Green Open Access added to TU Delft Institutional Repository

'You share, we take care!' - Taverne project

https://www.openaccess.nl/en/you-share-we-take-care

Otherwise as indicated in the copyright section: the publisher is the copyright holder of this work and the author uses the Dutch legislation to make this work public.
Stability and Accuracy Analysis of a Real-time Co-simulation Infrastructure

Luca Barbierato*, Enrico Pons*, Andrea Mazza*, Ettore Francesco Bompard*, Vetrivel Subramaniam Rajkumar†, Peter Palensky*, Enrico Macii*, Lorenzo Bottaccioli* and Edoardo Patti*

*Energy Center Lab, Politecnico di Torino, Turin, Italy. Email: name.surname@polito.it
†Delft University of Technology, Delft, The Netherlands. Email: n.surname@tudelft.nl

Abstract—Co-simulation techniques are gaining popularity amongst the power system research community to analyse future scalable Smart Grid solutions. However, complications such as multiple communication protocols, uncertainty in latencies are holding-up the widespread usage of these techniques for power system analysis. These issues are even further exacerbated when applied to Digital Real-Time Simulations (DRTS) with strict real-time constraints for Power Hardware-In-the-Loop (PHIL) tests. In this paper, we thoroughly test and demonstrate an innovative co-simulation infrastructure that allows to interconnect different DRTS through the Aurora 8B/10B protocol to reduce the effects of communication latency and respect real-time constraints. The Ideal Transformer Method Interface Algorithm (ITM IA), commonly used in PHIL applications, is used to interface the DRTS. Finally, we present time-domain and frequency-domain accuracy analyses on the obtained experimental results to demonstrate the potential of the proposed infrastructure.


I. INTRODUCTION

In the last few years, robust research effort has been undertaken in computer-aided power system analysis for designing, developing, and testing future Smart Grids. Different domain-specific software simulation tools have been developed to emulate innovative functionalities and/or specific components of innovative power networks with high precision and accuracy [1]. In particular, time-domain modelling is crucial in the planning, design, and operation of modern power transmission systems. Owing to the limits of pure software-based simulations, rising interest in testing real-world hardware for commercial Digital Real-Time Simulators (DRTS) is the significant computational resources required for the solution of detailed EMT models, thereby limiting the size of the AC system that can be accurately simulated [6]. In fact, a growing effort of the power system research community is concentrating on combining two or more DRTS, exploiting novel methodologies, communication protocols and standards [7], such as co-simulation techniques. Such techniques allow splitting the power system under analysis into sub-networks, each one executed on a DRTS, exploiting high-bandwidth communication channel (e.g. IEEE 802.3) to exchange interface voltages and currents between each other. However, such interconnections could lead to numerical instability and accuracy issues due to communication latency among DRTS like in the case of PHIL.

The main difficulty for commercial Digital Real-Time Simulators (DRTS) is the significant computational resources required for the solution of detailed EMT models, thereby limiting the size of the AC system that can be accurately simulated [6]. In fact, a growing effort of the power system research community is concentrating on combining two or more DRTS, exploiting novel methodologies, communication protocols and standards [7], such as co-simulation techniques. Such techniques allow splitting the power system under analysis into sub-networks, each one executed on a DRTS, exploiting high-bandwidth communication channel (e.g. IEEE 802.3) to exchange interface voltages and currents between each other. However, such interconnections could lead to numerical instability and accuracy issues due to communication latency among DRTS like in the case of PHIL.

