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Empirical Study of Simulation Fidelity in Geographically Distributed Real-Time Simulations

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***Abstract*—Interconnection of digital real-time simulators over wide-area communication networks is an innovative approach to extend local real-time simulation capabilities to enable large-scale simulations. Furthermore, it allows the integration of geographically distributed assets as Power Hardware-in-the-Loop and Controller Hardware-in-the-Loop, thus providing a flexible framework for performing unique research experiments. In most cases, it is not possible to perform large scale real-time simulations and comprehensive experiments locally due to lack of simulation capacity and unavailability of unique assets. Main challenge associated with geographically distributed real-time simulation is to ensure simulation fidelity of the same degree as in the case when the entire simulation is performed at the same location. Simulation fidelity in geographically distributed real-time simulation is investigated and an empirical characterization is provided in this paper. Fidelity degradation caused by different values of time delay and sending rate of data exchange between two digital real-time simulators is presented. Two methods for representation of interface quantities in co-simulation interface algorithms are considered for performing simulations. The first method is based on representation of interface quantities as root mean square of magnitude, frequency, and phase angle of the current and voltage waveforms. The second method utilizes representation of interface quantities in form of time-varying Fourier coefficients, known as dynamic phasors. The empirical study is performed for transmission-distribution co-simulation using two racks of Real-Time Digital Simulator (RTDS®).**

I. Introduction

Power systems around the world are undergoing fundamental transition on its pathway towards a sustainable, reliable, and affordable system of the future. In this context, Real-Time Simulation (RTS) plays a significant role in academic research and for industrial applications to assess and understand such transitions in power systems [1]. Applications range from fully digital real-time simulation, such as model-in-the-loop and software-in-the-loop simulation, to Controller Hardware-in-the-Loop (CHIL) and Power Hardware-in-the-Loop (PHIL) testing. To address the requirements of large-scale simulation and to allow for interconnection of CHIL and PHIL setups, the concept of geographically distributed RTS (GD-RTS) was proposed [2]. GD-RTS refers to interconnection of Digital Real-Time (DRT) simulators hosted at geographically distributed laboratories via wide-area communication network, typically the Internet. The model to be studied is distributed into multiple subsystems that are simulated in multiple DRT simulators.

Review of a set of innovative applications of GD-RTS is summarized in [2]. GD-RTS approach is particularly beneficial for simulation of transmission-distribution case studies. Although transmission and distribution systems have been studied separately in the past, there is need of performing joint simulation for studying interactions between the two systems. To accommodate detailed models of transmission and distribution systems in the simulation, large RTS resources are required. GD-RTS addresses this requirement by leveraging simulation resources from multiple laboratories. Another potential requirement for transmission-distribution simulation studies is collaboration of research groups with different expertise as well as collaboration among system operators. GD-RTS enables flexible collaboration for performing joint simulations and experiments without involving proprietary information transfer of systems under study.

In GD-RTS, DRT simulators are hosted at different locations and exchange values of subsystem interface quantities with the objective to preserve conservation of energy at interfaces. The simulation fidelity of GD-RTS can be ensured, only if conservation of energy at interfaces is preserved. Simulation fidelity of GD-RTS refers to the degree to which GD-RTS based on geographically distributed, multiple DRT simulators, can reproduce the simulation results obtained from RTS performed locally. Time delays (varying and unpredictable), data sending rate, packet loss and other characteristics of a shared communication network impose significant challenges towards ensuring conservation of energy at interfaces and hence the simulation accuracy. These issues can significantly degrade simulation fidelity of GD-RTS and at times lead to unacceptable simulation results. A co-simulation Interface Algorithm (IA) represents a method to couple subsystems simulated at multiple DRT simulators. The main objective of co-simulation IA is to compensate the impact of a communication network based on prediction methods [3] and advanced representation of interface quantities [4]. Co-simulation IA determines how the interface quantities are exchanged between subsystems and is a critical research component in GD-RTS.

