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***Abstract*—The intrinsic complexity of smart grids requires computer-aided power system analysis to evaluate novel monitoring and control strategies and innovative devices. Due to the enormous computational requirements and the necessary Hardware-In-the-Loop (HIL) and Power Hardware-In-the-Loop (PHIL) applications, real-time power system simulation plays a fundamental role in this context. However, performing real-time simulations in a monolithic way, i.e. exploiting a single Digital Real-Time Simulator (DRTS) rack, could result in the inability to create reliable and accurate digital twins of increasingly complex power systems such as smart grids. This paper proposes a digital real-time power system co-simulation to link different DRTS and scale up the viable Power System Under Test (PSUT). It exploits Aurora 8B/10B to manage the data exchange and a Distributed Transmission Line Model (DTLM) to split the PSUT into the two real-time simulation environments. Furthermore, the DTLM permits the absorption of the communication latency, which normally occurs in real-time co-simulation, into the propagation model of a transmission line. With the presented setup, a time step duration of $50\,\mu s$ proves to be stable and accurate when running a co-simulated Electro-Magnetic Transients (EMT) analysis of a power grid scenario by interconnecting two commercial DRTS (i.e. OPAL-RT) with comparable results compared to the monolithic simulation, extending the scalability of future real-time smart grid simulations.**

***Index Terms*—Power System, Digital Real-Time Simulator, Co-simulation Techniques, Distributed Transmission Line Model**

ACRONYMS

CPU	Central Processing Unit
DRTS	Digital Real-Time Simulator
DTLM	Distributed Transmission Line Model
DER	Distributed Energy Resources
EMTP	Electro-Magnetic Transients Program
EMT	Electro-Magnetic Transients
HIL	Hardware-In-the-Loop
ITM	Ideal Transformer Method
IA	Interface Algorithm
MAPE	Mean Absolute Percentage Error
PSUT	Power System Under Test
PHIL	Power Hardware-In-the-Loop
PTP	Precision Time Protocol
SFP	Small-form Factor Pluggable

I. INTRODUCTION

The analysis of power systems requires real-time simulation over Digital Real-Time Simulator (DRTS) for a reliable and accurate study of the complex behaviour of transmission and distribution networks. This is even further essential in the context of high penetration of Distributed Energy Resources (DER) and storages that requires improving the energy systems integration [1]. DRTS technologies not only permits solving power system network using nodal analysis but also accelerate the study and development of power system equipment through the application of HIL and PHIL. To this extent, various DRTS commercial solutions (e.g. OPAL-RT and RTDS Technologies) have been proposed to accelerate the required computation for high-intensive tasks, such as EMT analysis [2]. However, the real-time simulation of innovative smart grids requires massive computing capabilities, especially to coordinate complex systems for large-scale scenarios.

Several works in the literature have already implemented parallel computing strategies to solve EMT analysis of scalable PSUT. For instance, the MATLAB Simulink Simscape library [3] enables the partitioning of a power system by using the propagation delay of a transmission line to absorb the inherent delay required to avoid direct feedthrough. Traditional power systems present many transmission lines long enough to decouple points in the network, allowing parallel computation on multiple cores of a Central Processing Unit (CPU) [4].

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The same concept is applied in ARTEMiS library [5] to split a power system across different cores of OPAL-RT Technologies DRTS to improve their real-time scalability [6]. However, the computational capability of a single DRTS rack is limited and cannot overcome the problem of analyzing large and increasingly complex smart grid scenarios.

Therefore, the scientific community proposed to interconnect different DRTS racks through communication protocols (e.g. Ethernet) to combine their computational capabilities in a unique distributed digital real-time power system co-simulation environment [7]. Communication latencies, synchronization, and time regulation are the main issues in these interconnections, where the time step duration reaches tens of microseconds. Thus, to achieve this goal, new technologies must be developed that allow DRTS racks to be connected without compromising simulation performance, particularly in terms of dynamic simulation accuracy. Most of the solutions proposed in the literature are inspired by the PHIL application and its stability and accuracy intrinsic issues [8]. For instance, the time delay compensation method presented in [9]. However, these strategies restrict the analysis to slower dynamics than EMT ones. Other works are inspired by the Interface Algorithm (IA) proposed for PHIL real-time simulation. The most suitable IA for these interconnections is the Ideal Transformer Method (ITM) [10]. However, the effect of the latency experienced by the signal exchanged (i.e. voltages and currents) still generates a noticeable non-linear effect, affecting the accuracy of the real-time co-simulation solution. In the end, none of the previous solutions permits linking with flexibility different DRTS together, maintaining the accuracy of a monolithic simulation.

