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Abstract: The framework for virtual integration of laboratories enables co-simulation and joint experiments that include hardware and software resources hosted at geographically distributed laboratories. The underlying concept of such framework is geographically distributed real-time (RT) co-simulation. To this end, digital RT simulators are interfaced over long distances via shared communication network such as the Internet. This study proposes an architecture for a modular framework supporting virtual integration of laboratories that enable flexible integration of digital RT simulators across Europe. In addition, the framework includes an interface that enables access for third parties via a web browser. A co-simulation interface algorithm adopted in this study is based on representation of interface quantities in form of dynamic phasors. Time delay between RT digital simulators is compensated by means of phase shift that enables simulation fidelity for slow transients. The proposed architecture is realised for the integration of laboratories across Europe that are located at RWTH Aachen University in Germany, Politecnico di Torino in Italy and at European Commission Joint Research Centres in Petten, Netherland and in Ispra, Italy. The framework for virtual integration of laboratories presented in this study is applied for co-simulation of transmission and distribution systems.

1 Introduction

The changing paradigm of power systems imposes emerging challenges for power system design, planning and operation [1]. The paradigm shift of power systems has been reflected on modelling and simulation methods used for power system analysis as well. Simulation frameworks are urged to continuously follow growing demand for large-scale system simulation, simulation of fast system dynamics and high-fidelity models. There is a tendency toward performing joint simulation of systems that have been studied separately in the past. For instance, a joint simulation including detailed models of transmission and distribution systems is performed nowadays to analyse interdependencies and unforeseen interactions between the two systems, particularly in case of scenarios with high level of penetration of distributed generation (DG) [2]. In addition, envisioned complexity of future power systems requires simulation frameworks that enable interdisciplinary and multi-domain studies. Multi-physics simulation approach is utilised for the holistic analysis of city district energy systems that represent hybrid energy systems [3]. Studies on architectures and concepts in smart grids require a simulation framework that enables joint analysis of power system and information and communication technology system.

The requirements described above have motivated development of innovative solutions for simulation frameworks utilised for power system analysis [4]. Various co-simulation and hybrid simulation frameworks have been proposed based on custom solutions or on integration of existing tools. Advanced technologies such as high-performance computing, and specialised hardware such as field-programmable gate array are more often used for simulation of power systems compared with traditional approaches in the past.

Digital real-time simulation (DRTS) and (power) hardware-in-the-loop (PHIL) testing have rapidly increasing roles in power system research. Thus, they are urged to follow requirements for large-scale and multi-domain studies ensuring high-fidelity frameworks. Dedicated DRTS setups and specialised test benches have been deployed at various laboratories to support and accelerate the research on on-going transition of power systems. One innovative trend in DRTS and (P)HIL testing, which is studied in this work, is virtual integration of laboratory setups across long geographical distances. This concept relies on the geographically distributed RTS approach and aims at integrating geographically distributed laboratories to perform RT co-simulation and joint experiments.

The rest of this paper is organised as follows. Section 2 introduces the concept of virtual integration of laboratories across long geographical distances. It includes an overview of the main advantages and challenges as well as related literature review. An architecture of a framework for virtual integration of laboratories is proposed in Section 3. The architecture is developed for the integration of laboratories across Europe, located at RWTH Aachen University in Germany, Politecnico di Torino (PoliTO) in Italy and at European Commission Joint Research Centres in Petten, Netherland and in Ispra, Italy. The co-simulation interface algorithm (IA) that is adopted in this work is described in Section 4. An application of the framework for virtual integration of laboratories for simulation of transmission and distribution systems is included in Section 5 with obtained simulation results. Section 6 concludes this paper highlighting the main contributions followed by an outlook on future research.

2 Geographically distributed RTS of power systems

The aim of DRTS and (P)HIL is to enable design and testing of new concepts or devices in an environment that is close to reality. Distributed computing with multiple units operating in parallel is a common feature of DRTS in order to increase computing capabilities and achieve scalability [5]. In case multiple units are used for simulation of a model, the model is decoupled into multiple subsystems and conservation of energy at interfaces must be ensured as subsystems are naturally coupled in the original system. This is considered a challenge even for locally distributed

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DRTS and advanced synchronisation, data exchange and delay compensation techniques are used.

Geographically distributed DRTS refers to the concept of integrating DRTS systems located at different geographical locations for RT co-simulation. The challenge of ensuring conservation of energy between subsystems increases with longer geographical distances. Methods for delay compensation used for locally distributed DRTS typically cannot be considered for applications in geographically distributed DRTS. For instance, a method for decoupling based on travelling wave property of a transmission line would require a line of a length of ∼3000 km for delay compensation of 10 ms. In addition to the problem of large delays, in an arbitrary case it is unrealistic to assume existence of a dedicated communication medium that would provide hard RT characteristics. Thus, data exchange between subsystems in geographically distributed DRTS is characterised by time-varying delay, packet loss, packet reordering and other non-deterministic characteristics of a shared communication network such as the Internet.

Capabilities and applications of DRTS and (P)HIL concepts can be significantly enhanced in case of a geographically distributed framework for DRTS. Geographically distributed DRTS environment allows for sharing of computational resources, software and hardware assets and specific expertise available at different laboratories. This is particularly beneficial for studying modern power systems that are more interconnected and interdependent compared with traditional systems [6]. An extreme future scenario in this context is a globally interconnected grid, known as global grid [7], which includes a long high-voltage (HV) direct current line between Europe and the USA. Interconnected and interdependent systems must be designed and tested in an integrated environment to fully assess their operation and unprecedented interactions. The paradigm shift of power systems toward a sustainable, reliable and affordable system of the future has been recognised as a shared challenge that requires the involvement and alignment of academics, industries, utilities and other factors. Many initiatives address this requirement and aim at achieving a tight collaboration between different factors. In this respect, a geographically distributed DRTS environment provides a shared virtually coupled infrastructure that allows each group to work locally within its facilities but still collaborate and conduct experiments jointly, without potential confidentiality issues [8]. The described flexibility is considered as an important advantage of geographically distributed DRTS, in addition to sharing resources for large-scale and multi-domain experiments that would be difficult to achieve otherwise.

2.1 Summary of related work

One of the earliest realisations of a virtual environment for remote testing of devices in power system field has been reported in [9]. The implementation of the virtual environment was based on the virtual test bed (VTB) and a LabVIEW virtual instrument. Experiments were pursued for remote model validation and design verification with physical devices located at the Polytechnic University of Milan, Italy, and VTB-based virtual environment hosted at the University of South Carolina, USA. VTB simulation platform was further extended by a field programmable gate array-based module for coordination of simulation clocks of simulators hosted at dispersed geographical locations [10]. The module was based on a common time signal derived from the global positioning system.

Further efforts toward geographically distributed simulation have been focused on development of IAs for system decoupling [11]. Multiple University Research Initiative, supported by the Department of Defense, US, investigated the concept of virtual integration of laboratories over long distances on a larger scale with five universities involved. The work was mainly focused on all-electric ship studies. Within this context, the VTB environment was utilised for implementation and validation of IAs [12].

