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Remote PHIL Distributed Co-Simulation Lab for TSO-DSO-Customer Coordination Studies

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***Abstract*—The paper presents the results of an on-going collaboration between two Italian universities, Politecnico di Bari (PoliBa) and Politecnico di Torino (PoliTo), for the setting up of a permanent cooperative co-simulation platform, that permits to share real-time laboratory resources for both research and education applications. The two laboratories, LabZERO and G-RTSLab, are located at a geographical distance of about 1,000 km. By sharing their lab resources, PoliBa and PoliTo aim to increase number and extent of the possible methodologies, control apparatus and power devices that can be jointly tested, and to develop specific applications of Remote Power-Hardware-in-the-Loop (R-PHIL) co-simulation in the framework of Transmission-Distribution-Customer coordination. Test results are presented to assess delays in remote communication and to estimate how much sample rate and size of data packets affect such delays. An experimental test of the R-PHIL platform is also presented to demonstrate the stability of the proposed co-simulation architecture.**

***Index Terms*—Power Hardware-in-the-Loop, TSO/DSO Coordination, Smart Grids, Power System Laboratory, Real-time Simulation, Microgrids**

I. INTRODUCTION

Smart and modern grids can be seen as complex agglomerations of variegated and tightly connected infrastructures, constantly subjected to the influence of the multiple actors and components that utilize them or govern their uses. Due to this complexity, the testing of smart grid applications and physical devices should be tackled using a co-simulation environment, which, consisting of multiple simulators coupled by a common software interface, allows to simulate the response of multiple interacting hardware and software components, and the behaviour of different grid operators and actors [1]. Co-simulation applies very well to studies that must take into account the mutual interaction among subsystems that belong to distinct geographical areas, or operate on different hierarchical level or operational time frameworks. In addition to this, co-simulation constitutes also a unique cooperative tool which allows different research institutes, and also other institutions such as Transmission System Operators (TSOs) and Distribution System Operators (DSOs), to perform conjunct studies and simulations without the need to share data and models, or to develop models using the same simulation platforms [2].

The necessity to develop complex tools to simulate the interaction of grid operators (and also other actors such as generating plants, virtual power plants, demand response aggregators, etc.), which control different portions of the grid, is at the basis for example of the co-simulating environment *OpSim*. In [3], *OpSim* was proposed to study the interactions between the operative control actions undertook by a TSO Optimizer, which solves an Optimal Power Flow routine considering DSOs active and reactive power flexibility resources among control variables, with the DSO Optimizers that receive the flexibility requests from TSO and react according to them by dispatching their own resources.

In the context of what has been recently defined as transmission-distribution-customer (TDC) coordination framework [4], new flexibility services can be provided to operate optimally TSO/DSO interconnections by optimizing Distributed Energy Resources (DERs). This process requires the coordination of multiple components and energy resources which can be located on different voltage levels (HV, MV and LV) and operate on different time scales, and the overcoming of the general problem of lack of observability and controllability on demand-side components and LV grids. In [5] and [6], the authors recognized the necessity of adopting real-time simulators and integrating techniques such as Software-in-the-Loop (SIL) and Hardware-in-the-Loop (HIL) in testing the controllability of microgrids in the presence of a TSO/DSO coordination framework. In general, the complexity of modern electric grids, which are environments where a large variety of energy players, hardware devices, software and ICT components coexist, can be studied through the combination of the two most advanced methods to model and simulate complex cyber-physical systems: co-simulation and Power Hardware-in-the-Loop (PHIL) [7].