In this paper, we present a frequency-domain stability and time-domain accuracy analysis of the point-to-point interconnection of two DRTS (i.e. RTDS Technologies NovaCor). This architecture aims at extending the scalability of the Power System Under Test (PSUT) by splitting it on different DRTS that exchange data through communication protocols. The communication protocol used is Aurora 8B/10B. The key contributions of this paper are as follows: first, the communication latency between the two DRTS is analyzed; then, the PHIL IA is applied for splitting a simple power system test circuit across the two DRTS and a theoretical study is carried out to assess its frequency-domain stability constraints; finally, the calculated latency and theoretical results are exploited to test the co-simulation solution.
II. RELATED WORKS

Time-domain analysis (e.g. EMT) of large AC power systems requires significant computational power to reduce the simulation time-step, enlarge network sizes, and accurately capture the fast transients. For EMT analysis, a widely accepted and well used pure software solution is Electromagnetic Transients Program (EMTP) [8] that implements Dommel algorithm for the network solution. The requirements for real-time simulation, however, make it necessary to exploit a parallel computing architecture. Different works analysed multi Digital Signal Processors (multi-DSP) [9]–[11], multi Reduced Instruction Set Computers (multi-RISC) [12], PC-cluster architectures [13], [14] and FPGA solutions. For instance, Chen et al. [15] present a FPGA-based real-time EMTP simulator based on a deeply pipelined paralleled Dommel algorithm.

In the last decades, different commercial real-time power network simulators have gained the interest of power system designers to address real-time constraint and apply PHIL testing. The most important DRTS producers for power system analysis are RTDS Technology, and Opal-RT. In particular, RTDS Technology proposes the NovaCor chassis, a POWER8 RISC 10-core architecture, capable of continuous real-time EMT. Different plug-and-play external boards enable Digital I/O, Analogue I/O and standard communication protocols for power systems (e.g. PMU, GOOSE, SV, MODBUS, etc.) according to Standards IEEE C37.118 [16] and IEC 61850 [17], widening its scope of application. However, RTDS suffers a limited number of nodes that restricts the scalability of the PSUT. Different works have proposed to relax the complexity of the simulation of some parts of the power network in analysis and scale up the PSUT, so called Multi-rate approach [18]. Multi-rate approach proposes to define different time resolutions for different areas of the PSUT but still the scalability is limited.

To cope with such a limitation, the power system research community starts proposing to interconnect together different DRTS exploiting fast high-bandwidth telecommunication protocols (e.g. TCP and UDP). But even with these optimistic premises, DRTS interconnection suffers a series of inaccuracies due to time latencies, jitter, limited bandwidth, and network interface management of the communication link. These inaccuracies could affect stability of a PSUT co-simulation as in PHIL systems when trying to interconnect a DUT to a simulated ROS.

In [19], Ren et al. present the PHIL instability problem highlighting the importance of checking the closed-loop stability and improving it through a particular Interface Algorithm (IA). In [5], the most interesting IAs are compared together: i) Ideal Transformer Model (ITM) and its variants [20]–[22], and ii) Damping Impedance Method with different estimation algorithms of the damping impedance [23], [24]. The outcome of this comparison highlights that ITM is the straightforward and the simplest IA to implement PHIL application.

So, the common thread of the proposed analysis is inspired from theory of PHIL application. The novelty of this paper is the application of the ITM IA to a DRTS co-simulation infrastructure. Exploiting ITM IA, we could obtain the decoupled PSUT numerical solution. This is demonstrated by following the Nyquist principles of frequency-domain analysis commonly used in PHIL context to determine the stability of IAs. Furthermore, the application of the fastest communication protocol ensure the lowest communication latency, ensuring the lowest non linear effect on the PSUT numerical solution originated by the ITM IA application. The proposed frequency-domain and time-domain analysis fund the basis for the application of co-simulation infrastructure in power system analysis.

III. METHODOLOGY

Co-simulation is a flexible approach to integrate different domain specific simulators together in a shared and distributed simulation environment. Following this paradigm, a complex scenario is decomposed in a system of systems topology in which each node (i.e. subsystem) is simulated by a different simulator engine (or solver). This decomposition allows to choose among a set of domain specific simulation tools to find the best solution that enhance numerical calculation and boost computational time of a single subsystem. For instance, DRTS is a plus to fulfil a Smart Grid simulation in a distributed co-simulation infrastructure.

The co-simulation approach must preserve high efficiency and accuracy in each single subsystem simulation. Furthermore, the complex dynamic system of systems simulation obtained by coupling different simulators may not cause instabilities and inaccuracies. The main challenges in this regards are Time Synchronization and Regulation, and Communication.