This paper provides simulation fidelity analyses based on an empirical study based on different sources of fidelity degradation. The two main characteristics i.e., data delay and transmission rate of the communication network are included in the study. Two different co-simulation IA are analyzed in this work to assess GD-RTS accuracy. The aim is to provide comparison of the two methods for co-simulation IA and generate basic guidelines for the development of advanced methods for improving simulation fidelity. The study includes

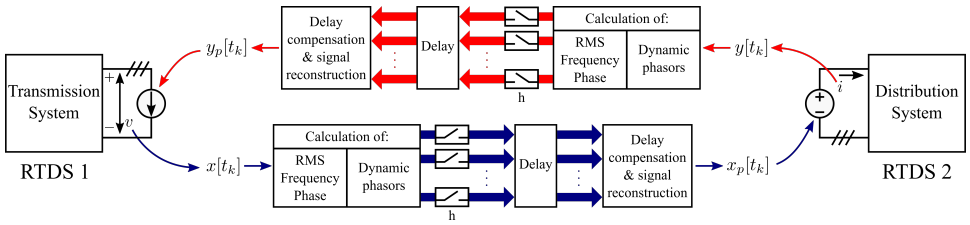


Fig. 1: Co-simulation Interface Algorithm based on Ideal Transformer Model

evaluation of simulation fidelity of transmission-distribution simulation under various simulation scenarios.

II. Co-Simulation Interface Algorithms

GD-RTS requires system under study to be decoupled into multiple subsystems. Multiple DRT simulators execute simulation of subsystems concurrently in real-time and exchange subsystems interface quantities based on a defined co-simulation IA. Accuracy of co-simulation IA is essential for achieving simulation fidelity in GD-RTS. Design objectives of co-simulation IA is to compensate impact of communication network and to ensure conservation of energy at the interface. Common methods for co-simulation IA are based on Ideal Transformer Model (ITM). ITM utilizes controlled current and voltage sources to impose the behavior of the remote subsystem in the local subsystem. ITM is widely adopted and straightforward method for PHIL applications in RTS [5].

While IAs for local co-simulation and PHIL are typically based on instantaneous values of current and voltage waveforms, this is not a common approach in GD-RTS. Time-varying delay, packets loss and reordering, due to inherent characteristic of a shared wide-area communication network, would significantly deteriorate the waveforms and impose dynamics that is an artifact of GD-RTS. To address this issue, a co-simulation IA for GD-RTS applies a transformation on current and voltage waveforms to obtain quantities that are exchanged between DRT simulators. The goal is to utilize representation of current and voltage waveforms that provides quantities that vary slower with time and that can be used to reconstruct a waveform on the receiving end. Transformation is applied on current and voltage waveforms on the sending end, reconstructed on the the receiving end, and imposed as an input to the controlled source of ITM.

We analyze two different methods for representation of interface quantities in co-simulation IA for GD-RTS in this work. The first method is based on representation of interface quantities in form of Root Mean Square (RMS), frequency and phase angle of current and voltage waveforms [3]. The second method utilizes representation of interface quantities in the form of time-varying Fourier coefficients, known as dynamic phasors [4]. Application of the described co-simulation IAs for transmission-distribution co-simulation is illustrated in Fig. 1. The controlled current source imposes the behavior of distribution system in transmission system, while the controlled voltage source in distribution system represents the voltage on interface bus of the transmission system.

A. Co-simulation IA based on RMS, frequency and phase

The first co-simulation IA studied in this paper utilizes representation of interface quantities in form of RMS, frequency and phase angle. As shown in Fig. 1, the voltage waveform is measured on the interface bus at transmission system. Before sending the interface quantities to the DRT simulator that simulates distribution system, RMS value V_{TS} is calculated at fundamental frequency. The next interface quantity that is included in the co-simulation IA is estimated system frequency f_{TS}. Phase angle between the voltage waveform of the interface and slack buses is also calculated θ_{TS}. The 3-tuple $[V_{TS},\ f_{TS},\ \theta_{TS}]$ represents the interface quantities that are sent to the DRT simulator simulating the distribution system. These interface quantities are sampled at the defined sending rate, and transferred via communication medium to the remote DRT simulator. The DRT simulator that simulates distribution system reconstructs the time-domain values for controlled voltage based on the values received for the 3-tuple $[V_{TS},\ f_{TS},\ \theta_{TS}]$:

$$v_A(t_k) = \sqrt{2}V_{TS}\sin(\varphi(t_k) + \theta_{TS}) \tag{1}$$

$$v_B(t_k) = \sqrt{2}V_{TS}\sin(\varphi(t_k) + \theta_{TS} - 2\pi/3) \tag{2}$$

$$v_C(t_k) = \sqrt{2}V_{TS}\sin(\varphi(t_k) + \theta_{TS} - 4\pi/3) \tag{3}$$

where $\varphi(t_k) = \int_0^{t_k} 2\pi f_{TS} dt$, and t_k represents simulation time. Note that Eq. 1, 2, and 3 use current simulation time t_k for the signal reconstruction. This approach compensates the phase shift caused by time delay between the two systems. It ensures alignment of the voltage waveform at the interface bus of transmission system and the reconstructed waveform utilized for controlled voltage source in distribution system. This is an important characteristic of co-simulation IA as it preserves power balance between two subsystems during steady state, which is necessary for energy conservation at the interface. Similarly, current measurements on the interface node at distribution system are transformed to the 5-tuple $[I_{DS,A}, I_{DS,B}, I_{DS,C}, f_{DS}, \psi_{DS}]$ that is transferred to the DRT simulator and used for signal reconstruction for controlled current source.

B. Co-simulation IA based on dynamic phasors

The second IA analyzed in this work utilizes time-varying Fourier coefficients for time-frequency representation of interface quantities, known as dynamic phasors [9]. Dynamic

phasor approach extends the conventional phasor representation of system quantities as it includes representation of non-stationary conditions. Dynamic phasors are introduced based on an assumption that a time-domain waveform $x(\tau)$ can be represented within the interval $\tau \in (t-T, t]$ in the following form:

$$x(\tau) = \sum_{k=-\infty}^{\infty} X_k(t) e^{jk(2\pi/T)\tau} \tag{4}$$

where T refers to the fundamental period of the system. Time-varying Fourier coefficients $X_k(t)$ are referred to as dynamic phasors. The co-simulation IA includes estimation of k-th coefficient of dynamic phasors based on the time-domain waveforms of interface voltage or current quantities with the following averaging function:

$$X_k(t) = \int_{t-T}^{t} x(\tau) e^{-jk(2\pi/T)\tau} \, \mathrm{d}\tau \tag{5}$$

where t represents the simulation time at which the coefficients are estimated. A subset of dynamic phasors is included in this work which refers to the following set of dynamic phasors coefficients $K \in \{0, 1, 2, 3\}$. For each phase (A, B and C) of the interface current or voltage, a complex-number 4-tuple $[X_0, X_1, X_2, X_3]$ representing a set of dynamic phasor coefficients are calculated and sent through the communication channel to the remote simulator. On the receiving end, the time-domain value for the controlled source is reconstructed based on the received interface quantities:

$$x(t_s) = \sum_{k \in K} X_k e^{jk(2\pi/T)t_s} \tag{6}$$

where t_s represents simulation time.

III. Simulation Environment

This section described the simulation setup and test scenarios used for the empirical study, and a metric for simulation fidelity.

A. Simulation setup

Simulation setup used in this work represents a simplified setup that replicates the main characteristics of a GD-RTS system. Two units of Real-Time Digital Simulator (RTDS) are interconnected based on communication interface with artificially imposed delay and sending rate of values.

B. Case study and test scenarios

Simulation fidelity is evaluated for the case study of transmission-distribution co-simulation. The transmission system utilized for the case study is 2-Area 4-Generator system [6]. Distribution system that is used for the case study is IEEE 13-node distribution test feeder [7], [8] that represents an unbalanced test feeder. System dynamics and transients under study are important aspects for evaluation of simulation fidelity and are assessed here. The first set of test scenarios refer to the transients in transmission system that are generated due to connection and disconnection of a step load. These two test scenarios are characterized by system frequency transients. As the co-simulation IAs utilize representation of interface quantities in time-frequency domain, it is considered important to evaluate simulation fidelity with respect to frequency transient. The second set of test scenarios refer to events initiated in distribution system. Disconnection and connection of a part of the feeder are studied which will cause a specific type of transients that are unbalanced.