Remote PHIL (R-PHIL) is an even more complex co-simulation environment that allows to exploit geographically distributed real-time simulation resources, extending the number and variety of possible test cases and systems' combinations. First examples or remote co-simulation have been presented in [8], where two real-time simulation facilities performed coupled simulations on a large distance (from Mississipi State to Texas). Since then, several other successful implementations of remote real-time co-simulation have been presented, including both PHIL and non-PHIL applications [9], [10] and trans-oceanic co-simulation [11]. The idea of building a network of laboratories that can share their real-time simulation resources is also at the basis of large international cooperation projects such as the EU funded project *ERIGrid* [12] and the one leading to the setting up of a *RT-SuperLab* [13]. The latter case represents the first transatlantic real-time power system simulation which was performed to demonstrate the feasibility of integrating geographically distributed simulation tools, lab facilities and knowledge, in one large global laboratory. Ten digital real-time simulators from different producers, located in eight leading laboratories from the US and Europe, were integrated. The simulation consisted of multiple AC distribution grids, one AC transmission grid, a HVDC link, as well as multiple controller and PHIL setups.

In [14], the authors have shown the results of preliminary tests carried out while establishing a R-PHIL co-simulation platform connecting two Italian universities (Politecnico di Bari and Politecnico di Torino) and their real-time laboratories (namely LabZERO and G-RTS Lab) across a geographical distance of about 1,000 km. These first tests were mostly aimed at estimating latencies in communication and identifying a suitable methodology to interconnect both real-time simulations with a physical microgrid. In this paper, a more systematic set of communication tests have been carried out, aiming at estimating how the sample rate and the size of data packets influence the transmission delay and the number of lost packages. The results of a Remote PHIL test reproducing the possible TDC interactions with the dispatch of distributed reactive resources are described.

II. THE REMOTE PHIL CO-SIMULATION PLATFORM

The results presented in this paper refer to a collaboration between two Italian universities, Politecnico di Bari (PoliBa) and Politecnico di Torino (PoliTo), which led to the setting up of a permanent cooperative co-simulation platform, that permits to share real-time laboratory resources for both research and education applications. The two laboratories are located respectively in Bari (Southern Italy) and Turin (Northern Italy) at a geographical distance of about 1,000 km. This initiative stems from their activities within the project *Living Grid*, where the two universities, together with other Italian academic and research bodies, and in collaboration with the Italian TSO (Terna) and the largest Italian DSO (e-distribuzione), carry out R&D studies on TSO/DSO coordination. In particular, the activities are focused on studying the role and potential support that microgrids can provide to the system operator(s) (either TSO or DSO). The microgrid is seen as a player able to perform control actions on the DER connected to it, by shaping in this way its contribution according to the system needs. PoliBa and PoliTo participate to this project sharing the resources of the two laboratories LabZERO [15] and G-RTSLab [16], respectively.

A. Advantages and limitation of the co-simulation from previous experiences

As confirmed by [3], [5], [7], co-simulation and PHIL can be very helpful in demonstrating the feasibility of demand-side applications in a TDC coordination framework. Examples of how PHIL tests can help to demonstrate the feasibility of approaches for LV network observability and controllability, and for the use of DERs to provide network ancillary services, can be found for example in [17], [18]. In these last two studies, PHIL tests were run at LabZERO exploiting the PHIL facility and the availability of an electrical power connection between a (real-time) programmable power source and the dispatchable DERs of the local microgrid.

The use of resources connected to the distribution grid to support the TSO for the frequency regulation has been investigated in the project RESERVE [19], where the facilities of G-RTSLab were used to simulate a portion of a urban distribution network with connected a number of DERs equipped with droop control systems [20].

By sharing their lab resources, PoliBa and PoliTo aim to increase number and extent of the possible methodologies, control apparatus and power devices that can be jointly tested. The co-simulation approach permits to increase the computation capabilities of the real-time simulations, developing more realistic models to represent the interaction among networks and components, set on different voltage levels. In the specific context of TDC coordination and *Living Grid*, the remote PHIL architecture will allow to test the response of dispatchable distributed resources in credible system operation scenarios. Typical functions of TSO/DSO coordination are based on the exchange of dispatching orders, for example with the TSO requiring the use of flexible resources to decrease active power or increase injected reactive power and control the nodal voltage at the point of interconnection. Following this dispatch, the DSO can decide to use its own control resources (if available), and/or exploit distributed resources by sending control or price signals to generate a reaction from flexible demand-side resources. The feasibility of such approaches is affected of course by the actual time response of the distributed resources and this response coordinates with all other automated or operator-based functions developed by the system operators.