This paper proposes a digital real-time power system co-simulation implementing a Distributed Transmission Line Model (DTLM) as an adapter to split and extend the scalability of a PSUT concerning a monolithic digital real-time simulation. The DTLM is applicable to transmission lines with a minimum length determined by the characteristic propagation velocity ν of the line. The co-simulation setup is accomplished by interconnecting two DRTS by means of an optical fiber link between their Small-form Factor Pluggable (SFP) ports, exploiting the Aurora 8B/10B protocol. Aurora, in a nutshell, ensures the minimum communication latency among the available protocols on commercial DRTS. The proposed solution absorbs the communication latency experienced during the data exchange management of the co-simulation setup in the propagation time of the travelling wave of the DTLM. Because the communication latency is typically a multiple of the time step duration T_S depending on the commercial DRTS setup [10], the proposed DTLM allows for the setting of a variable communication latency attribute based on the laboratory configuration. To avoid complex time regulation and synchronisation schemes, the co-simulation setup has been tested over a laboratory setup with a single DRTS by employing an optical fiber echo link among two SFP ports of an OPAL-RT OP5700. The proposed solution has been tested over a simple PSUT to demonstrate the stability and accuracy

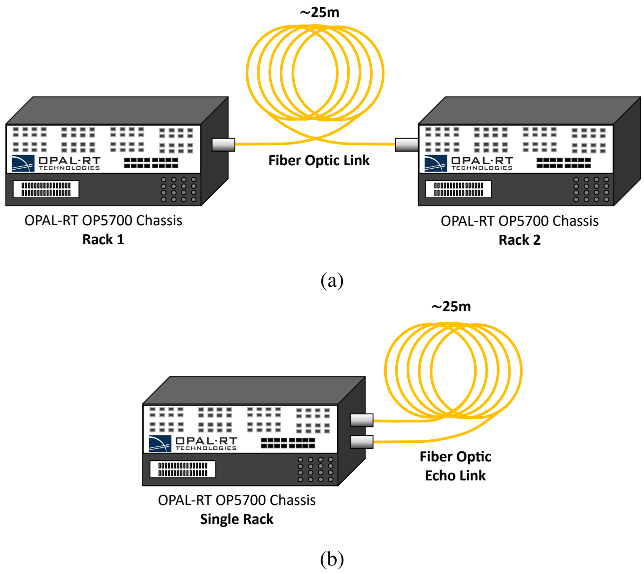


Fig. 1: The digital real-time power system co-simulation infrastructure (a) and its testbed exploiting an echo loop configuration (b)

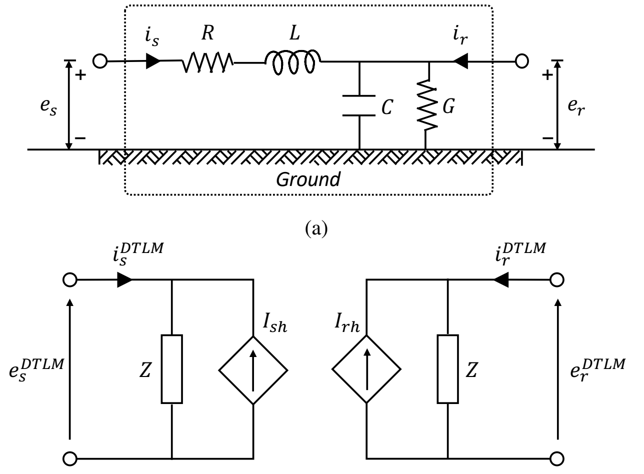
of the co-simulated scenario, providing identical experimental results concerning a monolithic simulation.