Time Synchronisation is mandatory when the distributed co-simulation infrastructure interacts in a time-dependent manner. It refers to the algorithm used to ensure temporally correct ordering among events generated by various simulators. Time Regulation instead refers to the need of instituting a policy to regulate how individual simulators evolve time. For instance, a particular simulator could be leader of the distributed environment (i.e. time-regulating), some others could be follower (i.e. time-constrained). Depending on the application, a policy must be created using a correct time regulation scheme for the simulators involved, which can have a major impact on performance and correctness of the distributed co-simulation environment.

Time Synchronisation and Regulation issue could be neglected choosing the right time regulation schema and synchronising the starting point of each subsystem simulation. In the real-time world, each DRTS normally manages time evolution independently to fulfil its real-time constraint and cannot be controlled from an external source. So, the best time regulation schema is setting all node as time-regulating ones. The evolution in time is ensured by considering each DRTS independent by each other and following the same wall clock time. Synchronisation instead is important to run specific PSUT that require precise phase relationships among
Fig. 1: Distributed RTDS co-simulation infrastructure (a) exploiting an Aurora link and (b) its virtual implementation.

As depicted in Figure 1b, a single rack has been used, creating an echo link, to avoid complex time regulation and synchronisation schema. The RTDS interconnection could be virtually deployed on a single rack exploiting Aurora protocol between two different SFP transceiver ports (i.e. 23, 24). To avoid conflict with the sequence number blocking setting, each Aurora block must be assigned to a different processor (i.e. 1, 2).

B. Ideal Transformer Model IA

Communication latency is normally experienced in PHIL application with similar effects to co-simulation application. In the PHIL context, a monolithic electric system (see Figure 2a) is split into a real hardware DUT, and a simulated ROS. However, the splitting is not ideal because the power interface (i.e. power amplifier) and the sensors to retrieve real measure-
ments between the ROS and the DUT may experience delays and errors (e.g. offset, harmonics distortion, nonlinearities, etc.). Specific techniques must be applied to ensure stability and accuracy of the overall PHIL system, so called Interface Algorithm (IA).

In particular, the Ideal Transformer Method (ITM) described in Figure 2b is the simplest way to set-up a PHIL system. ITM exploits a controlled voltage generator in the right part of the circuit (the power amplifier in the PHIL setup) that reproduces the voltage $v_A$ measured in the left part (i.e. $v'_A$), and a current generator in the left part of the circuit to reproduce the current $i_B$ measured in the right part on the hardware DUT (i.e. $i'_B$). Moreover, it applies a latency that is proportional to the latency experienced by the exchanged variable from ROS to DUT to take effect on the DUT circuit (i.e. $T_{D_1}$) and vice versa (i.e. $T_{D_2}$).

The ITM circuit described in Figure 2b has been reproduced in RSCAD software. The sinusoidal voltage source $u_1$ in RSCAD software. The sinusoidal voltage source $u_1$ has been configured with a voltage magnitude of 100 kV and a frequency of 50 Hz. Moreover, the pure resistive impedance $Z_A$ has been fixed to 50 Ω. A metering point $v_A$ is imported into the network solution core $A$ and a current $i_B$ is sent to ensure stability. As depicted in Figure 4, the ratio $Z_A/Z_B$ must be minor than 1 to ensure the Nyquist criterion. Also in case stability is ensured by this criterion, a large latency $T_{D_1} + T_{D_2}$ could provoke nonlinearities (i.e. phase shift) that impact both frequency-domain and time-domain accuracy of the overall system.

$$G_{ol} = \frac{Z_A}{Z_B}e^{-s(T_{D_1} + T_{D_2})}$$

The ITM IA can be applied also in DRTS interconnection. In particular, the ITM IA has been applied in the RSCAD model, exploiting an Aurora link between RTDS NovaCor SFP port 23 and 24, for the implementation of the co-simulation infrastructure proposed in Figure 1b. In fact, the novelty of this paper is the application of the ITM IA algorithm in DRTS interconnection and the study of stability and accuracy of the co-simulated PSUT.