Geographically distributed simulation as an approach to multi-domain simulation was pursued for thermo-electric co-simulation of an all-electric ship [13]. Within this context, two different off-the-shelf simulators, RT digital simulator (RTDS) and OPAL-RT were interconnected over the distance of 3500 km.

A test bed that integrates a PHIL platform for testing of solar inverters with a large-scale distribution system simulation represents an example of a hybrid virtual interconnection of hardware and software assets over the Internet [14]. GridLAB-D, an open-source distribution modelling platform, is hosted at the Pacific Northwest National Laboratory, while PHIL setup is located at the National Renewable Energy Laboratory, which is more than 1600 km away. The two facilities exchange data over the Internet based on a custom JavaScript Object Notation (JSON) protocol with user datagram protocol (UDP) as a transport layer.

An importance of a holistic approach to design, analysis, testing and evaluation of smart grids has been described in [15]. Advanced research infrastructures, as well as their interconnections to establish laboratory clusters, play a significant role in that respect. As the role of lab-based testing increases, standardised validation procedures and benchmark criteria become more substantial to enable systematic and integrated studies of smart grids. However, flexibility and scalability of software-based simulation methods are advantageous during the initial stages of the smart grid design process. To provide better integration and smooth transition between different design stages, from basic design toward deployment, a comprehensive smart grid co-simulation framework mosaik has been coupled with OPAL-RT DRTS [16]. Furthermore, mosaik enables integration of actual devices located at remote laboratory. Therefore, framework allows for software and hardware integration that can be hosted at geographically dispersed locations.

3 Architecture of a framework for virtual integration of laboratories

In this work, we propose a framework for virtual integration of laboratories across Europe that demonstrates feasibility of such approach. A conceptual architecture diagram of the framework for federation of laboratories is illustrated in Fig. 1 and referred to as virtually interconnected laboratories for large systems simulation/emulation (VILLAS). As it is depicted in Fig. 1, VILLAS architecture enables integration of digital RT simulators, RTDS and OPAL-RT, located at dispersed geographical locations. RTDS is hosted at the facility of the Institute for Automation of Complex Power Systems (ACSs), RWTH Aachen University, Germany while OPAL-RT is located at the laboratory of Energy Department (DENERG) at PoliTO, Italy. Furthermore, two facilities of the Institute for Energy and Transport, Joint Research Centre (JRC-IET) of the European Commission, located at Petten, Netherlands and Ispra, Italy, are integrated. As illustrated in Fig. 1, JRC-IET facilities demonstrate interconnection of facilities beyond integration of RTS resources. Namely, JRC-IET in Petten provides an online input to the simulation scenario. The JRC-IET facility in Ispra provides a consolidated online monitoring of the simulation scenario based on data sets from all facilities being involved in the architecture. The laboratories are interconnected via DFN and GÉANT networks which, as part of the public Internet, are national and pan-European data networks that interconnect national research and education institutions. On top of these networks, a virtual private network (VPN) between facilities that are directly involved in the simulation scenario is established while a public server acts as a gateway to provide monitoring access from the Internet.

The following sections describe required interfaces for the framework that are laboratory-to-laboratory (lab-to-lab) and laboratory-to-cloud (lab-to-cloud) interfaces. A generic and modular design of the main component of the framework that manages lab-to-lab and lab-to-cloud interfaces at each laboratory, referred to as VILLAS node in Fig. 1, is described below in more details. In addition, results of loopback communication tests for data exchange between lab-to-lab interfaces are analysed to empirically characterise the performance of the communication link used for RT co-simulation.

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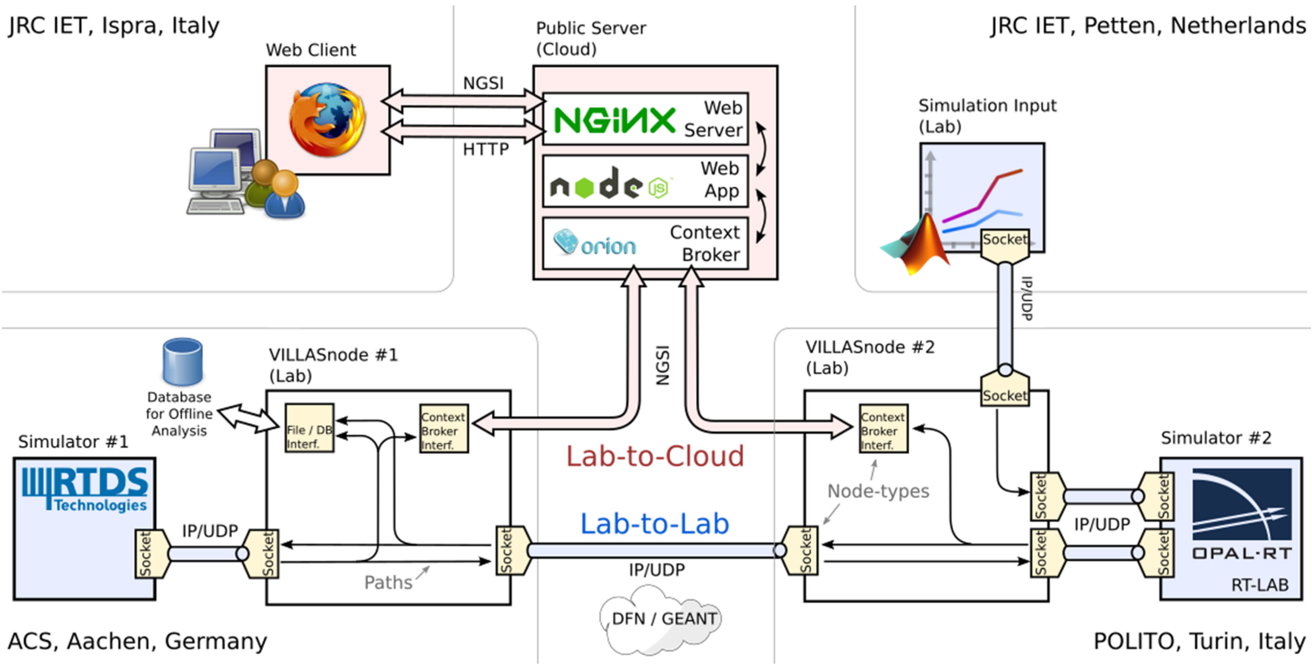

Fig. 1 *Architecture diagram of a framework for virtual integration of laboratories*

3.1 Generic and modular VILLAS node

Every facility that is integrated in the framework for virtual integration of laboratories hosts a VILLAS node as depicted in Fig. 1. VILLAS node refers to a set of interfaces and functionalities required for integration of diverse facilities into a joint architecture. In contrast to the common client/server model which is used by existing machine-to-machine protocols such as MQTT, NGSI or OPC-UA, VILLAS uses a decentral approach where there is no central omniscient broker. The gained scalability allows VILLAS to build more complex co-simulation topologies because there it avoids a central bottleneck. However, it comes at the cost of more complex control and data collection mechanisms.