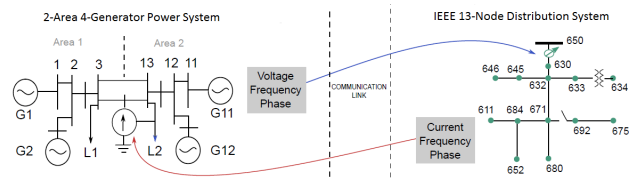


Fig. 2: Co-simulation of transmission-distribution systems [2]

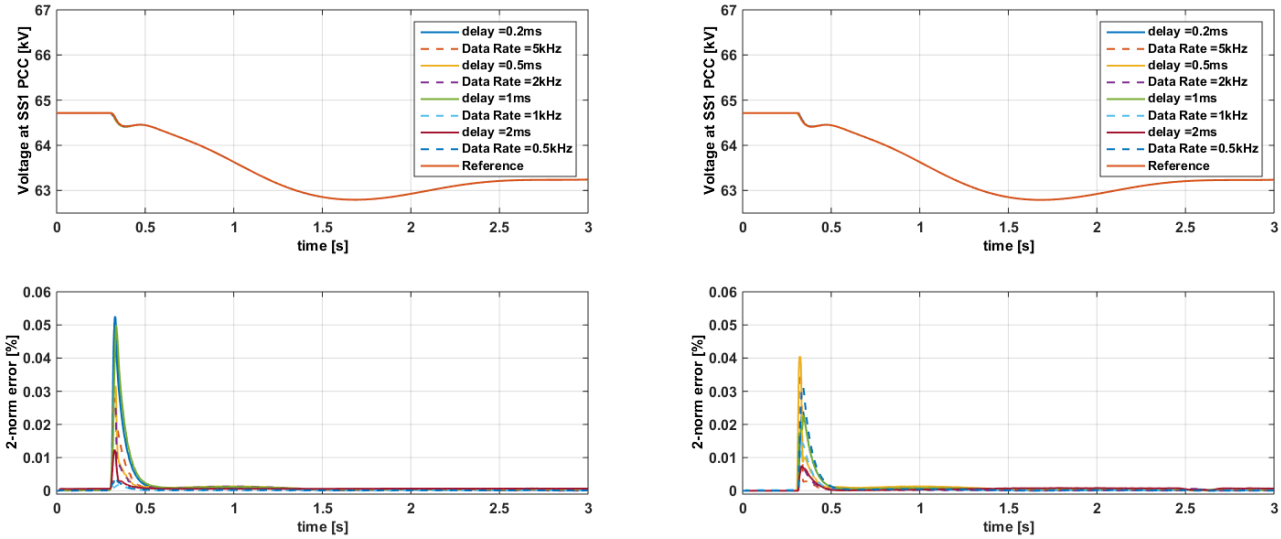
C. Simulation fidelity

Simulation fidelity assessment is important for developing advanced methods for GD-RTS. An ideal co-simulation IA provides the same simulation results for GD-RTS case as the system that is being simulated within a single DRT simulator. However, it is typically not possible to achieve ideal accuracy of co-simulation IA. Simulation fidelity of GD-RTS represents a measure of closeness of the response of GD-RTS with respect to the original system simulated within locally connected DRT simulator/s. In general, simulation fidelity is influenced by fidelity of simulation models and simulation time step used by simulators. In this work, we assume that original simulation model and setup within a single DRTS is of acceptable fidelity for the study. When decoupling the system into multiple subsystems, the selected decoupling point will affect simulation fidelity of the distributed DRTS. In this work we assume that the impact of decoupling point is negligible. All our analyses are performed for the same decoupling point and consideration of the effect of choice of decoupling point on simulation fidelity is out of the scope.

The evaluation introduced in this work is focused on the impact of time delay and data sending rate on simulation fidelity. We introduce a metric for characterization of simulation fidelity in GD-RTS based on the response of voltage and current values at the interface of both subsystems to the reference response of the system simulated in a single DRT simulator. The interface quantities are compared to the reference response for the case when the communication between the two subsystem is ideal, which means that interface quantities are exchanged every simulation time step without any time delay. Simulation fidelity metric for an interface quantity x obtained in GD-RTS system is defined as a 2-norm of the error relative to the reference response x_r described above:

$$M_2 = \frac{||x - x_r||_2}{||x_r||_2} \tag{7}$$

The error is normalized based on the 2-norm of the reference quantity in order to provide more realistic error comparison of system quantities of different scale, such as voltage and



(a) Co-simulation IA: RMS, frequency and phase angle

(b) Co-simulation IA: dynamic phasors

Fig. 3: Voltage at the interface bus in transmission system for test scenario: connection of the load in the transmission system