IV. ANALYSIS OF NUMERICAL STABILITY AND ACCURACY

In the following Section, two different experiments are described: i) Communication Latency Calculation, and ii) ITM IA application. Afterwards, both time-domain and frequency-domain analyses are conducted over the results obtained by the ITM IA application.

A. Communication Latency Calculation

The communication latency calculation has been carried out exchanging a reference clock through the Aurora link to calculate the difference with the receiving simulation time. The reference clock has been sent from 2 to 128 times for each simulation time step, that are the minimum and maximum values allowed to be exchanged following the specification of the RSCAD Aurora block. This set up has been repeated for different time step duration $T_{Sim}$ from 5 μs to 500 μs.

Latency results 0 for all $T_{Sim}$ values and all number of variables exchanged since the reference clock is a control variable and does not requires to be exchanged with the network solution cores. These results confirm the set-up of the co-simulation infrastructure described in Section III-A.

B. ITM IA Application

The ITM circuit described in Figure 2b has been reproduced in RSCAD software. The sinusoidal voltage source $u_1$ has been configured with a voltage magnitude of 100 kV peak and a frequency of 50 Hz. Moreover, the pure resistive impedance $Z_A$ has been fixed to 50 Ω. A metering point $v_A$ is set to retrieve the voltage and will allow to export the network variable to the control core. This operation will take $1/T_{Sim}$. For each timestep, the exported control variable $v_A$ is sent through the Aurora link on port 23 and received by the control core on the port 24. As previously demonstrated by the test in Section IV-A, this operation takes no timestep. The control variable received $v'_A$ is imported into the network solution core.
The case quantitative time-domain accuracy of the numerical solution.

obtained for the worst case scenario, that is when $T_s$ accuracy results. The results presented in the next sections are that applying a electric circuit in Figure 2a has been run simultaneously to lithic electric circuit solution for both $C$. Time-domain Accuracy Analysis

and forces the controlled voltage source to generate $v_A$. This operation will take $2T_{Sim}$. The total latency for sending $v_A$ to the right part of the circuit is therefore $3T_{Sim}$.

In the right circuit, $Z_B$ is set to two different values, respectively i) 50.5Ω to test the ITM near the instability region, and ii) 500Ω to present a stable ITM IA application. The current $i_B$ flowing into the impedance $Z_B$ is then exported to the control core, sent through Aurora from port 24 to port 23, and then applied to the controlled current source to generate $i'_B$. As the controlled current source requires only $1T_{Sim}$ to fulfil the operation of exchanging the received Aurora variable from the control core to the network variable $i'_B$, this operation takes in total $2T_{Sim}$. So, the complete round-trip latency results in $5T_{Sim}$.

The timestep duration $T_{Sim}$ has been changed from 50μs to 500μs to run different tests and analyse voltages $v_A, v_B$ and currents $i_A, i_B$ for the two $Z_B$ values. The monolithic electric circuit in Figure 2a has been run simultaneously to the ITM case in order to retrieve the correct voltages and currents, namely $v_A^{real}$ and $i_A^{real}$. The test results demonstrate that applying a $T_{Sim}$ lower than 500μs ensures good time-accuracy results. The results presented in the next sections are obtained for the worst case scenario, that is when $T_{Sim}$ is set to 500μs. The results are presented only for voltages to avoid repetition, as the power factor of a pure resistive circuit is 1 and currents and voltages are in phase.

C. Time-domain Accuracy Analysis

Results of ITM IA voltages are compared with the monolithic electric circuit solution for both $Z_B$ values to assess a quantitative time-domain accuracy of the numerical solution. The case $Z_B = 500$ Ω is presented in Figure 5a. $v_A$ (green line) is overlaying $v_A^{real}$ (blue line) confirming that the calculation in both cases are comparable with a 2.28% rise of the $v_A$ voltage peak due to the latency experienced by $i_B$ to be reflected on the left part of the ITM circuit. $v_B$ (orange line) instead correctly presents a latency of 1500μs that is equal to 3$T_{Sim}$. Also $v_B$ experiences a rise in respect to $v_A^{real}$ following $v_A$ trend.

