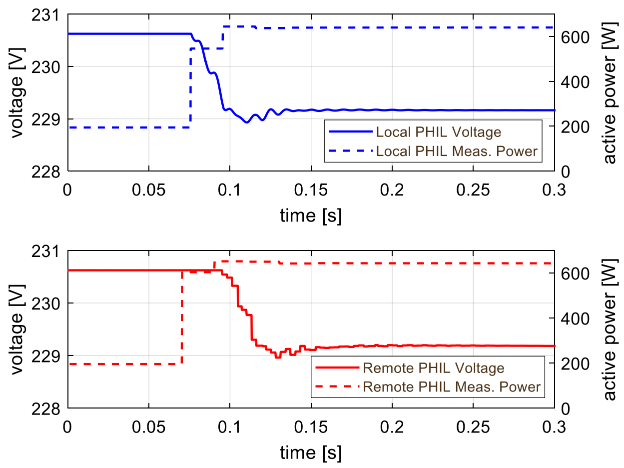

Fig. 6. Voltage and active power trajectories recorded at PoliBa for an upward load step variation: *Local PHIL test* (up) and *Remote PHIL test* (bottom)

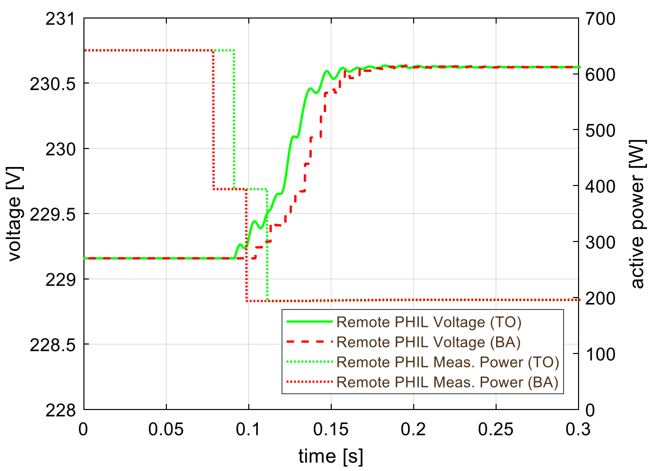

Fig. 7. Voltage and active power trajectories recorded at PoliTo and PoliBa during the *Remote PHIL test* (downward load step variation)

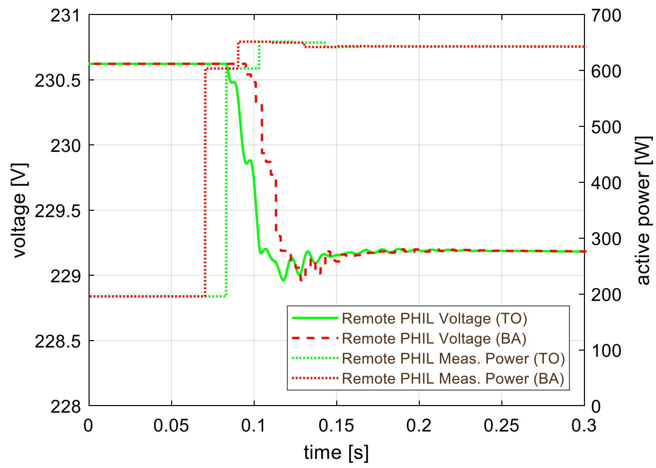

Fig. 8. Voltage and active power trajectories recorded at PoliTo and PoliBa during the *Remote PHIL test* (upward load step variation)

Figs. 9 and 10 compare the voltage and the power trajectories recorded at PoliBa (during the *Local PHIL test*) and PoliTo (during the *Remote PHIL test*). The objective of this comparison is to analyse the impact of PHIL on the simulated network. The main features referring to these two step responses are reported in Table II and Table III, respectively. These features have been evaluated by feeding the recorded trajectories to the *stepinfo* Matlab tool.

The dynamic responses in the local and remote tests appear to be very similar in terms of steady-state values, overshoot and settling times (calculating the settling time from the moment that a *P*, *Q* variation is recorded and with a 2% band around the steady-state value). This proves that the proposed methodology allows to reproduce with good approximation the response of the physical system on the simulated remote network. The only appreciable difference is in the unavoidable delay due to the transmission. This delay can affect the accuracy of simulations that require short time resolutions (for example EMT simulations for short-circuit studies), however it is small enough to allow a suitable description of transients and regulators that are characterized by slower time responses (voltage regulation, electromagnetic transients, load and generation shedding, etc.).