The structure of the manuscript is described as follows. Section II reports the methodological framework used to complete the digital real-time power system co-simulation and develop the DTLM adapter. In Section III, the selected PSUT is described. Section IV presents experimental results on the proposed PSUT confirming the identical solution of the digital real-time power system co-simulation via DTLM w.r.t. a monolithic simulation. Finally, Section V reports concluding remarks and future works.

II. Methodology

The digital real-time power system co-simulation is accomplished by interconnecting two DRTS via a bidirectional fiber optic link exploiting Aurora 8B/10B. Aurora is an optical fiber serial link protocol capable of reducing the communication latency among involved DRTS at around hundreds of nanoseconds, ensuring the minimum impact on the co-simulation application. Figure 1a represents the interconnection implemented among two OPAL-RT OP5700 racks. However, the co-simulation infrastructure has been tested on a single OPAL-RT OP5700 rack employing an echo link among two different SFP ports, as depicted in Figure 1b. This configuration provides a virtual co-simulation infrastructure with identical communication latency that avoids complex time synchronisation, alignment, and regulation schema among the two racks.

Although the communication latency experienced by the fiber optic link is negligible w.r.t. to the DRTS time step duration T_S, the data exchange management among the Aurora channel and the available power system solution cores in DRTS architectures strongly impacts with a latency proportional to T_S depending on the commercial DRTS solution implemented in the co-simulation framework [10]. To cope



(a)

(b)

Fig. 2: Lossy line (a) and the equivalent impedance circuit (b)

with this variable latency, the PSUT is split by means of a Distributed Transmission Line Model (DTLM) based on Bergeron's travelling wave method [11] used by Electro-Magnetic Transients Program (EMTP) [12]. By implementing this model, the overall co-simulation latency experienced by the interface signals (i.e. voltages and currents) can be absorbed into the propagation time of the travelling wave, resulting in an identical solution with respect to a monolithic simulation.

A. Theoretical Background

This section presents the theoretical formulation of the EMTP transmission line model for the sake of self-consistency and clarity of the manuscript. In [12], the lossless distributed LC line is characterised by two values for a single-phase line: *i)* the surge impedance $Z_c = \sqrt{L'/C'}$, and *ii)* the wave propagation speed $v = 1/\sqrt{L'\,C'}$, where L' and C' are the per-unit length inductance and capacitance respectively. Figure 2 shows the equivalent circuit of a single-phase line. For a lossless line (i.e. $R' = 0$), the quantity $e + Z_c\, i$, where e is the voltage of the line and i is the current of the line of one subsystem, must arrive unchanged at the other subsystem after a transport delay τ.

$$\tau = \frac{d}{\nu} \tag{1}$$

where d is the length of the line and ν is the propagation speed. The model equations for a lossless line are:

$$e_r(t) - Z_c\, i_r(t) = e_s(t-\tau) - Z_c\, i_s(t-\tau) \tag{2a}$$

$$e_s(t) - Z_c\, i_s(t) = e_r(t-\tau) - Z_c\, i_r(t-\tau) \tag{2b}$$

knowing that:

$$i_s(t) = \frac{e_s(t)}{Z} - I_{sh}(t) \tag{3a}$$

$$i_r(t) = \frac{e_r(t)}{Z} - I_{rh}(t) \tag{3b}$$

in a lossless line, the two current sources I_{sh} and I_{rh} are computed as:

$$I_{sh}(t) = \frac{2}{Z_c}\, e_r(t-\tau) - I_{rh}(t-\tau) \tag{4a}$$

$$I_{rh}(t) = \frac{2}{Z_c}\, e_s(t-\tau) - I_{sh}(t-\tau) \tag{4b}$$

When losses are taken into account, new equations for I_{sh} and I_{rh} are obtained by lumping $R/4$ at both ends of the line and $R/2$ in the middle of the line where R is the total resistance of the line:

$$R = R'\, d \tag{5}$$

where R' is the characteristic resistance per unit length. The current sources I_{sh} and I_{rh} are then computed as follows:

$$\begin{aligned} I_{sh}(t) = &\left(\frac{1+h}{2}\right)\left(\frac{1+h}{Z}\, e_s(t-\tau) - h\, I_{rh}(t-\tau)\right) + \\ &+ \left(\frac{1-h}{2}\right)\left(\frac{1+h}{Z}\, e_r(t-\tau) - h\, I_{sh}(t-\tau)\right) \end{aligned} \tag{6a}$$

$$\begin{aligned} I_{rh}(t) = &\left(\frac{1+h}{2}\right)\left(\frac{1+h}{Z}\, e_r(t-\tau) - h\, I_{sh}(t-\tau)\right) + \\ &+ \left(\frac{1-h}{2}\right)\left(\frac{1+h}{Z}\, e_s(t-\tau) - h\, I_{rh}(t-\tau)\right) \end{aligned} \tag{6b}$$

where:

$$Z = Z_c + \frac{R}{4}$$
$$h = \frac{Z_c - \frac{R}{4}}{Z_c + \frac{R}{4}}$$
$$Z_c = \sqrt{\frac{L'}{C'}}$$
$$\nu = \frac{1}{\sqrt{L'\,C'}}$$
$$\tau = d\sqrt{L'\,C'}$$

L' and C' are the inductance and capacitance per unit length of the line, R is the total resistance of the line, and d is the line length. For a lossless line, $R = 0$, $h = 1$, and $Z = Zc$.

It is worth noting that the proposed DTLM has intrinsically a limitation of the minimum length of the line d caused by: *i)* the propagation velocity ν that is related to the characteristic inductance L' and capacitance C' per unit length, and *ii)* the latency τ_{min} experienced from the Aurora communication, normally multiple of the time step duration T_S.

$$d \gg \nu\, \tau_{min} \tag{7}$$

where:

$$\tau_{min} = T_S$$

for our digital real-time power system co-simulation infrastructure exploiting the OPAL-RT OP5700 racks.

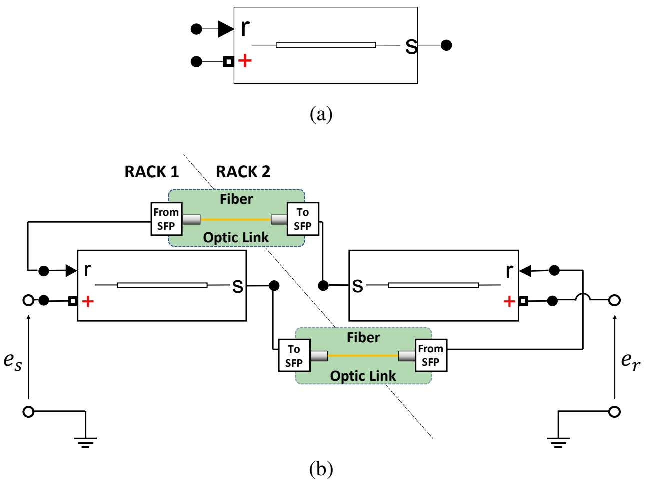


Fig. 3: The DTLM block developed in RT-LAB environment (a) and its application to decouple a transmission line (b)

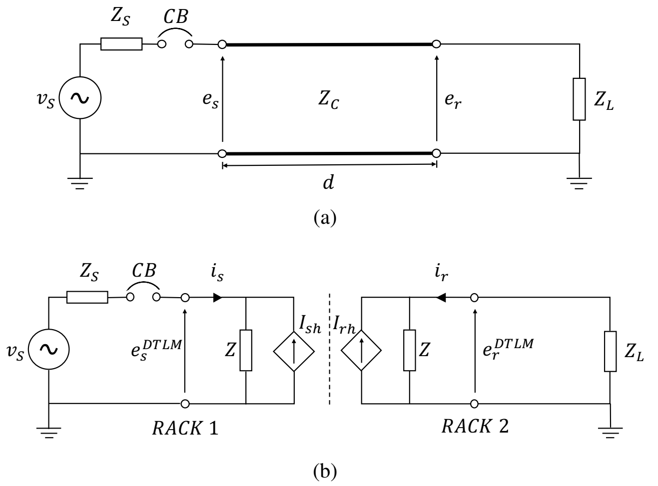


Fig. 4: PSUT composed by a voltage source v_S with pure resistive impedance Z_S, a circuit breaker CB, a single-phase transmission line with characteristic impedance Z_c and length d, and a pure resistive load Z_L (a) and its co-simulated equivalent (b)