Other possible applications that can be tested thanks to the remote PHIL platform can be aimed at exploring the possibility of increasing LV DERs observability thanks to sensitivities analysis and parameter identification. This analysis can be for example carried out by perturbing the grid voltage profiles with predefined small variations of on-load tap changers (OLTC), or by injecting small amounts of reactive power. The real-time response of the distributed LV prosuming nodes, such as the LabZERO microgrid, can be studied not only as an aggregated response at the secondary substation, but also making use of the actual measurement sets that are locally available, and that can be integrated by DSO through a Automated Metering Infrastructure (AMI). The co-simulation

PHIL platform allows not only to study the actual interaction between the operators and the physical nodes, but also to include in the feasibility study the realistic behaviour of power meters, with their limitations in accuracy, time response and time resolution [17].

With regards to the interaction between TSO/DSO operation and distributed resources, in a possible future evolution, the PoliBa/PoliTo co-simulation platform could extend its reach to other Italian (or international) universities and research institutes, but also to industrial labs such as the real-time Smart Grid Laboratory of e-distribuzione [21]. The advantages in the connections are manifold. This interface will allow for example to increase the number of power equipment involved in the simulations and test new operative SCADA/DMS function in a SIL/PHIL environment, by interfacing with the SCADA application development servers. Moreover, remote co-simulation can help to overcome typical problems encountered in R&D projects when system operators have to share sensitive information, models and software. The co-simulation approach will allow each part to preserve its own data and models, safeguarding confidentiality of customers and network security. Up to a certain extent and depending on the interoperability of the interacting hardware and software, co-simulation can also help in mutually exploit each partner's competences and avoid the need of specific training. This is also an important issue, since training on real-time software and hardware can be a very time consuming process.

One of the main limitations of remote co-simulation with respect to "monolithic" simulation is given by latency [2]. The latency of communication can affect heavily simulations, especially if the dynamics under study are very fast. For this reason, remote co-simulation approaches are often limited to latency tolerant applications [7] with time responses usually spanning from few seconds to minutes [1]. In [14], the communication latency in the communication between Bari and Turin of UDP datagrams was estimated in about 12 ms. This is a notable result (packets are exchanged at a rate that is about one quarter of the theoretical light speed), and was confirmed by the several tests made. However a systematic study was never performed, especially with regard to the size of the packets, the amount of information exchanged, and the number of lost packets. In the following paragraph the results of new extensive tests will be presented along with a simple demonstration of the interaction between the real-time models and components in Bari and Turin.

B. Communication and Simulation Architecture

The R-PHIL co-simulation architecture, first presented in [14], is outlined in Fig.1. It is designed to integrate the response of LabZERO's microgrid in the simulation of a larger electrical power system, simulated in real-time, by both units located in Bari and Turin. The real-time simulators communicate by means of a VPN tunnel, employing an IPsec encryption key for security reasons. Both laboratories employ an OPAL RT OP5600 real-time simulator. At PoliBa, the real-time simulator is connected to a 16kVA 4-quadrants programmable power source Triphase PM15A30F60.

The two simulators were programmed to exchange data using asynchronous messaging with UDP protocol. Although this real-time transport layer protocol does not guarantee delivery, it has the advantage of always using the most updated data available. This means that, when packets are missing or affected by heavy delays, the normal communication can be restored as soon as a new proper real-time packet arrives [9].