VILLAS node allows interfacing one or more resources available at each laboratory by acting as a gateway between local devices and other remote instances using the lab-to-lab interface. It enables integration of the resources available at each laboratory. To leverage the framework beyond RT co-simulation application and enable flexible user interaction, VILLAS node hosts above-described lab-to-cloud interface. Generic and modular design of VILLAS node addresses challenges imposed by diversity of required interfaces with the goal to abstract this complexity with respect to simulators and other devices involved in experiment.

The underlying concept of VILLAS node is a modular design with the goal to achieve flexibility and portability among laboratories. To this end, the aim is to minimise implementation of the interfaces based on specific devices or simulators but to focus implementation of required interfaces on the VILLAS node that can be utilised in different laboratories. A generic architecture of the VILLAS node enables extension with other interfaces in the future.

VILLAS node manages multiple interfaces for data exchange between different nodes in the framework. A node refers to a physical device such as a simulator or a sensor or to any other type of functionality or a service that processes or manages simulation data. For instance, a node can be an interface to FIWARE context broker or a functionality of locally recording data to a file for post-processing. Data exchange between different nodes within VILLAS node is based on independent processes. To this end, a path represents a unidirectional pipe between nodes and might have multiple destination nodes. For instance, a simulator can act as a single source node for three destination nodes – a remote VILLAS node, FIWARE context broker and a local file. Thus, while VILLAS node supports nodes of different types, simulators and other resources require only an interface to a local VILLAS node as in example illustrated in Fig. 2. For instance, simulation data are sent to FIWARE context broker via a protocol that is not supported by simulators itself. Setup of interfaces of simulators to VILLAS nodes can be considered as static, while all complexity of the topology for different experiments and different interfaces are managed by VILLAS node. This modular concept enables complex and arbitrary co-simulation topologies within and across laboratories while providing an abstraction layer that simplifies interfacing to simulators and other devices.

VILLAS node is developed in-house by ACS using the C programming language in order to achieve the lowest latencies possible. Each instance runs on a commercial-of-the-shelf PC with an RT patched and optimised version of Linux. In the context of this work, the Linux systems handle the VPN connection to remote sites mentioned above. All clocks in this distributed system are synchronised using the network time protocol in order to enable consolidated monitoring and offline analysis by adding timestamps to the simulation data.

3.2 Lab-to-lab interface

Data exchange between the simulators for the purpose of RT co-simulation is managed by lab-to-lab interface. Lab-to-lab interface at each laboratory acts as a gateway between local simulators and handles local communication with a simulator and a remote lab-to-lab. This way, an abstraction layer between simulators is introduced which is beneficial for both security concerns but also for practical aspects. Namely, a simulator, or other assets, is equipped with a communication interface to a local lab-to-lab interface only. Complexity of interconnections of simulators of different types [13], or hardware and software assets, is handled by a generic lab-to-lab interface. Thus, in the context of multi-site federation of facilities this approach aims at enabling scalability and flexibility of interconnection of diverse assets.

Lab-to-lab interfaces exchange time-sensitive data between subsystems included in simulation. Deterministic and reliable communication between lab-to-lab interfaces is a basic requirement for RT co-simulation and integration of hardware-in-the-loop setups. However, it is not realistic to assume availability of a dedicated communication infrastructure in all cases and it is difficult to guarantee deterministic behaviour of a communication link over a shared communication network. To this end, lab-to-lab interface provides functionalities of dropping reordered and duplicated packets, buffering of packets to eliminate delay variation, adjusting rates for sending data to and from simulators and collecting statistics of the communication link. In addition, it

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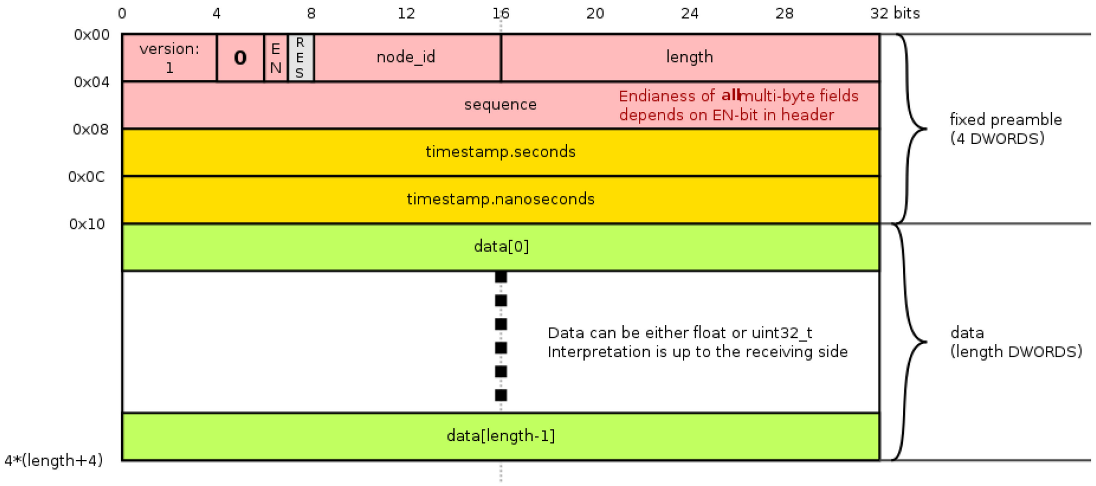

Fig. 2 *UDP packet format for simulation data*

adds a time stamp to data packets and other arbitrary operations on the forwarded data can be performed as well.

Packets are sent from each interface to the remote interface with a selected sending rate, regardless of whether packets from remote laboratory are being received. This avoids unnecessary waiting times and ensures that communication issues in one direction do not affect the reverse direction. Lab-to-lab interfaces exchange data in the form of UDP. State-less protocols such as UDP are preferred for RT applications as delay variation is lower compared with connection-oriented protocols such as TCP whose retransmission of lost packets and required acknowledgment of received packets increase latency and jitter.

Fig. 2 illustrates the binary UDP packet format which is used for the lab-to-lab interface. This custom format is designed to be lightweight and easily readable by machines in order to avoid more complex parsers which are required for human readable formats such as JSON. For Internet distributed co-simulation scenarios, this overhead is likely to be negligible. However, the same protocol can also be used for local EMT-based co-simulations between simulators in the same laboratory. In such scenarios, sending rates are around five to ten times higher and processing time has an impact.

3.3 Lab-to-cloud interface

High-level services that are available on demand during an experiment are hosted on a cloud platform that is indicated in Fig. 1 as a public server. These services refer to remote access and user interaction during an experiment as well as post-processing of simulation results or setting up tunable simulation parameters. Data exchange between laboratory and the cloud platform is managed by lab-to-cloud interface. Opposite to lab-to-lab interface, lab-to-cloud interface manages data in soft RT manner.

A public server illustrated in Fig. 1 hosts a webserver [17] running a NodeJS application and a FIWARE Orion context broker [18]. Laboratories in the framework typically act as context producers while web applications act as context consumers. Similarly, a user interaction can be enabled with a setup where a web application represents a context producer. Thus, FIWARE context broker acts as a mediator between context consumers and producers. Simulators send data to lab-to-cloud interfaces that further publish data to the context broker. A web client can request sets of data from both laboratories while visualisation service provides a consolidated overview of the simulation to a user.

