Ensiel National Energy Transition Real Time Lab: a Novel Tool to Shape the Future Energy System

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***Abstract*—The energy transition represents the actual challenge in the next future, and requires new scientific tools of analysis in order to quickly and effectively deploy the most suitable technological solutions. This is required both to reduce as much as possible the long test phases on the field and to make investments more effective. This paper presents the Ensiel National Energy Transition Real Time Lab (ENET-RT *Lab*), which was launched in April 2022. The geographical distributed co-simulation real time laboratory is composed of five partners, and aims to become one of the main platforms to test novel solutions and technologies that can effectively support the energy transition in Italy.**

***Index Terms*—Real Time Simulation, Co-simulation, Power Hardware-in-the-Loop, Software-in-the-Loop, Control-in-the-Loop, Frequency Control.**

I. Introduction

The European Union has set ambitious goals for a competitive and sustainable energy transition, in particular for the deployment of renewables. The European Parliament has established a headline target of 32% energy generation from renewable sources at EU level by 2030 [1]. The EU aims at achieving climate neutrality by 2050, committing to the intermediate step of cutting emissions by at least 55% by 2030. As stated in the COP26 climate pact [2], part of the mitigation actions is related to the electrification of the transportation sector and to the enhancement of the energy generation. This will translate in a growing penetration of distributed renewable energy sources and introduce significant technical and operational issues that will need to be tackled. The European directives have been implemented in the Italian legislative environment, with the legislative decree of the 8$^{\text{th}}$ November 2021 [3] regulating the renewable sources in the Italian system. In this context, the development of advanced tests and validation systems will be required and real time simulations (RTS) are going to become a fundamental tool to test new solutions and models as close as possible to the real world. Unfortunately, the hardware to perform such tests, especially in power hardware in the loop (PHIL) configurations, could be not available due to its prohibitive costs. To overcome this issue, a strong and close cooperation is nedeed. The pooling of resources and the collaboration of different laboratories can fully enable the RTS potential with geographically distributed simulations [4].

Simulations are often exploited to conduct experiments when these are impossible or impractical on the real systems. First of all, a distinction has to be made between offline and online simulations [5]. In offline simulations the time required to solve all the system equations exceeds the time step, so a variable time step could be used. Conversely, in online simulations, the system equations need to be solved in a time interval which is shorter than the chosen (fixed) time step. If the available calculation resources fulfill this requirement, it is possible to interface the virtual environment with the real world through I/O boards, making the simulation environment closer to a real world scenario. Co-simulation may be suitable for studies that have to take into account the mutual interactions among physical phenomena. In the case of electrical systems, these can be significantly different and are therefore enclosed in separate subsystems, each operating on a separate hierarchical level or operational time framework. To correctly simulate the subsystem dynamics, the RTS systems can synchronize the simulation with the evolution of the considered phenomena [6]. The overall simulation is obtained by launching all the connected simulation units, which exchange data among them and act as a black-box for each other. In this way, each simulator can represent a specific aspect of the system, allowing a detailed analysis within each subsystem. Thanks to its parallel computation capabilities, RT co-simulation allows the creation of a distributed simulation environment with simulators that can even operate in different countries.

The advantages of setting up a remote co-simulation framework were shown by Politecnico di Bari and Politecnico di Torino during the activities of the research project *Living Grid*, carried out also in collaboration with the Italian Transmission System Operator and the largest Italian Distribution System Operator. During this project, the two universities established a peer-to-peer communication channel between their real-time simulators, allowing the execution of remote Power Hardware-in-the-Loop tests at a geographical distance of about $1,000\,\mathrm{km}$ [7]. Remote PHIL tests proved that remote co-simulation can be useful, for example, to test TSO/DSO coordination techniques without having to share sensitive details and to perform conjunct studies, without the need to share sensitive data and models, or to develop models using the same simulation platforms [8]. The effects of communication latency, estimated in about $12\,\mathrm{ms}$ each way, were studied in terms of simulation fidelity and stability in [9], highlighting the necessary conditions to achieve a stable and robust co-simulation, and the limitations of remote PHIL.