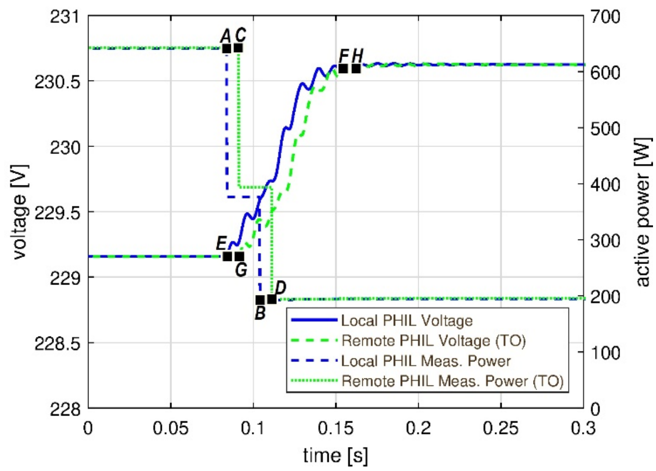

Fig. 9. Voltage and active power trajectories recorded at PoliBa (*Local PHIL test*) and PoliTo (*Remote PHIL test*), for a downward load step variation

TABLE II. STEP-INFO ANALYSIS - DOWNWARD LOAD STEP

Response features	Local Voltage (BA)	Remote Voltage (TO)	Local Power (BA)	Remote Power (TO)
Peak	230.6324 V	230.6348 V	192.8060 W	193.9371 W
Peak Time	0.185 s	0.1827 s	0.104 s	0.1113 s
Initial Value	229.1587 V	229.1578 V	640.7272 W	641.9134 W
Settling Value	230.6235 V	230.6229 V	194.4793 W	195.9165 W
Initial Time	t_E =0.084 s	t_G =0.097 s	t_A =0.0838 s	t_C =0.0963 s
Settling Time	t_F =0.1545 s	t_H =0.1623 s	t_B =0.104 s	t_D =0.1113 s
Overshoot	0.6%	0.81%	0.38%	0.44%

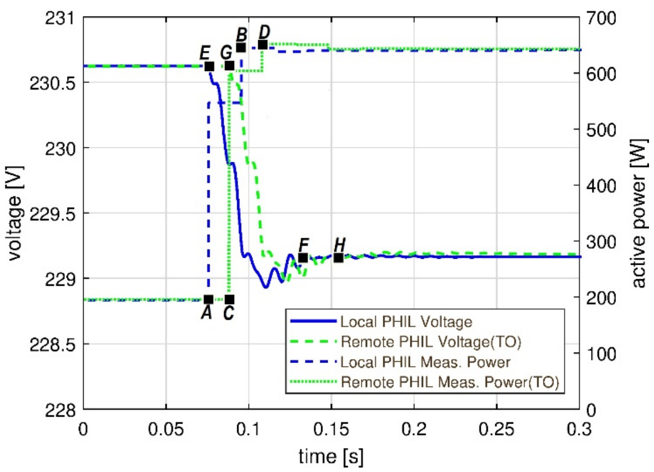

Fig. 10. Voltage and active power trajectories recorded at PoliBa (*Local PHIL test*) and PoliTo (*Remote PHIL test*), for an upward load step variation

TABLE III. STEP-INFO ANALYSIS - UPWARD LOAD STEP

Response features	Local Voltage (BA)	Remote Voltage (TO)	Local Power (BA)	Remote Power (TO)
Peak	228.9295 V	228.9620 V	644.8419 W	651.5475 W
Peak Time	0.01104 s	0.1228s	0.0956 s	0.1882 s
Initial Value	230.6245 V	230.6226 V	194.4285 W	195.8244 W
Settling Value	229.1628 V	229.1827 V	640.5527 W	642.8618 W
Initial Time	t_E =0.0759 s	t_G =0.0885 s	t_A =0.0755 s	t_C =0.088 s
Settling Time	t_F =0.1312 s	t_H =0.1542 s	t_B =0.0956 s	t_D =0.1081 s
Overshoot	15.95%	15.33%	0.96%	1.94%

CONCLUSIONS

This work has shown how it is possible to share hardware resources among laboratories, resorting to the connection of real time simulators through a VPN, by performing a remote co-simulation with PHIL. Preliminary tests were performed to analyse the VPN performances. Thanks to these tests it was possible to choose the proper methodology and time step for exchanging electric variables in the co-simulation. Then a real *R-L* load was driven by a programmable source controlled by the real time simulator in one lab, interconnected to a MV network simulation run on the real-time simulator in the other lab. The Remote Power Hardware-in-the-Loop co-simulation architecture was compared with the Local Power Hardware-in-the-Loop one, analysing system responses to load step variations.

Since the exchange of the entire waveform is not convenient, because of the delay in the communication and the waveform shape, an alternative signal exchange has been introduced, based on the value of V module, frequency, active power P and reactive power Q. The tests showed that a delay exists in the voltage variation when a load change occurs. Although a perfect overlapping of the local and remote response is not possible, due to the unavoidable communication delay and different experimental conditions, the accuracy of power and voltage is adequate to replicate remotely the real-time simulation performed locally.

The tested approach was proved to be feasible for the connection of two remote power laboratories. This approach will be used in future work with larger power system models and additional control schemes, with the aim to study the support that microgrids (lying existing internal grids of large industry and tertiary activities) can provide to the bulk system to increase the service reliability in case of external disturbing factors. Further studies will also investigate the possibility of improving the co-simulation methodology by reducing the measurement delays and developing more complex models, for example including an unbalanced representation of LV networks or the presence of harmonics.

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