Communication between VILLAS node and the context broker and between web browsers and the web server are using the OMA NGSI 10 protocol which is an HTTP REST API using JSON or extensible markup language to update or retrieve the simulation state. Owing to causal nature of the RTS data, a high number of HTTP requests is required to continuously provide updates to the web interface. In this use case, the OCB represents a bottleneck which limits the achievable update rate of the web interface. Future versions of VILLAS node replace the OCB with a new WebSocket-based interface to increase the update rate of the interface.

3.4 Evaluation of lab-to-lab data exchange

As described above, two laboratories located at universities in Aachen, Germany and Torino, Italy, are interfaced over a shared communication network for RT co-simulation application. More precisely, data exchange is performed over national research and education networks that are interconnected via high-bandwidth pan-European network. Utilisation of a communication link for co-simulation application is not considered to be data intensive as only interface quantities are exchanged between simulated subsystems. Main requirements for such link are related to delay, delay variation, packet loss and reordering that are inherent characteristics of a best-effort network where quality of service for data exchange is not guaranteed. Loopback communication tests are performed to empirically characterise the performance of data exchange between the two laboratories. Although direct control of the overall traffic in a shared network is not available, some aspects of data exchange for a particular application can influence the performance of the link. In this respect, we assessed the impact of utilisation of VPN layer, number of values included in an UDP packet and sending rate of UDP packets. The main idea is to achieve the best possible performance of the communication link under normal operating conditions.

The VPN solution selected for the virtual integration of laboratories is the open-source software Tinc. It establishes a fully meshed network of VPN tunnels between all participating nodes. In contrast to most commercial VPN products, no central server is used which avoids additional hops over the central server when routing data between more than two sites. Tinc VPN encapsulates tunnelled data in UDP packets, while TCP is only used for the control plane [19]. Fig. 3*a* illustrates probability and cumulative probability of round-trip-time (RTT) values of loopback tests for data exchange with different sending rates and different number of values in UDP packets. Comparison of results of loopback tests with and without utilisation of the VPN indicates that selected VPN layer does not influence performance significantly of the link in terms of RTT values. Obtained results are in line with performance evaluation of various VPN solutions reported in [19]. Thus, the following analyses refer to the case when VPN is used.

Results of loopback communication tests are compared with respect to different number of values included in an UDP packet for the case when VPN is utilised and illustrated in Fig. 3*b*. While average RTT values are not significantly increased, maximum values of RTT detected in performed tests is significantly increased for the case of UDP packet with 300 floating point values compared with the rest of cases. As only interface quantities should be exchanged between lab-to-lab interfaces, number of values in an UDP packet of 150 are sufficient though interface quantities are transformed in the form of time-varying Fourier coefficients including higher-order harmonics as well.

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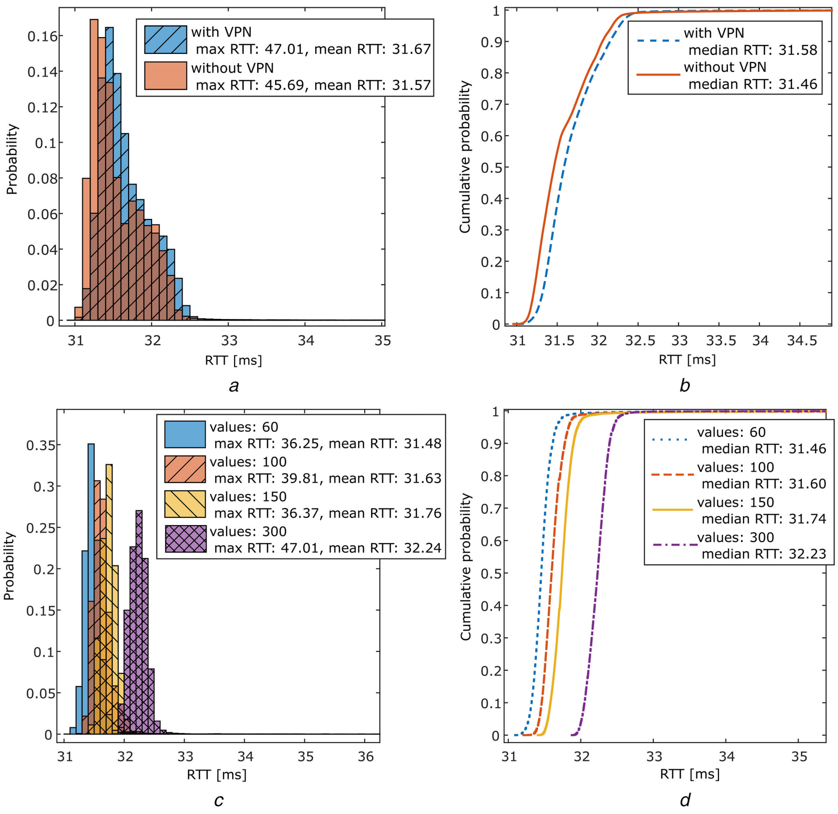

Fig. 3 *RTT results of loopback communication tests between two laboratories for data exchange of UPD packets*

(a) Sending rates: 100, 200, 300, 400, 500, 1000, 1500, 2000, 2500 and 3000 p/s with different number of values: 20, 40, 60, 80, 100, 150, 200, 250 and 300, ***(b)*** Sending rates: 100, 200, 300, 400, 500, 1000, 1500, 2000, 2500 and 3000 p/s

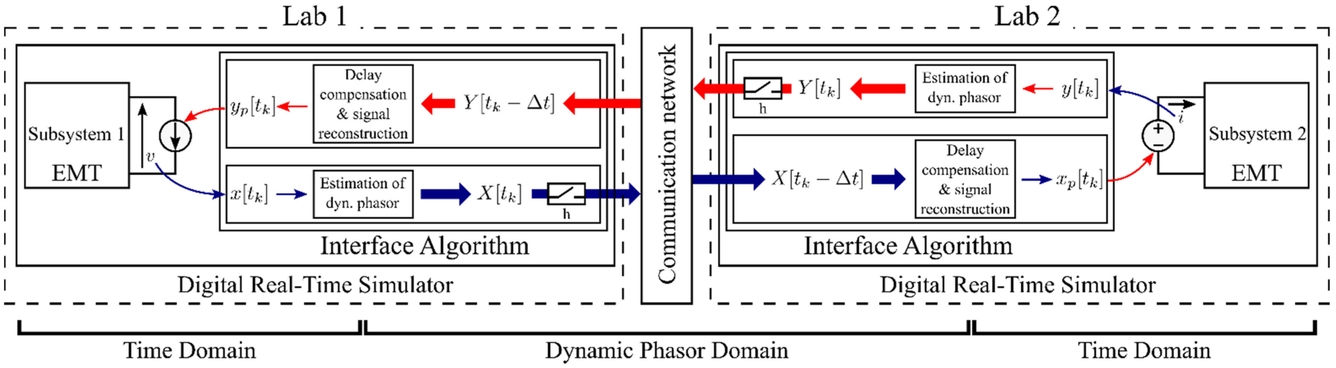

Fig. 4 *Co-simulation IA*

Different sending rates of UDP packets between two laboratories are assessed based on results of packet loss of loopback tests with different number of values included in UDP packets. Negligible packet loss is detected for sending rate lower than 2000 p/s. Typical simulation time step of 50 μs is used in electromagnetic transient simulation performed by simulators utilised in this work. However, sending rate of 2000 p/s is sufficient as estimation of time-varying Fourier coefficients of interface quantities includes time averaging and sending an update every time step might be redundant.