The proposed architecture assumes that each real-time machine simulates a subsystem set on a different layer. The interaction between two layers can be modelled using V, f reference signals to control the lower layer, whose response is fed back in the form of P, Q signals. In Fig.1 the real-time simulator at PoliTo is used to solve the model of the primary distribution network, imposing voltage and frequency on the MV/LV substation, which is the interconnecting point with the secondary distribution network simulated at PoliBa. This choice is justified because the physical microgrid is assumed connected to one of the LV nodes of the secondary substation.

The programmable source controls the microgrid using a grid-forming scheme and, therefore, by establishing the voltage and frequency profiles simulated by the real-time machine at PoliBa on the microgrid. The real-time response of the physical equipment is fed back, under the form of voltage and current waveforms, to the Target PC that controls the power source. Active and reactive power measurements are then sent back through synchronous communication on optical fibre to the real-time machine at PoliBa, which solves the MV/LV network. The amount of power exchanged with the MV node is transferred back to PoliTo for the HV/MV simulation.

III. COMMUNICATION TESTS

These tests were aimed at assessing the communication delay between PoliTo and PoliBa using asynchronous messaging with UDP protocol. The tests were carried out assuming that, at the end of a sample period, a new set of data is available and is sent to the remote machine. Data are transferred in the form of double precision numbers. The data received at the remote station were recorded and sent with a loop-back to the sending station for verification of the two ways communication. Several tests were run considering different sample periods (ranging from 1 to 20 ms) and datasets with different size. The largest packet represents the maximum theoretical number of information that can be passed from the real-time simulator at PoliBa onto the programmable power source with a sample period of 1 ms.

The tests were run in different days at different hours. For each test a total of 10,000 samples were exchanged. Table I reports the number of packets that were lost on a single communication route (from PoliTo to PoliBa). The loss of data is minimal in all cases, but higher for the one with a 1 ms sample period. In this case, many lost packets can be observed with respect to the other cases. However, due to the properties of UDP communication, data is not really lost; simply delayed packets are discarded because more recent

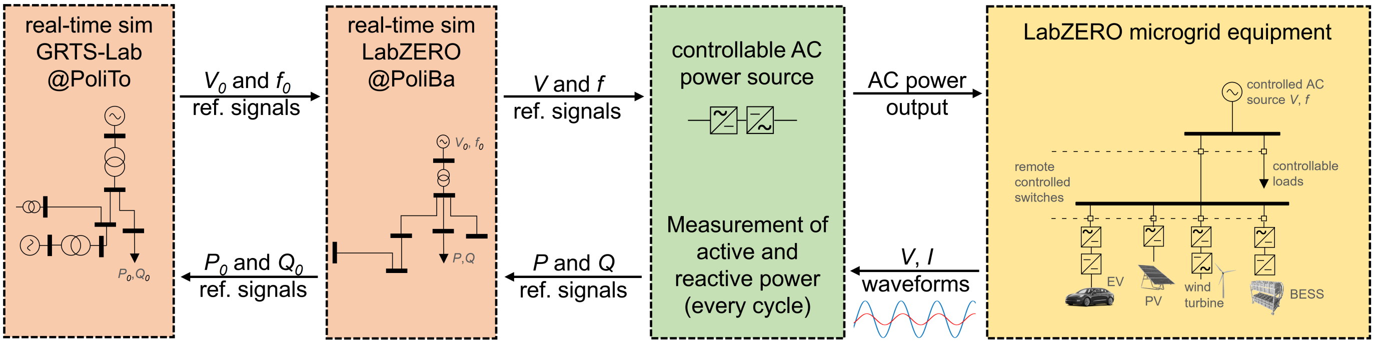

Fig. 1. Schematic diagram of the remote co-simulation PHIL platform.

ones already arrived. This observation can be confirmed also thanks to Table II, which collects the average delays for each test. The tests with a sample period of 1 ms are characterized by the shortest delays, because, in real-time communication, data with higher delays are discarded. This is also confirmed by looking at standard deviation in Table III, that appears to be lower in the case of a 1 ms sample period.