B. DTLM Application

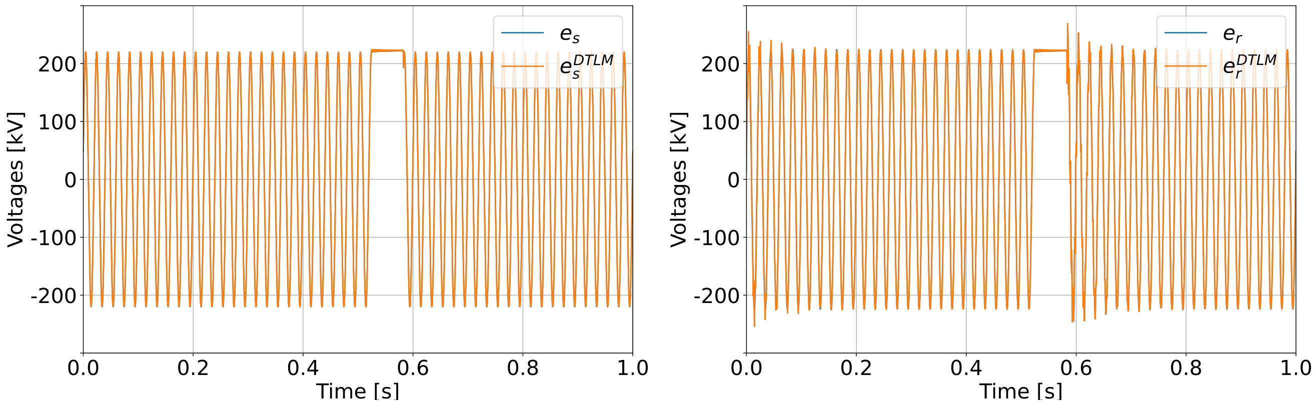
This section describes the proposed DTLM block and its generic application in a power system scenario. To achieve the digital real-time power system co-simulation, the PSUT must be analysed and a transmission line where to split the power system must be identified considering the constraint in Equation 7. Once selected, the transmission line must be substituted by two DTLM blocks. The DTLM block shown in Figure 3a implements Equations 6 in the RT-LAB environment [13], a specific simulation tool to perform modelling of real-time power system for OPAL-RT targets. It presents two inputs, namely the voltage input **+** and the receiving input **r**, and an output **s**, so-called the sending output. The voltage input **+** receives the electric connection with the power system. The receiving input **r** and the output **s** instead exchange signals with the other block via the Aurora channel to fulfil Equations 6 and reproduce the transmission line behavior. The block also allows setting different parameters, respectively: *i)* the line length d (km), *ii)* the resistance per unit length R' ($\Omega\,\text{km}^{-1}$), *iii)* the capacitance per unit length C' ($\text{F}\,\text{km}^{-1}$), *iv)* the inductance per unit length L' ($\text{H}\,\text{km}^{-1}$), *v)* the frequency used for rlc specification f_s (Hz), and *vi)* the communication latency in multiple N of the time step duration T_S.

The communication between the two DTLM blocks is shown in Figure 3b. The DTLM block of rack 1 is connected to the left line terminal e_s through the **+** connector and executes different operations in the same time step, respectively: *i)* it measures the voltage at the left line terminal e_s; *ii)* it receives the output **s** of the DTLM block of rack 2 via the **r** connector; iii) it computes the current i_s imposed to the **+** connector by solving Equation 6a and Equation 3a; *iv)* it computes the component of Equation 6b excluding e_r voltage contribution; and, finally, *v)* it sends the calculated component from the output connector **s** to let the DTLM block of rack 2 executing operations *iii)* and *iv)* in the next time steps. The DTLM block of rack 2 executes the same operations, taking into account the equations related to the right line terminal e_r. As depicted in Figure 3b, the data exchange between **s** and **r** connectors of rack 1 and 2 happens through the Aurora channel in both directions. To achieve this data exchange, the **s** signal is taken by the **To SFP** block from the real-time simulation environment of a rack that codes and inserts it in the Aurora data stream of the physical fiber optic link. At the receiver side, the stream is decoded and the data is presented into the real-time simulation environment of the other rack via the **From SFP** block. The signal is then redirected to the **r** connector of the DTLM block.