Empirical characterisation of the communication link between two laboratories indicate that, under normal conditions, selected VPN solution can be used for sending UDP packets with 150 floating point values with sending rate of 2000 p/s. Described settings do not significantly jeopardise performance of the available communication link. The following section introduces co-simulation IA and shows that these settings are sufficient for the application studied in this paper.

4 Co-simulation IA for geographically distributed RTS

The co-simulation IA adopted here is based on one of the most commonly employed IA for PHIL interfaces, which is the ideal transformer model (ITM) [20]. ITM IA is based on controlled current and voltage sources that impose in the local subsystem the behaviour of the remote subsystem. Therefore, ITM IA requires current and voltage interface quantities to be exchanged between the simulators. Simulators perform electromagnetic transient simulation where voltage and current quantities are represented in the form of time-domain (TD) waveforms. However, TD waveforms are significantly deteriorated when exchanged between simulators over non-deterministic communication network characterised by large delays with respect to simulation time step. To this end, voltage and current interface quantities are transformed in the form of time-varying Fourier coefficients, known as dynamic phasors (DPs) [21], before being sent to the remote simulator. Two different domains are utilised in the co-simulation setup – TD within simulators, and DP domain for co-simulation IA and data exchange. A hybrid approach to the design of co-simulation IA is illustrated in Fig. 4.

The concept of DPs extends the conventional phasor representation of system quantities to include non-stationary system conditions. This concept assumes that a TD waveform $x(t)$

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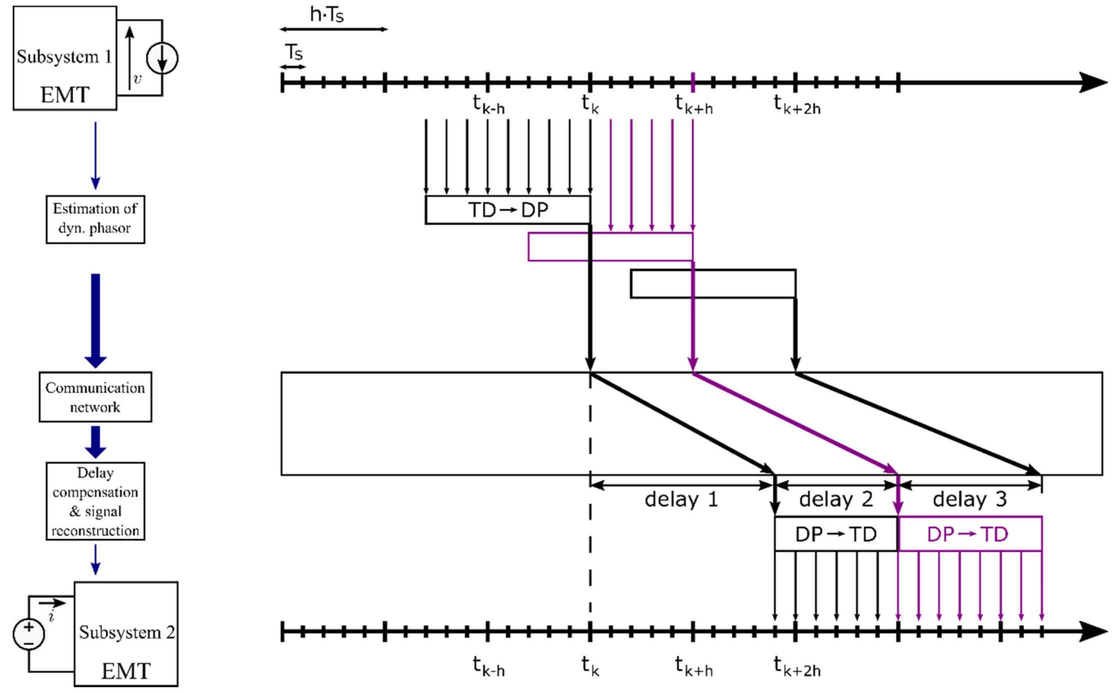

Fig. 5 *Timing diagram of the co-simulation framework (TD – time domain, DP – dynamic phasor domain)*

can be represented on the interval $t \in (\tau - T, \tau]$ based on the complex Fourier coefficients $X_k(\tau)$

$$x(t) = \sum_{k=-\infty}^{\infty} X_k(\tau) e^{jk\omega t} \tag{1}$$

where $\omega = 2\pi/T$, T represents fundamental system period. We refer to time-varying Fourier coefficients $X_k(\tau)$ as DPs. The main application of the DPs is in the context of synchronised phasor measurements that are applied in power system monitoring, protection and control [22]. Furthermore, methods for modelling and simulation of power systems based on the DP approach have been applied [21]. Advances in DP-based simulation have motivated research in the context of hybrid simulation where a subsystem is simulated by means of TD electromagnetic transient simulation while another subsystem is simulated based on DP representation [23].

This work utilises DPs for co-simulation IA, while both subsystems perform electromagnetic transient simulation based on TD waveforms. As illustrated in Fig. 4. DP is estimated based on the TD waveform of interface quantity and then sent to the remote digital RT simulator. Estimation of DPs is based here on the following discrete-time calculation that is at time instant $t = nT_s$ given by:

$$X_k(n) = \frac{1}{N} \sum_{m=n-(N-1)}^{n} x(m) e^{-jk(2\pi/N)m} \tag{2}$$

where fundamental period of the system is given by $T = NT_s$. Note that the estimation of the DP includes absolute time $t = nT_s$ that enables synchronised DPs obtained from remote simulators assuming that time clocks of the two simulators are synchronised to the global time.

The advantage of co-simulation IA based on DPs is their representation that naturally allows for compensation of time delay by means of phase shift. This approach was studied for time-delay compensation in PHIL [24]. Phase-shift-based compensation of significantly larger time delay that typically exists in geographically distributed RTS was evaluated in [25]. An interesting result of this paper was comparison of stability regions with respect to time delay of co-simulation IA based on TD waveforms and DPs. It was demonstrated that co-simulation IA with DPs provides larger stability region in some cases. Furthermore, the study demonstrated improved simulation fidelity for co-simulation interface based on DPs.

In this work, estimated DPs are sent to the remote simulator, which receives data with time delay Δt that is compensated by means of the phase shift. The phase shift requires the knowledge of time delay of a data packet which can be determined only after the packet has been received. All packets that are exchanged between simulators are time stamped which provides possibility to calculate the time delay at the receiving end of the data exchange channel.