The case $Z_B = 50.5$ Ω in Figure 5b instead presents major voltage distortion. In fact, $v_A$ presents a distortion transient that is a direct effect of the phase shift due to the round trip latency of the ITM application, equal to 5$T_{Sim}$, and also of the magnitude of $Z_A/Z_B$ equal to 0.9999. The initial peak of the distortion exceeds the 40% in respect to $v_A^{real}$. $v_B$ clearly follows the same $v_A$ trend with a latency of 1500μs that is equal to 3$T_{Sim}$. Moreover, the distortion transient presented in Figure 6 gets absorbed in 0.4s stabilising the result with an 7.92% rise in respect to the voltage arise of the case $Z_B = 500$ Ω. Furthermore, a distortion can be appreciated due the effect of the phase shift generated by the identified latency.

D. Frequency-domain Accuracy Analysis

The frequency-domain accuracy analysis is obtained applying the Welch’s method for the Power Spectral Density (PSD) estimation to obtain a frequency description of the voltage signals for both $Z_B$ values. For $Z_B = 500$ Ω, $v_A$ PSD is overlaying the $v_A^{real}$ peak at $f = 50$ Hz, that is the power supply frequency. Thus, the frequency content representation of the sine is correctly replicated as depicted in Figure 7a.
The case $Z_B = 50.5 \, \Omega$ instead presents three different frequency peaks at $f = 200$, $600$ and $1000$ Hz as well as the former peak at $f = 50$ Hz. The phase shift time-domain effect is similar to a triangle wave trend. A triangle wave can be approximated in time-domain with additive synthesis, summing odd harmonics of the fundamental sine wave of frequency $f_\Delta$ while multiplying every other odd harmonic by $-1$ and multiplying the amplitude of the harmonics by one over the square of their mode number $n$ as described in Equation 2:

$$x_{\text{triangle}}(t) = \frac{8}{\pi^2} \sum_{n=0}^{N-1} (-1)^n n^{-2} \sin(2\pi f_\Delta n t)$$

As for each $5T_{Sim}$ the phase shift time-domain effect changes signs, we can consider the fundamental sine wave period of the generated triangle wave $T_\Delta$ twice the round trip latency, resulting $10T_{Sim}$. The fundamental frequency $f_\Delta$ is equal to the inverse of the period $T_\Delta$, as $T_\Delta$ is equal to $10T_{Sim}$, the fundamental frequency $f_\Delta$ is equal to $200$ Hz, confirming the empirical results. Consequently, the frequencies of the odd harmonics are $600$ Hz, $1000$ Hz, and so on. This effect can be noticed clearly also for $Z_B = 500 \, \Omega$ but is mitigated by the magnitude of $Z_A/Z_B$ equal to $0.1$.

V. CONCLUSION

A stability and accuracy analysis of the infrastructure proposed to interconnect DRTS for co-simulation was presented. Similarly to what happens in a PHIL set-up, the application of the ITM IA to DRTS interconnection ensures stability and accuracy of the numerical solution of a PSUT with the constraint: $Z_A/Z_B << 1$. The adoption of the Aurora protocol for communication helps reducing the latency and therefore improving stability and accuracy. A worst case scenario with a simulation time step of $500 \, \mu$s has been analysed to assess the time-domain accuracy of the solution in both stability and near the instability regions. The ITM IA application ensures in both cases an acceptable accuracy in reproducing the behaviour of the monolithic electric circuit. As EMT analysis commonly uses smaller time steps, around $50 \, \mu$s, we can assume that we can exploit the ITM in DRTS interconnection to ensure the numerical stability. Moreover, a smaller time step also allows for a relaxation of the constraint related to the impedance ratio, making it possible to operate with $Z_A/Z_B \approx 1$. In order to avoid synchronisation issues, the interconnection was tested on a single DRTS with an echo link. Future work will involve interconnecting different types of DRTS in order to expand the computational capabilities of individual laboratories.

REFERENCES