III. Scenario

The proposed methodology is tested over a very simple but effective power system scenario for the re-energization of a transmission line. The monolithic circuit, depicted in Figure 4a, consists of a voltage source v_S with a standard European voltage level of 220 kV and a nominal frequency of 50 Hz and a source impedance Z_S of magnitude $1\,\mu\Omega$. To trigger a transient as a case study, a circuit breaker CB, with breaker resistance R_{on} equal to $0.1\,\Omega$ and snubber resistance R_s equal to $1\,\text{G}\Omega$, positioned after the voltage source is opened and re-closed after 66.67 ms. The transmission line is a single-phase line of 97.25 km with resistance R', capacitance C', and inductance L' per unit length, respectively: $0.095\,\Omega\,\text{km}^{-1}$, $12.39\,\text{nF}\,\text{km}^{-1}$, and $3.13\,\text{mH}\,\text{km}^{-1}$. Finally, the load impedance Z_L is set to $1\,\text{T}\Omega$ to impose an open circuit terminal to the transmission line. The transient that is triggered is therefore the re-energization of a transmission line, in a no-load condition.

The monolithic circuit is split by substituting the transmission line with two DTLM blocks that implement the equivalent impedance network described in Figure 4b. The left and right line terminals, respectively e_s^{DTLM} and e_r^{DTLM}, are represented by two controlled current sources I_{sh} and I_{rh}



(a) (b)

Fig. 5: Voltage plots of the transient generated by the re-energization of the single-phase transmission line for the monolithic and co-simulated scenario with a time step duration $T_s = 50\,\mu\text{s}$ for the left terminal (a) and right terminal (b) of the line

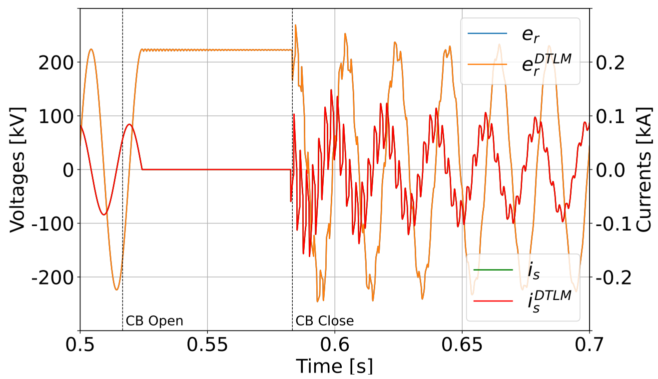


Fig. 6: Right terminal voltages (i.e. e_r and e_r^{DTLM}) and left terminal currents (i.e. i_s and i_s^{DTLM}) transient generated by the re-energization of the single-phase transmission line for the monolithic and co-simulated scenario with a time step duration $T_s = 50\,\mu\text{s}$

and their relative surge impedance Z. It is worth noting that the resulting co-simulated equivalent topologically splits the source and load circuit line terminals by indirectly representing the effect of each circuit via the controlled current sources I_{sh} and I_{rh}. This permits to run the circuits on two different DRTS racks and exchanging the component described in Section II-B via the proposed digital real-time power system co-simulation to update and calculate the corresponding i_s^{DTLM} and i_r^{DTLM}.