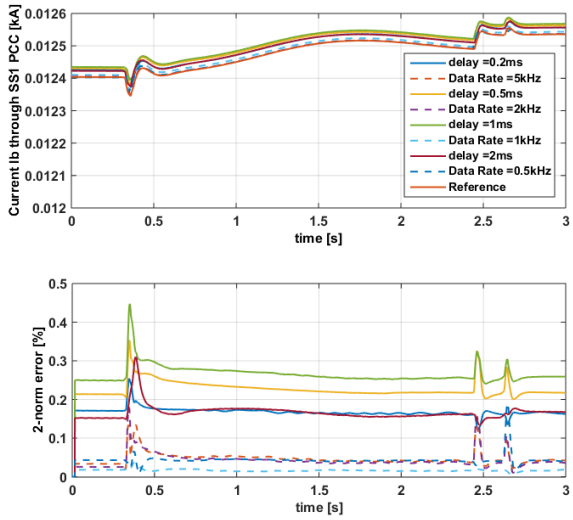


Fig. 4: Current at the interface bus in transmission system for test scenario: connection of the load in the transmission system

current. The error M_2 is calculated over a moving window of one system cycle.

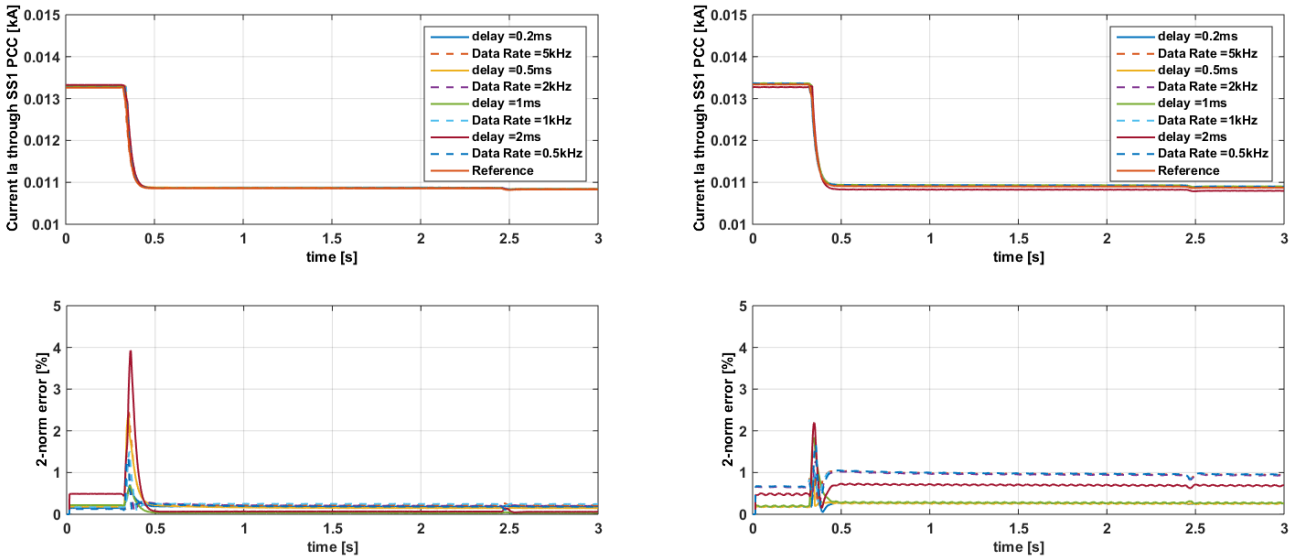
IV. GD-RTS Results and Discussion

A. Impact of time delay and sending rate

At first, we assessed the impact of comparable values of time delay and sending rate, e.g., time delay $\tau_d = 1\,\text{ms}$ compared to sending rate $h = 1\,\text{kHz}$. Simulation fidelity is assessed for values of time delay $\tau_d \in \{0.1\,\text{ms}, 0.2\,\text{ms}, 0.5\,\text{ms}, 1\,\text{ms}, 2\,\text{ms}\}$ while $h = 20\,\text{kHz}$, which refers to sending new values of interface quantities every simulation time step. The following equivalent values of sending rate $h \in \{10\,\text{kHz}, 5\,\text{kHz}, 2\,\text{kHz}, 1\,\text{kHz}, 0.5\,\text{kHz}\}$ are simulated while $\tau_d = 50\,\mu\text{s}$. The objective is to analyze which characteristic has larger impact on simulation fidelity.