The proposed framework is the first Italian implementation of an interconnection of multiple geographically distributed laboratories. In this context, each participant carries out one or more tests/experiments composing a larger collaborative experiment, giving the opportunity to test new strategies and technologies. This approach has the important advantage to allow the share of resources and expertise, among the partners on a National scale. The collaboration with international partners required to set up the communication over the internet with appropriate communication protocols. This kind of set-up allowed to extend the distance range of the partners, leading to some advantages:

- National expertise sharing.
- Sharing of models and simulations instruments.
- Sharing of hardware and software resources, making them available on a National basis, without moving them physically.
- Improved computation capability for each laboratory without new investments.
- Increasing the possible size of the simulations.
- Opportunity to keep some hardware or software resources confidential, allowing at the same time their use by the partners through the co-simulation.

II. The ENET-RT *Lab*: Laboratories in the Network, not a Network of Laboratories

A. Motivation and goals

The Ensiel National Energy Transition Real Time Lab (ENET-RT *Lab*) initiative represented the first National-wide implementation of the “laboratories in the network concept”. The test was carried out on 11$^{\text{th}}$ April 2022. In Figure 1 the connected facilities are showed, with green circles indicating a functioning data connection.

The implementation of this activity was possible thanks to the increasing number of universities equipped with RTS facilities, which provided the unique opportunity of developing a joint facility which represents the “Italian RT node”. In this context, the contribution of the Ensiel consortium was fundamental to coordinate the entire initiative. The goals of the lab are: *i*) strengthening the RTS culture within the Italian scientific community; *ii*) reinforcing the collaboration among the different universities; *iii*) widening the use of the RTS philosophy also to industries (“digital twin” of the actual infrastructure); *iv*) collaborating at European level with the already existing and well-established real-time facilities; *v*) being identified as one strong partner in trans-National collaborative projects (e.g., European Projects), with a recognizable leadership role in the RTS field; and *vi*) supporting institutional and industry partners in the decision making process for the deployment of energy strategies to complete the energy transition towards a carbon-free energy system and for the development of the required technologies. The founding partners, coordinated by Ensiel are: Joint Research Centre (JRC) Ispra, Politecnico di Torino, Politecnico di Bari, Università di Genova (with two involved laboratories), and Università di Napoli ”Federico II”. In the following subsections, a brief description of each partner laboratory is provided.

B. European Commission, Joint Research Centre - SGILab

The Smart Grid Interoperability Laboratory (SGILab) is a research platform designed to foster a common European approach to interoperable digital energy. The SGILab is situated at two distinct sites: the laboratory facilities in Ispra (IT) focus on grid studies and integration of electric vehicles whereas the facilities in Petten (NL) are dedicated to smart grids and smart homes [10]. The Ispra site, which participates in the ENET-RT *Lab* activities, is equipped with a RTDS simulator and a Triphase 90 kVA power amplifier. A wide range of assets are available to conduct PHIL experiments, including a 450kWh Battery Energy Storage System (BESS), DC and AC programmable loads and different types of EV charging columns. The SGILab has been active in the area of geographically-distributed real-time simulations since its inauguration in 2015, with the first demonstration of a European platform for RTDS co-simulation. In addition to its experimental activities, the laboratory is actively involved in theoretical research on stability, robustness and implementation of geographically-distributed RTDS setups.

C. Politecnico di Torino - G-RTS Lab

The Global-Real Time Simulation Lab (G-RTSLab) [11] is part of the Energy Center Lab, which is a multi-disciplinary laboratory of Politecnico di Torino. The laboratory has been established in 2015 within the Energy Department and has been expanded between 2018 and 2020 with an investment of almost 2M€ to develop *real-time simulation* facilities.