IV. Experimental Results

The proposed digital real-time power system co-simulation is implemented in a testbed with a single OPAL-RT OP5700. This configuration provides a virtual co-simulation infrastructure with identical communication latency that avoids complex time synchronisation, alignment, and regulation schema among the two racks, such as IEEE 1588 Precision Time Protocol (PTP). Indeed, the testbed exploits an echo loop configuration among SFP Port 0 and 1 of the rack with a 25 meter fiber optic link. Aurora 8B/10B is enabled in the RT-LAB environment by using the **From SFP** and **To SFP** block, two *OpCtrl* blocks that allow defining: i) the *SFP Port Number* of the front panel of the rack, and ii) the *Data Width* of the channel in numbers of double variables. The power system scenario presented in Section III is developed in the RT-LAB environment in both the monolithic and co-simulation configurations. The monolithic power system in Figure 4a has been run simultaneously with the co-simulated case of Figure 4b in order to retrieve the correct alignment among voltages and currents of both results. The experiment is run at a time step duration T_S of $50\,\mu\text{s}$, a typical EMT analysis setting for sufficient details of the transient.

In Figure 5, the time domain accuracy results among the monolithic and co-simulated power systems are presented. Figure 5a presents the comparison among e_s and e_s^{DTLM}. The voltages e_s^{DTLM} of the co-simulated scenario accurately reproduce the monolithic scenario without significant error w.r.t. e_s. In fact, the Mean Absolute Percentage Error (MAPE) defined in Equation 8 is equal to $0.689\,\%$.

$$MAPE = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{e_i - e_i^{DTLM}}{e_i}\right| \tag{8}$$

where N is the total number of simulation time steps, e_i are the monolithic voltage results, and e_i^{DTLM} are the co-simulated voltage results.

The same result is achieved when comparing e_r and e_r^{DTLM} in Figure 5b, where e_r^{DTLM} reproduce precisely e_r with a MAPE of almost $0.0026\,\%$. It is worth noting that both e_r and e_r^{DTLM} present an initial transient due to the fact that the monolithic circuit implements a distributed parameter model for the transmission line. This effect refers to the empty memory of the model at the beginning of the experiments. In fact, both the distributed parameter model of the monolithic scenario and the DTLM memories of the co-simulated scenario are initialised to zero.

Figure 6 shows the transients generated by the re-energization of the transmission line in the no-load condition for left terminal currents (i.e. i_s and i_s^{DTLM}) and the right terminal voltage (i.e. e_r and e_r^{DTLM}), which present the most interesting transients that could depict DTLM issues in reproducing high-frequency details. Once the open command arrives at the circuit breaker CB at $t = 0.516\,67\,\mathrm{s}$, the opening of the line takes place at the first zero-crossing condition of the current i_s that is $t = 0.525\,\mathrm{s}$ to avoid arc generations. At this point, the current at the sending terminal remains zero until the breaker is re-closed. Vice-versa, the voltage at the receiving terminal remains constant, at $311.126\,\mathrm{kV}$, because in the line model, the shunt conductance G is neglected and the shunt capacitance C remains charged. When the CB is closed again, a re-energization transient is triggered, with some oscillations due to the line parameters.

The precision in reproducing the monolithic results is appreciable also in Figure 6, where all DTLM voltage and currents plots overlay the standalone ones with high accuracy.

V. Conclusion

A digital real-time power system co-simulation via the application of a Distributed Transmission Line Model (DTLM) was presented. The application of the DTLM ensures stability and accuracy of the numerical solution of a PSUT with results identical to a monolithic real-time simulation with the constraints of Equation 7. The proposed infrastructure that adopts the Aurora protocol for communication guarantees the minimum latency and so the lowest constraints of the minimum distance of the transmission line to be substituted by the DTLM. A simple but effective single-phase scenario with a simulation time step of $50\,\mu\mathrm{s}$ has been analysed to assess the time-domain accuracy of the solution. It may be argued that a single-phase transmission line is not realistic, but this scenario found the basis for a three-phase modal analysis, where each mode can be considered as a single-phase line without mutual dependencies. The DTLM replicates precisely and with the highest accuracy in reproducing the behaviour of the monolithic power system. 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 with proper time synchronization, alignment, and regulation schema in order to expand the computational capabilities of individual laboratories. Moreover, the DTLM block will be extended to manage a three-phase line with mutual dependencies implementing modal transformation.

Acknowledgments

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