Signal reconstruction that includes delay compensation based on the phase shift is defined based on the following:

$$x_p(n + d_n) = \sum_{k \in K} X_k(n) e^{+jk(2\pi/N)n} \underbrace{e^{+jk(2\pi/N)d_n}}_{\text{phase shift}} \tag{3}$$

where $K = [-(N/2), (N/2) - 1]$ if N is even and $K = [-(N-1/2), (N-1/2)]$ if N is odd with respect to N defined in (2). Time delay of received DPs with respect to the time instant $t = nT_s$ when the values of DPs were sent is d_n. This parameter is time varying and it is not deterministic but the method to reconstruct a sample of the TD waveform remains deterministic. This is advantageous for compensation of time-varying delays but also of packet losses. In case a packet loss has encountered, the previous values of DPs will be used with time delay for phase shift increased by T_s. Timing diagram of the described co-simulation IA is illustrated in Fig. 5.

DPs are known to provide an adequate representation of the signal based on a few coefficients which is one of the main motivations for their application for simulation of power systems. The co-simulation IA is implemented in this work within simulators and it includes a subset of DPs $K = \{0, 1, 2, 3\}$. A simple empirical case study is based on a reference signal that has been transferred through the co-simulation IA without characteristics of a communication channel. Therefore, the error is caused only due to DP estimation and signal reconstruction. The error of a reconstructed TD waveform with respect to the reference signal in cases of slow and fast transients of the reference signal was analysed. In particular, we studied steady state, amplitude modulation and signal with ramping up amplitude. DP representation provides an adequate accuracy in case of slow transients of TD waveform.

Fig. 6 illustrates steady-state condition of the reference signal followed by a slow ramp transient of a magnitude. As expected, if all components of DPs are included in the co-simulation IA the

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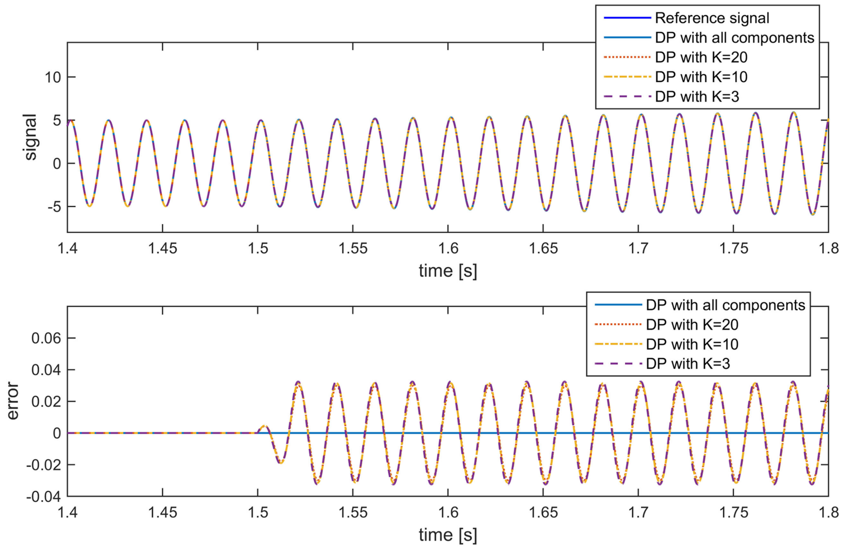

Fig. 6 *Comparison of reference signal and signal transferred through co-simulation IA with different numbers of DP components*

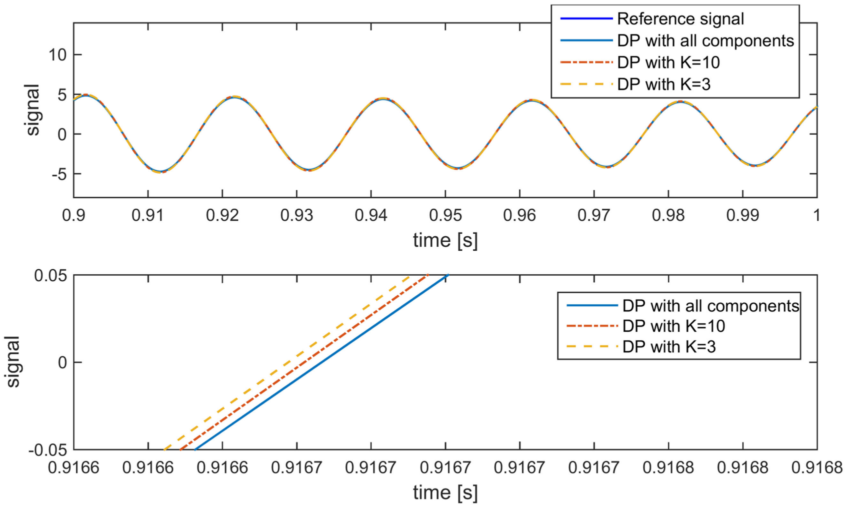

Fig. 7 *Comparison of reference signal and signal transferred through co-simulation IA with different numbers of DP components*

reconstructed signal perfectly matches with the reference signal and error is equal to zero. If limited number of components is included, the error can be observed. The error can be neglected in case of slow transients. Fig. 7 illustrates error caused by amplitude modulation transient in the reference signal. In this case, it is important to emphasise that the frequency of the reference signal is different from fundamental frequency. The role of number of components of DPs to reconstruct the reference signal is important in the context of matching frequency of reconstructed signal to the reference signal. As it can be seen in the enlarged section of this figure, larger number of DP components reduces the shift of the reconstructed signal.

The application of the described co-simulation IA in the context of communication delay is illustrated in Fig. 8. The reference signal has been transferred through communication medium with constant and time-varying delay. The waveform that has been transferred based on the proposed IA with DPs is not affected by time shift in the remote subsystem. Otherwise, in case when DPs based interface is not applied, TD waveform is shifted in time with respect to the reference signal due to time delay. Furthermore, significant improvement can be observed in case of time-varying delay. Time-varying delay does not significantly deteriorate the received signal when DPs based IA is applied. If DP-based interface is not applied, delay variations introduce dynamics that does not exist in the reference signal.

5 Experiment of a framework for virtually interconnected laboratories

In this section, we present an example of a simulation case using the demo architecture. The simulation goal is to assess how different prosumers behaviour in the distribution system would affect the electricity grid performance at both transmission and distribution levels [26].

Prosumers behaviour depends on many parameters from social factors to weather conditions but can eventually be translated to some consumption/production time-variant profiles from the grid point of view, and can consequently affect the grid operational behaviour.