Apart from the case with shortest sample period, the analysis of communication delays shows that, in the range under study, delays are not affected by communication rate or packet size. Mostly, delays are influenced by the instantaneous network traffic, which can vary depending on the moment on which the test was run. Unfortunately, unless network traffic is monitored or somehow conditioned, it is difficult to assess how much traffic will impact the real-time remote simulation. In any case, the effects of the random influence of network traffic can explain why the tests with a higher period (20 ms) are characterized by a higher dispersion of samples and sometimes higher delays. In facts, since the number of exchanged data remains the same, in these tests the communication is active for a longer time and the probability to exchange data in a sudden moment of higher network traffic is higher.

Please note that the delays observed with loop-back are perfectly homothetic, proving that the direction of data flow does not influence delays. These results are not presented for the sake of briefness.

From the boxplot in Fig. 2 it can be observed how in most cases the delay ranges $10 - 20$ ms. Outliers with higher delays are observed only in the 20 ms case, for the reasons just reported above. These results suggest that during R-PHIL simulations, where actual electrical variables are processed and measured in real-time, a good strategy is to keep a communication period lower than the time resolution of measurements. In this way, a new measurement can be sent as soon as it is ready. Even if a packet is lost, the old measurement is retained at the receiving end-point, whereas the new measurement is sent again from the sending end-point every few milliseconds, until a new measurement is ready.

TABLE I
Number of Lost Packets (out of 10,000)

Sample Period [ms]	**Payload size [number of exchanged data]**					
	2	**6**	**12**	**24**	**48**	**96**
1	93	79	101	55	204	24
5	0	1	0	2	1	0
10	1	0	4	2	0	0
20	0	0	1	1	0	0

TABLE II
Communication Delay - Mean Value [ms]

Sample Period [ms]	**Payload size [number of exchanged data]**					
	2	**6**	**12**	**24**	**48**	**96**
1	10.72	10.51	10.80	10.77	10.97	10.81
5	13.00	11.27	11.60	12.98	11.87	10.39
10	10.79	10.90	12.94	13.25	12.53	15.12
20	15.32	16.10	11.53	13.41	12.92	11.68

IV. Remote Power Hardware In the Loop Test

The R-PHIL test case presented in this section exemplifies how the possible interactions of different actors in a TDC framework can be simulated. A Full-TSO coordination architecture is assumed [4]. This means that the TSO has the possibility to dispatch flexible resources at both transmission or distribution level. In the test, following a dispatching command signal from the TSO, the reactive power injected at distribution level is modified. This modification is made on a physical system (a R-C load bank at PoliBa) that interacts with a real-time model of the distribution network

TABLE III
Communication Delay - Standard Deviation

Sample Period [ms]	**Payload size [number of exchanged data]**					
	2	**6**	**12**	**24**	**48**	**96**
1	0.19	0.19	0.25	0.17	0.42	0.11
5	0.22	0.60	0.20	0.17	0.27	0.16
10	0.24	0.24	0.39	0.19	0.34	0.20
20	0.34	0.33	0.59	0.29	0.47	0.33