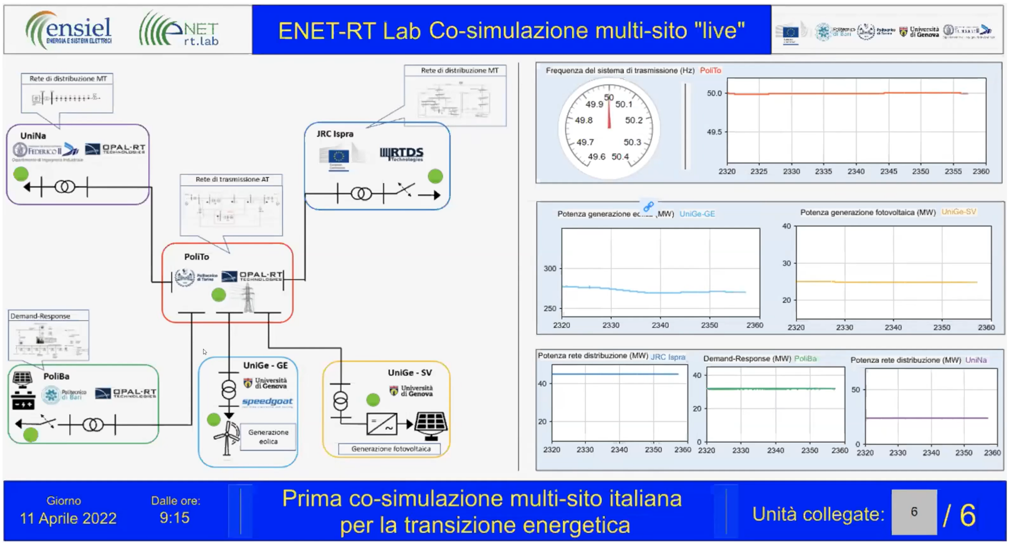

Fig. 1. Connected facilities

These include RTDS and OPAL-RT simulators to run RTS spanning from microseconds (for electro-magnetic transients) to milliseconds (electro-mechanical dynamics) and switching and linear power amplifiers (from 15 kVA to 60 kVA) to implement PHIL configurations. The laboratory is also equipped with battery, load and PV emulators (with size 15 kVA) and a *spinning group*, composed of a DC motor, an induction motor and a 60 kVA synchronous generator. Moreover, thanks to the industry collaboration with Edison SpA, two 11 kW charging points and one EV [12] are also available in the laboratory. The laboratory took part in 2015 to the first European real-time co-simulation named ERIC-Lab (with RWTH Aachen, JRC Petten and JRC Ispra) [13] and to the first trans-oceanic co-simulation in 2017, involving the three US Department of Energy Research Centers (NREL, SANDIA and INL), two US Universities (Colorado State University and South Carolina State University) and two European partners (RWTH Aachen and Politecnico di Torino) [14].

D. Politecnico di Bari - LabZERO

LabZERO is a multidisciplinary laboratory established at Politecnico di Bari around 2016, whose research activities are oriented towards energy efficiency, sustainable energy systems and smart grids [15]. LabZERO real-time simulation test facility is composed of an OPAL RT simulator coupled, through a 16 kVA Triphase programmable power amplifier, with a fully equipped microgrid for PHIL tests. The microgrid comprises a 5 kW PV generator, a 3.5 kW wind micro-turbine, a 5 kW/5 kWh battery energy system, a 22 kW EV charging station and a small scale biomass combined cycle generator [16]. The works for the expansion of the microgrid to include a smart parking station composed of a 20 kW PV canopy, a 30 kWh battery energy system and a 2×22 kW EV charging station, are almost completed. Among other applications, the PHIL test facility has been recently used to test the dynamic response of power components, and their controllers, to electro-mechanical transients in system characterized by low inertia. These tests were carried out to test new frequency meters and synthetic inertia controllers [17], validate the response of fast frequency regulation techniques [18] and integrate new control strategies in non-synchronous geographical islands [19]. This last activity is still on-going and is based on research collaboration contracts stipulated with Università di Palermo (BLORIN project) and e-distribuzione (ISMI project).

E. Università degli Studi di Napoli "Federico II"

The Department of Industrial Engineering of the Università degli Studi di Napoli "Federico II" contributes to the co-simulation with an OPAL-RT4510, with one-core active. The laboratory aims to improve the equipment in the near future by reinforcing the computation capability of the centre and introducing power amplifiers for PHIL studies.

F. University of Genoa

The University of Genoa participates with two laboratories.

1) Network Infrastructure and Complex Energy System Laboratory: The laboratory has contributed to the extension of the ENET-RT *Lab* including a Speedgoat RT simulator. This is used to model a detailed version of a 500 MW wind power park where wind turbine generators are equipped with a Synthetic Inertia Controller. The controller is integrated in the simulation in a HIL fashion exploiting a prototype realization of the controller interfaced with the RT simulator by means of analog signals and an industrial frequency meter. The RT simulator in Genoa interacts with the real time grid by exchanging the voltage and frequency signals at the point of interconnection of the wind park and returning to the grid the active and reactive power production.