5.1 Simulation scenario

The main objective of the designed scenario is to show how such a distributed simulation platform satisfies the emerging needs of large-scale multi-level power system simulations through integrating different geographically distant modules/models. This scenario relies on a distribution system where high amounts of DG are injected into the grid. The DGs in our case study are photovoltaic (PV) generators in an urban medium-voltage (MV) network. During a sunny summer day, when a considerable portion of the distribution grid consumption is being supplied by local PV generation, a drop of generation due to sudden weather change (from sunny to cloudy) coincides with a rapid increase of consumption in the daily load profile, when a large number of electric vehicles (EVs) are plugged in for charging. Consequent voltage drop in the distribution system and frequency perturbations in the transmission system can be monitored while keeping all

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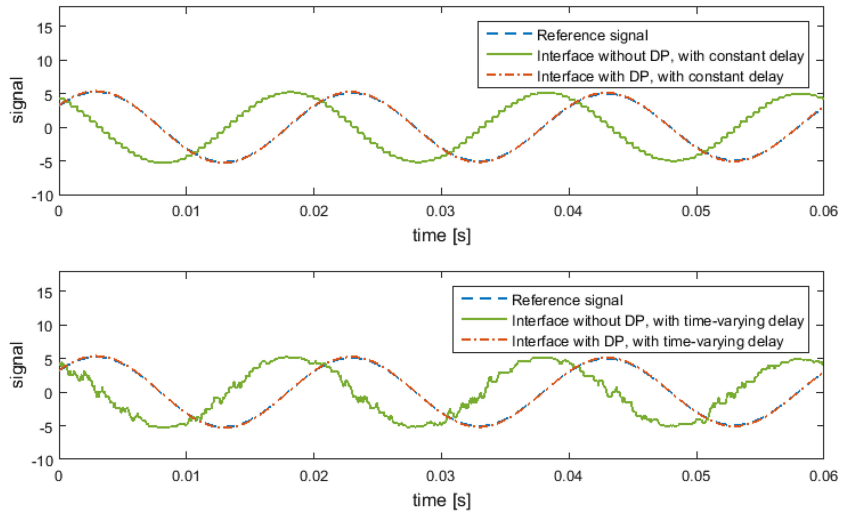

Fig. 8 *Comparison of co-simulation interface based on a TD waveform (interface without DP) and co-simulation IA based on DPs (interface with DP)*

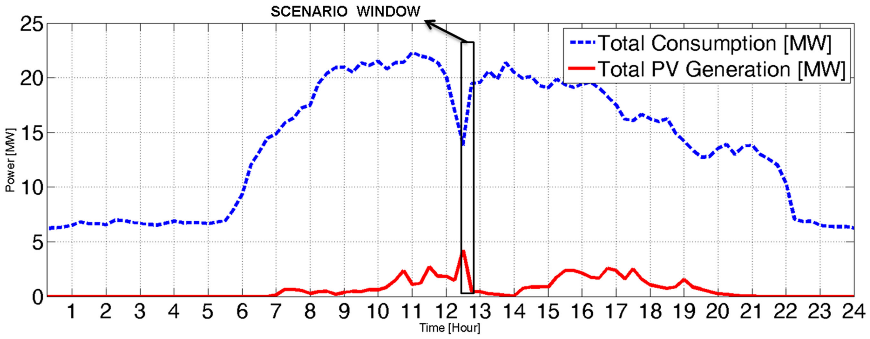

Fig. 9 *Indication of scenario window in 24 h total load/generation profiles*

modules including prosumer behaviour, transmission and distribution models geographically distributed.

5.2 Case study – transmission and distribution systems

We used a realistic case based on a portion of distribution system of Turin (1M-inhabitant city in northern Italy) and its upstream transmission system, which is a portion of Piedmont Region power system.

Table 1 Transmission network summary

number of 380 kV buses	26
number of 220 kV buses	60
number of generators	20
number of lines	110
number of loads	54
maximum total active capacity, MW	8458
maximum total reactive capacity, Mvar	4338

Table 2 Distribution network summary

HV/MV transformers	3 (220/22 kV, 2 × 63 MVA + 1 × 55 MVA)
number of MV feeders	5
number of MV buses	49
number of lines	49
total length of lines, km	38.54
number of MV/LV transformers	40
number of LV customers	742 mono phase and 8293 three phase
total contractual load, MW	37.056
number of equivalent LV models	40
number of MV customers	6

The transmission grid consists of 86 buses, 110 lines, 20 generators and 54 equivalent loads for the MV substations. This HV grid is interconnected with the MV network through an HV/MV substation, where the data exchange takes place between the two RT simulators.

The transmission system is modelled and simulated at ACS laboratory on a RTDS. Table 1 provides a summary of the transmission system. Four racks of RTDS are utilised to execute the modelled system with 50 µs time step.

The portion of the MV network consists of a primary substation with three 220/22 kV transformers. A summary of the network specifications is provided in Table 2. This grid is modelled and simulated on the RT simulator at Department of Energy of PoliTO (Italy). The simulator is an OPAL machine with 12 cores operating at 3.46 GHz. Four cores are used to execute the modelled distribution system with 50 µs time step for an electromagnetic transient analysis.

The behaviour of the prosumers in the distribution grid is generated as load and production profiles in the third laboratory (located in JRC – Petten, Netherlands), which periodically controls loads and PV models in the distribution system (Fig. 9).

A monitoring system in the fourth laboratory in JRC-Ispra supervises and monitors the data exchange and simulation performance through a developed cloud system.

5.3 RT co-simulation of transmission and distribution systems

The described setup demonstrates two substantial benefits of the geographically distributed virtual environment. First, the issue of large-scale simulation is addressed by leveraging resources from multiple facilities. This refers not only to sharing of computational resources but also to benefits of a joint effort for implementation and validation of detailed models for simulation of transmission and distribution systems.

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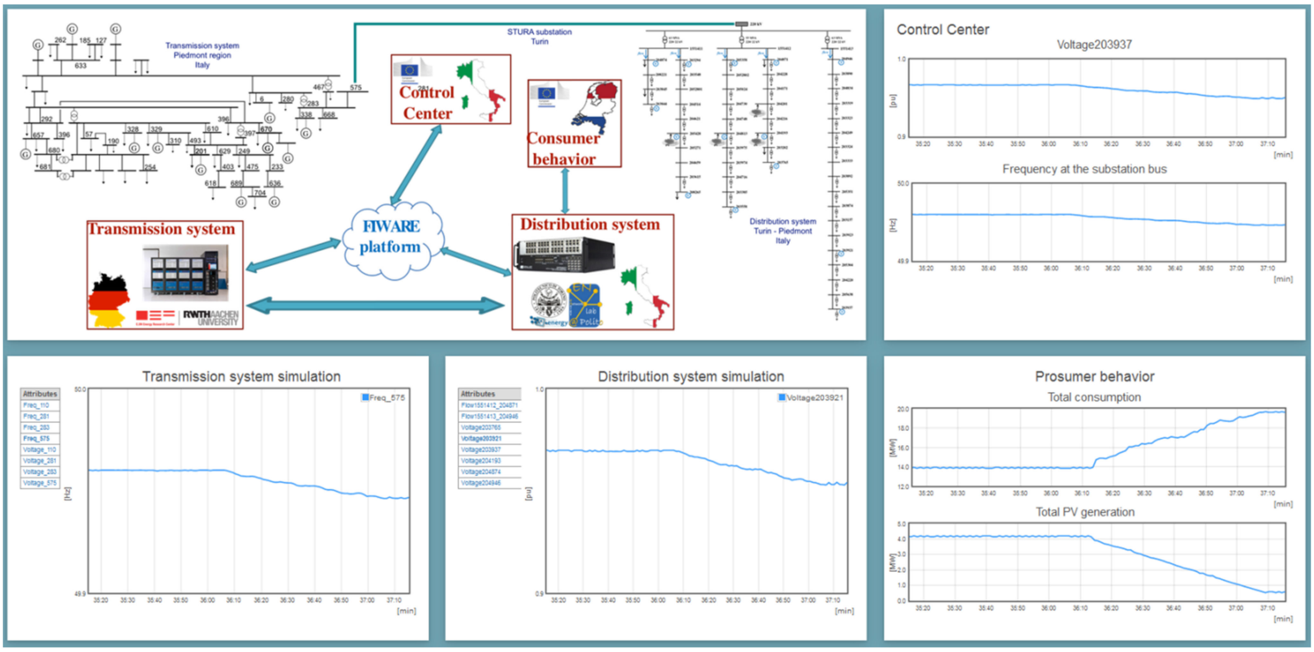