Simulation results for the test scenario that refers to the transients following the connection of the load in transmission system are illustrated in Fig. 3 and Fig. 4. Fig.3 indicates that 2-norm error of the voltage is relatively small, where co-simulation IA based on dynamic phasors achieves slightly smaller maximum value of the error. It can be observed in Fig. 4 that the value of the 2-norm error of the interface current is order of magnitude larger compared to the voltage error illustrated in Fig.3. Degree of degradation of simulation fidelity is not the same for all system quantities. Different sources of fidelity degradation can cause different values of error. The impact of the time delay is more significant compared to the fidelity degradation due to limited sending rate, with respect to the results in Fig. 4.

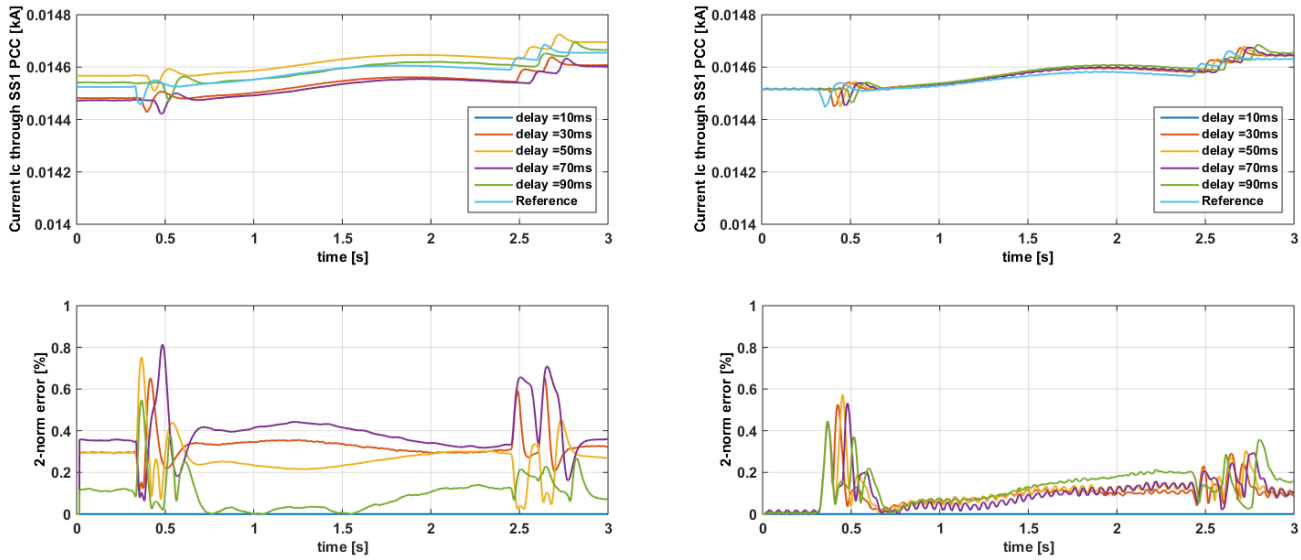
Analysis of simulation fidelity for the test scenario where the part of the feeder in distribution system is disconnected is illustrated in Fig. 5. It can be observed that the 2-norm error of the current is order of magnitude larger compared to the test scenario with transient in transmission system illustrated in Fig. 4. Co-simulation IA based on dynamic phasors achieves slightly smaller maximum error compared to the IA based on RMS, frequency and phase angle. Also, it can be observed that for co-simulation IA based on dynamic phasors sending rate has larger impact than time delay on simulation fidelity during steady state.