2) Savona Campus: At the Savona Campus the Smart Polygeneration Microgrid (SPM) is in operation since 2014. It consists of a three-phase low voltage distribution system, coupled with a thermal network, and connecting electrical and thermal sources (photovoltaic fields, a storage device, co-generation micro-turbines, chillers, etc.). The SPM is used both as a test bed for research purposes and to actually contribute to cover the electrical and thermal demands of the Campus, during its daily operation. In the context of the work presented in this paper, the SPM shares the real time value of the power produced by the main photovoltaic field (peak power: 80 kWp). This data, suitably scaled, allows emulating an active power injection of about 30 MW on the transmission network [20].

G. The communication infrastructure

The communication among the different partners is ensured by the VILLAS framework (developed by RWTH Aachen). The used communication protocol is the UDP (User Datagram Protocol) protocol because, unlike TCP (Transmission Control Protocol), it does not require the re-transmission of lost packets, reducing the delay. In this context a light-weight protocol, called VILLAS binary, easily readable by machines, is used to facilitate a fast transmission of packets.

III. Case study

In the framework of energy transition, due to the urge for environmental sustainability, a shift from fossil primary sources to renewable energy sources (RES) is needed. The penetration of RES may take place following two different and distinct paradigms: concentrated RES generation, constituted by a few large RES power plants connected to the power transmission system, and distributed RES generation, constituted by a large number of small size RES generators connected at the distribution level. The two paradigms are not mutually exclusive. The latter is particularly interesting, as it is worth to investigate if this large number of small generators, installed in (micro)grids at the MV or LV level which can include energy communities of prosumers, could be exploited as a replacement for traditional fossil fuels powered power plants connected at the transmission level. The feasibility of this replacement is crucial for the energy transition, as it is fundamental for guaranteeing the system adequacy (i.e. the system capability of maintaining the instantaneous balance between demand and generation in a certain area) and for providing ancillary services such as frequency and voltage control. The meshed structure and the area interconnections of the transmission system have traditionally guaranteed the possibility to exploit generators of the neighbouring areas in case of insufficient generation in the considered area that produces a strong unbalance between supply and demand. Due to the decommissioning of the conventional fossil fuels power plants and to the deep penetration of RES, this possibility may not be guaranteed anymore. Therefore, the involvement of the distributed resources in a certain territory for the instantaneous power balance between generation and demand becomes unavoidable. As the RES are typically non programmable, in order to participate to the frequency and voltage control, storage systems should be involved, together with prosumers, which are able to modify their production or demand in response to frequency and voltage deviations.

In this context, there is a clear advantage of developing a digital twin of the actual network, as this allows to verify the compliance of the resource aggregates with the specifications of the technical annexes and also their behavior and effectiveness under different conditions. An additional element to be verified is the behavior in case of failures and/or outages within the aggregates, which could reduce the regulation effectiveness.

The simulation presents an example of an electrical system consisting of a transmission grid with two connected distribution grids, loads with induced shedding (load-shedding), renewable and conventional generation plants. The transmission network, implemented at Politecnico di Torino, is shown in Figure 2. The network is based on a CIGRE benchmark and consists of twelve nodes and four generators [21].

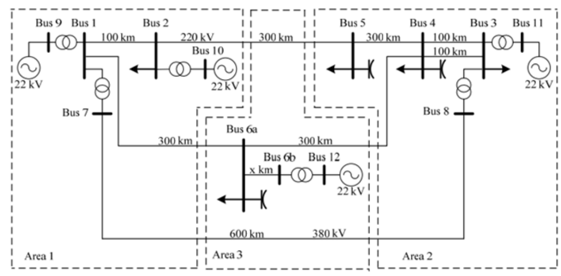

Fig. 2. Simulated transmission network

The network shown in Figure 2 was modified to emulate the decommissioning of part of the traditional generation facilities, replacing them with renewable generation (wind and photovoltaic). The following systems are connected to the transmission grid:

- Photovoltaic generation, physically installed at UniGe (Savona Campus), appropriately scaled to achieve a size of $30\,\mathrm{MW}$.
- Wind generation equipped with inertial controller, implemented and simulated at UniGe (metropolitan campus). It has a nominal power equal to $P = 260\,\mathrm{MW}$. However, the delivered power over time will not be constant, due to the variable wind profile.
- Demand-Response of PoliBa, with the size of $25\,\mathrm{MW}$. It can connect or disconnect itself from the transmission grid to automatically relieve the total load during critical events.
- Distribution network implemented at JRC-Ispra, which draws active power $P = 44\,\mathrm{MW}$ and reactive power $Q = 16\,\mathrm{Mvar}$. An automatic load shedding logic based on the frequency signal was implemented also in this case.
- Distribution network implemented at UniNa, draws active power $P = 58\,\mathrm{MW}$ and reactive power $Q = 43\,\mathrm{Mvar}$.

IV. Results

The overall electric system, simulated and implemented in a distributed way, has been tested in normal and emergency operating conditions. At first all the subsystems, which constitute the entire electric system, will be connected to the distributed simulation, in the following order: PoliTo, UniGe (Sv), JRC-Ispra, PoliBa, UniNa, UniGe (Ge).

A. Normal working conditions

Under normal conditions, small deviations from the nominal frequency are present in the transmission system. In this case, the frequency is maintained between $49.85\,\text{Hz}$ and $50.15\,\text{Hz}$ despite the standard range is $\pm 50\,\text{mHz}$. Figure 3 shows the frequency profile of the center of inertia (f_{COI}) under normal working conditions. The described frequency variation has been obtained with the Bari PHIL connected loads ($3.5\,\text{MW}$ load steps), represented in the Figure 4, and the power profile of the wind power plant simulated by UniGe (Ge).

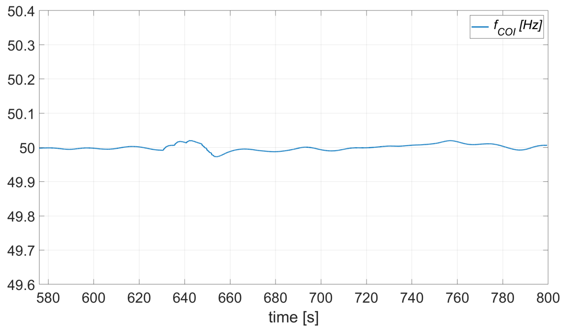

Fig. 3. Frequency profile in the inertia centre under normal conditions

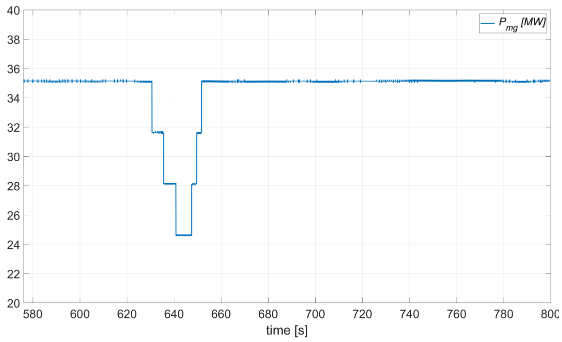

Fig. 4. power withdrawn variation in PoliBa microgrid

The test showed that the system responds adequately to small load variations load, while the frequency remains in its standard range ($50\,\text{Hz} \pm 50\,\text{mHz}$).

B. Emergency conditions

The operation of the electrical system in emergency conditions involves "large" frequency variations from the nominal value. In this setup, appropriate countermeasures must be taken to avoid system instability. In the demo, a generation loss is simulated at bus 2 of the grid in Figure 2, with a $\Delta P = 250\,\text{MW}$.Without any mitigation measures, the event would cause a frequency reduction to the value of $49.13\,\text{Hz}$, lower than the maximum allowed frequency deviation. Furthermore, without the implementation of secondary frequency

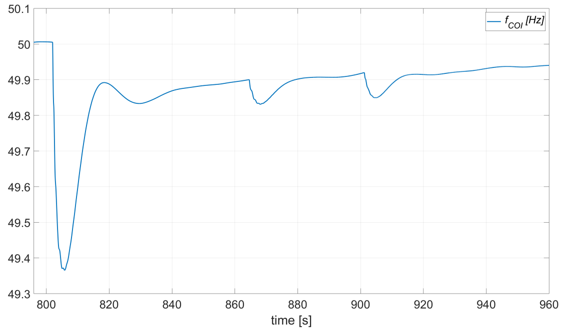

Fig. 5. Frequency profile in the inertia centre under emergency conditions.