Fig. 10 *Visualisation of transmission-distribution co-simulation based on a web application*

Second, the data exchange between TS and DS is performed by transferring currents and voltages at the transformer: interface quantities at the decoupling point. Exchanging only interface quantities is particularly beneficial for a realistic situation in which confidentiality aspects of sharing data and models among operators might represent an obstacle for performing integrated studies. Thus, a significant value of the proposed concept of virtual integration of laboratories is flexibility for collaboration in the context of system level and wide area studies, required to evaluate interoperability and identify possible unacceptable interactions.

In particular, this is beneficial for studies on how different levels of DG, EV penetration and consumer behaviour patterns in the distribution system would affect the system operation at both transmission and distribution levels. To this aim, we assessed transmission and distribution system operation under extreme consumer/prosumer behaviour at the distribution level.

In our example, we mainly focus on the balancing challenges from PV generators as one of commonly used non-programmable renewable energies in Italy. There are four PV generators in the portion of MV grid we studied. On the basis of the designed scenario, sudden drop of generation due to cloud cover coincides with the time consumption is increasing from more appliances utilisation and EVs plugging. The coincident results in a rapid increase of local total consumption (Fig. 9), while in normal operation, consumption changes have slow transients.

5.4 Simulation results and discussion

A web application-based monitoring, illustrated in Fig. 10, serves for visualisation of the online simulation data retrieved from both distribution and transmission systems. This kind of overview can be used either by a supervisory and monitoring party, or by any of the partner laboratories, that has only access to his local system. Moreover, exploiting this system would limit consolidated monitoring to a specific set of data in case of confidentiality issues.

Voltage drop in the farthest distribution substations from primary HV/MV transformers or generation buses and frequency drop due to power imbalance in the transmission system were selected as two examples to display results. These two parameters are selected from the web application, which was developed for overall system monitoring: voltage of one of MV feeders' terminals, and system frequency at the transmission level. Monitoring of distribution system simulation in Fig. 11 represents voltage drop at the end of a feeder during the described scenario event. Monitoring of transmission system simulation is shown in Fig. 11 with a frequency measurement at one of the neighbouring buses to the substation where distribution system is connected. The rotating inertia of the large conventional generators significantly reduces fluctuations caused by this kind of scenarios; nevertheless, high penetration of PV generators in most of neighbouring distribution grids could eventually have a significant impact on the transmission grid.

As shown in Fig. 11 that is captured from the web application, the user can select from a set of measurements for monitoring and analysis.

6 Conclusion

This paper has presented a framework for virtual integration of laboratories across Europe for RT co-simulation. An architecture of the framework was designed with the goal of enabling flexible integration of off-the-shelf RT digital simulators. Laboratories are interfaced over a high-bandwidth national research and education networks interconnected with the pan-European network while data exchange is based on UDP protocol. The communication link utilised for RT co-simulation is characterised empirically based on loopback communication tests. Obtained results demonstrated that selected VPN solution does not significantly decrease performance of the available link and provided recommendations for sending rate of UDP packets and number of values included. Co-simulation IA based on representation of interface quantities in the form of time-varying Fourier coefficients; otherwise, known as DPs was presented. It enables compensation of delay by means of phase shift that is performed on the receiving end of the co-simulation interface. A simple evaluation demonstrated that this approach is particularly beneficial for compensation of time-varying delays. The framework for virtual integration of laboratories is applied for co-simulation of transmission and distribution systems demonstrating the benefits of geographically distributed simulation for large-scale simulations. Satisfactory performance of the presented framework is obtained for simulation of slower voltage and frequency transients that are observed in the simulation scenario selected in this work. Namely, the scenario is focused on frequency and voltage deviations that are caused by change in PV generation following the perturbations in weather conditions with simultaneous increase of total power consumption.

7 Acknowledgments

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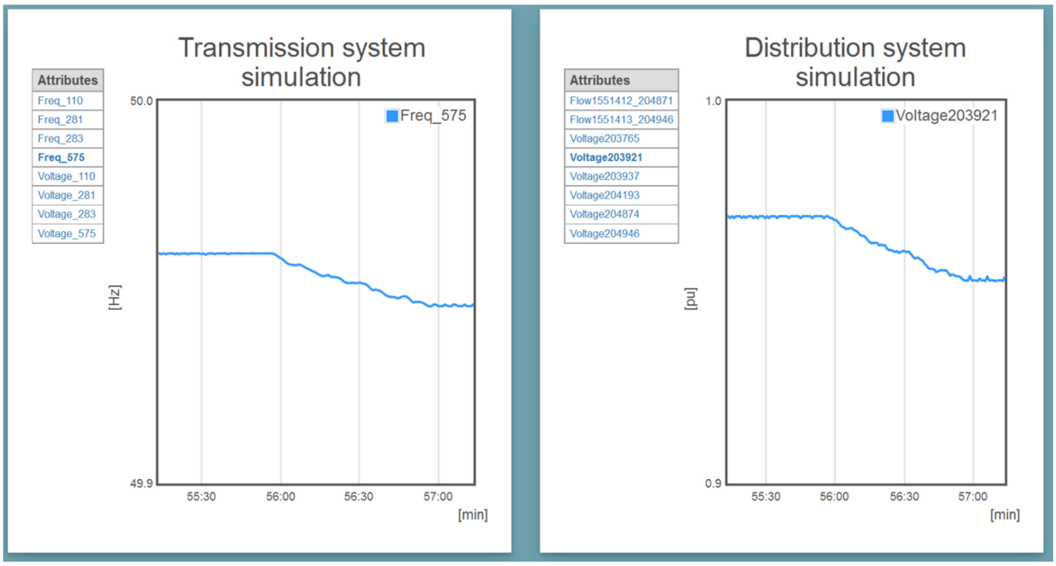

Fig. 11 *Monitoring of transmission system simulation (frequency measurement) and distribution system simulation (root-mean-square voltage at the end of the feeder)*

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