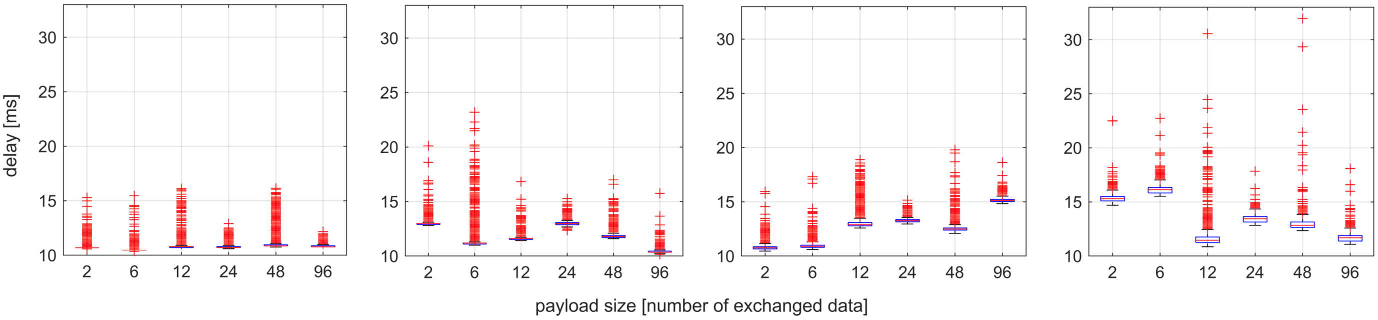

Fig. 2. Communication delays, boxplot with different sample periods: 1 ms (left), 5 ms (center-left), 10 ms (center-right), 20 ms (right).

(simulated at PoliTo). The subsequent voltage increase triggers the activation of the automatic OLTC regulator, which adjusts the tap position according to the new operating point. The scheme permits to obtain a realistic response of the distribution network, following the command initiated by the TSO.

The Remote PHIL test employs the PoliTo real-time simulator for modelling the distribution grid and the OLTC at the HV/MV substation. The PoliBa simulator is employed to pass on the voltage and frequency V, f references received from PoliTo and feed the active and reactive power P, Q measurements back to the grid model. The programmable power source is controlled in grid-forming mode, so that the V, f reference can be applied to its output. The power source is connected to a adjustable bank or R-L-C loads, activated by means of a smart controller. When the trigger signal is received, the smart controller activate a R-C load of (nominal) 64 W and 450 var. In order to cause an appreciable voltage deviation on the simulated HV/MV substation, the measured active and reactive power load is multiplied by a scale factor (x250) and then applied to the simulated grid.

The distribution grid model implemented in the PoliTo simulator is based on a portion of a MV grid in the city 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 modelled feeder connects eight MV/LV substations, and one of the MV/LV transformer is virtually connected to the PHIL system at PoliBa. The HV/MV tap changer is modelled according to the detailed OLTC model in [22], with a 0.0125 p.u. step size, 0.0250 p.u. deadband, a 1 s tap switching delay and a 0.978 p.u. voltage reference.

Fig. 3 shows the power demand at the physical LV node, whereas Fig. 4 shows the voltage magnitude at the equivalent MV/LV interconnection point. The dispatch signal is generated at $t = 0.05$ s and sent to the smart controller, which activates the R-C load at PoliBa (around $t = 0.11$ s). A new value of P, Q is measured and sent to PoliTo, which receives it with a delay of about 12 ms. The P, Q variation causes voltages to slightly increase in the simulated system. Voltage variations are communicated back to PoliBa and used to update the voltage reference on the physical system. Due to the voltage increase, at about $t = 1.65$ s the OLTC voltage regulator adjusts the tap position and the whole co-simulation system reaches a new equilibrium point. Please note that the transient following the tap change is characterized by a significant voltage dip. This behaviour does not represent an actual physical response to tap switching but is due to some model's limitations observed when a fixed step discretization rule is adopted. Future work will be devoted to improve the OLTC model to avoid this behaviour. Nevertheless, it should be pointed out that the R-PHIL simulation is stable and reaches rapidly a steady-state value, even in the case of such harsh voltage perturbation.

Fig. 5 shows how, through co-simulation, the TSO could observe the system response following a dispatch of flexible resources, without owning any information on the distribution network beyond the point of interconnection. From a technical point of view, however, the simulated response exemplifies also how, in a Full-TSO TDC scheme, the scarce observability of the distribution network could affect the effectiveness of control. It can be observed how, due to the activation of the OLTC automatic regulation, the control action effect was partially reduced. The effects of the voltage change could be even more evident if a voltage dependant load model was assumed also on the other simulated MV/LV substations, instead of a fixed P, Q model. This consideration strengthens the idea that suitable co-simulation schemes can be used by TSO and DSO to better define the mutual grid interactions that must be taken into account while defining the TDC coordination schemes.