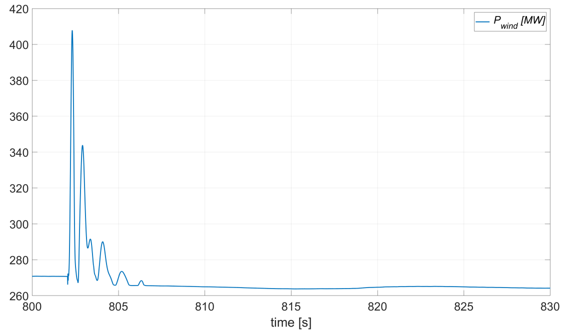

Fig. 6. Inertial control activation controlled by the centralized wind power plant in UniGe.

adjustments, the frequency would settle to a value of 49.66 Hz, again exceeding the maximum steady-state allowed deviation. For these reasons, different actions were implemented at the time of the load event:

- Inertial control by the wind power plant with storage at UniGe (Ge);
- Demand-response by the loads in the distribution network simulated in JRC-Ispra (detachment $\Delta P = 22\,\text{MW}$) and by the load installed at PoliBa ($\Delta P = 25\,\text{MW}$).

Figure 5 shows the frequency trend of the center of inertia during the test in emergency operation. The first transient, which occurred at the time of about $800\,\text{s}$, is caused by the abrupt increase of the load at node 2. Then, after the time $860\,\text{s}$, two transients are shown as a result of two successive reconnections, first by the PoliBa load and later by the load simulated in JRC-Ispra. Figure 6 shows the activation of the inertial controller of UniGe, Figure 7 shows the automatic shedding of both PoliBa load and JRC-Ispra load.

Inertial control is triggered as soon as a Rate of Change of Frequency (RoCoF) of 0.5 Hz/s is detected, while load shedding at the two locations is applied when the frequency reaches the threshold of $49.5\,\text{Hz}$. Since the network implemented at JRC-Ispra and the load at PoliBa are inserted at two separate points in the transmission network, the frequencies sent to the two locations are not exactly the same, therefore the disconnection does not occur at the exact same time. Thanks to these countermeasures, the frequency nadir reaches a value higher than $49.2\,\text{Hz}$, thus falling within the limits. To bring

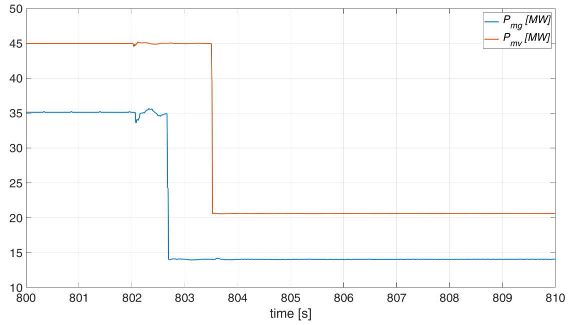

Fig. 7. Load shedding by JRC and PoliBa following the load event

the frequency back to the nominal value of 50 Hz, a secondary frequency adjustment was also implemented. The secondary frequency regulation is activated following the primary adjustment to recover the steady-state error. Re-connection of the loads in JRC-Ispra and PoliBa occurs at successive times: the load of PoliBa re-connects when the frequency reaches the value of 49.9 Hz while the load of JRC-Ispra re-connects when the frequency reaches the value of 49.92 Hz. At the end of the secondary adjustment, the frequency of the transmission system is restored to a value close to 50 Hz.

V. Concluding remarks

The paper presents the results of the first co-simulation of the ENET-RT *Lab*. The conducted test included all the typical real time experiment configurations and each partner contributed to the overall experiment with Software-, Hardware- and Power Hardware-in-the-Loop configurations.

The implementation of the platform highlighted the possibility of soft-sharing knowledge, modeling approaches, and hardware equipment. Moreover, by including an actual controller prototype, the value of the infrastructure for industrial uses was clearly demonstrated, widening the potential applications and representing a useful instrument for the growth of the Italian industry sector and the modernization of the prototyping processes.

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