(a) Co-simulation IA: RMS, frequency and phase angle

(b) Co-simulation IA: dynamic phasors

Fig. 5: Current at the interface bus in transmission system for test scenario: disconnection of the part of the feeder in distribution system



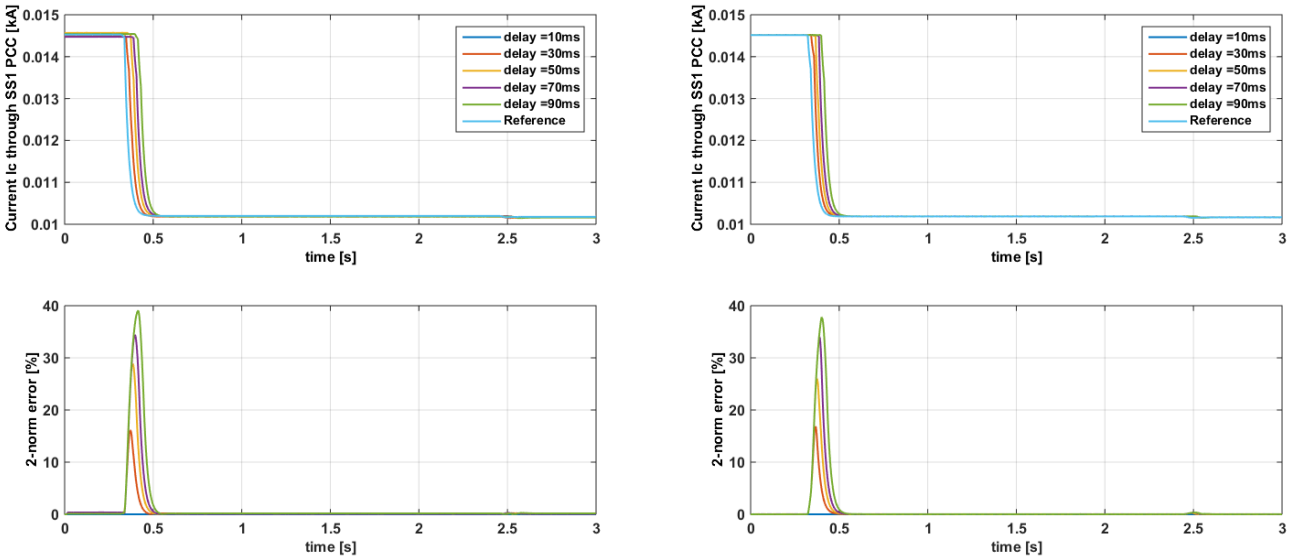
(a) Co-simulation IA: RMS, frequency and phase angle

(b) Co-simulation IA: dynamic phasors

Fig. 6: Current at the interface bus in transmission system for test scenario: connection of the load in the transmission system

B. Impact of different values of time delay

We analyze here the impact of time delay $\tau_d \in \{10\,\text{ms}, 30\,\text{ms}, 50\,\text{ms}, 70\,\text{ms}, 90\,\text{ms}\}$. Data sending rate that typically used in GD-RTS is $h = 2\,\text{kHz}$, which achieves relatively small percentage of packet loss [2]. Fig. 6 illustrates the results obtained for the interface current following the connection of the load in transmission system. With respect to the results of 2-norm error, it can be observed that simulation fidelity is still of high degree even for delay of $\tau_d = 90\,\text{ms}$. Slightly better performance is achieved with the co-simulation IA based on dynamic phasors. Simulation fidelity can vary significantly depending on transient under study. Fig. 7 shows



(a) Co-simulation IA: RMS, frequency and phase angle

(b) Co-simulation IA: dynamic phasors

Fig. 7: Current at the interface bus in transmission system for test scenario: disconnection of the part of the feeder in distribution system

simulation results for the test scenario where part of the feeder in distribution system was disconnected. Larger values of time delay significantly degrade simulation fidelity for this test scenario indicating that in this case simulation results are not of acceptable accuracy.

V. Conclusion

This study provides a comparison of performance between co-simulation IA based on RMS, frequency, and phase angle and co-simulation IA that utilizes dynamic phasors. Both the IA co-simulation approaches provide a similar degree of simulation fidelity in GD-RTS. Importance of developing co-simulation IA that compensates the time delay is emphasized in this work. Depending on the transients under study, simulation fidelity can be significantly degraded and obtained simulation results are not of acceptable accuracy in that case. While simulation fidelity was of high degree for the test scenario defined by load connection in the transmission system, simulation fidelity was significantly degraded for the transients observed in the test scenario where part of the feeder in distribution system was disconnected. A potential advantage of the co-simulation IA based on dynamic phasors is envisioned in the case of presence of power electronic converters in distribution system. This aspect will be part of the future research. Future work will also include development and implementation of advanced real-time prediction algorithms for time-frequency domain applications in GD-RTS.

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