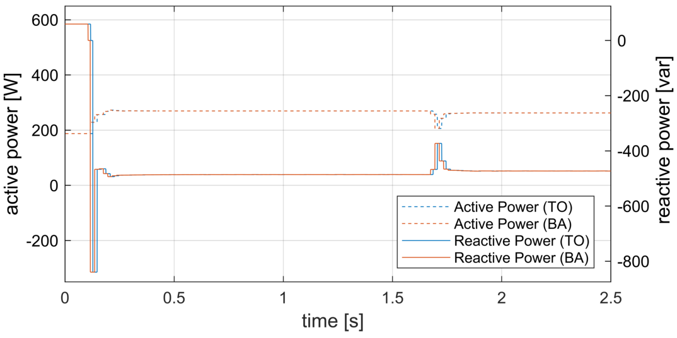

Fig. 3. Active and reactive power variation at the physical node.

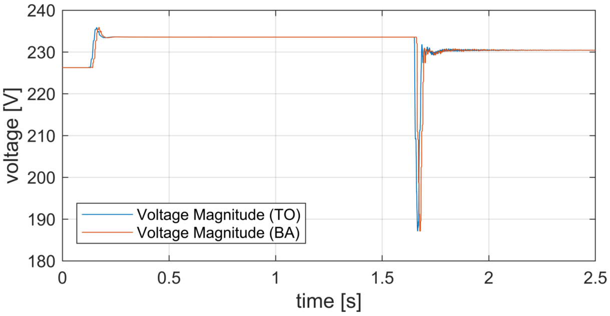

Fig. 4. Voltage magnitude at the equivalent MV/LV interconnection point.

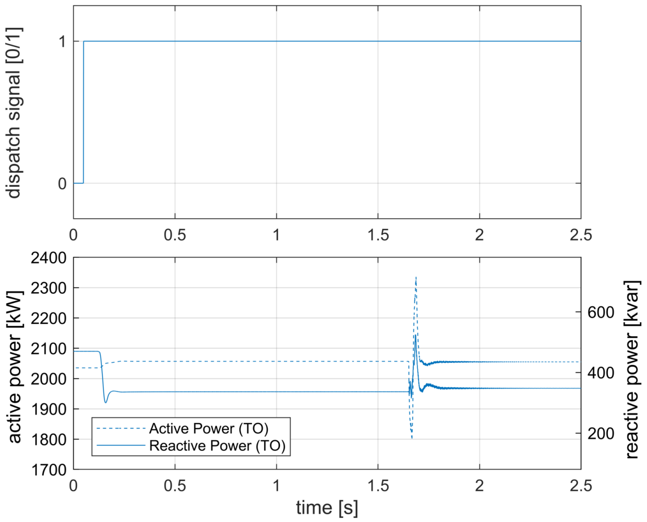

Fig. 5. Active and reactive power at the HV/MV point of interconnection.

V. CONCLUSIONS

This paper described the R-PHIL co-simulation infrastructure established between Politecnico di Bari and Politecnico di Torino, and used it to study the interactions among TSO, DSO and Customer (i.e., TDC), being the Customer a real micro-grid connected to the simulated distribution system.

The communication tests, in different internet network traffic conditions, showed how the loss of data is minimal and the delays are not affected by communication rate or packet size, but mostly by the variable network traffic. They also proved the feasibility of using the established co-simulation infrastructure for TDC interactions and coordination studies.

The R-PHIL test showed how the control signal sent by the TSO to modify the reactive power generated by the micro-grid can lead to a reaction of the OLTC installed in the HV/MV substation, partially reducing the effect of the control action. This should be carefully considered for the future TDC implementation.

In future works the OLTC model will be improved and the effects of the measurement sample time will be investigated.

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