Co-simulation of Real-Time Electromagnetic Transient and Transient Stability Simulations Using Dynamic Phasor T-Line Model

Harshani Konara, U. D. Annakkage, Rudi Wierckx

Abstract—**This paper presents techniques to interface a Transient Stability Analysis (TSA) based model to an ElectroMagnetic Transient (EMT) based model running on a Real Time Digital Simulator. Practical challenges of implementing such an interface are discussed. The proposed TSA model can be simulated using a substantially larger time-step compared to the EMT model. The interface between the EMT model and the TSA model is implemented using a transmission line modeled using Dynamic Phasors (DP). Time-step delay is the primary cause of numerical instability in co-simulations. In this work, a traveling wave model of a transmission line is used to decouple the EMT and TSA networks. The interface requires that the propagation delay of the interfaced transmission lines be greater than the EMT time-step even though the TSA is simulated using a much larger time-step than the EMT model. The proposed technique is validated using the IEEE 39 bus system and a power system with 500 buses.**

Keywords—**Co-simulation, dynamic phasors, electromagnetic transient, real-time, transient stability**

I. Introduction

ElectroMagnetic Transient (EMT) simulation is the most accurate tool available to analyze the dynamics of a power system. EMT simulations typically run using time-steps in the microsecond range. Therefore, EMT models can represent the power system dynamics in a wide frequency band [1]. Real-time EMT simulators provide the ability to interface physical control and protection devices to the simulation and observe their behavior and impact on the system under steady-state and dynamic conditions. Real-time EMT models can be computationally demanding, especially when a large power system is to be represented. Fortunately, the EMT algorithm has computational parallelisms that can be exploited using parallel processing. One such parallelism arises due to the nature of traveling wave transmission line models used in EMT simulations. Traveling wave line models split the network into subsystems that can be solved in parallel. However, when the system to be modeled includes 1000s of buses, carrying out EMT simulation for the entire system would require a substantial number of processing elements and may not be practical.

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One of the more challenging aspects of EMT simulation studies is to determine the extent of the system that must be modeled to accurately capture the dynamics of interest. It is common practice to model the portion of the system of interest (study zone) in EMT and then represent the surrounding system (external system) using equivalents. An equivalent is often made up of a fixed source voltage behind impedance. However, should a significant change to the portion of the system represented in the study zone occur (for example the opening of breakers to isolate a transmission line), the power flow in the overall simulated system may no longer be correct as the source behind the equivalent uses a fixed magnitude and angle. Different types of power system equivalents are discussed in [2],[3] and [4].

As an alternative to a system equivalent based on a source behind an impedance, it is proposed herein that a Transient Stability Analysis (TSA) is used to represent the system outside of the study zone. The larger simulation time-step and simplified component representation used in TSA provide a reduced computational burden and thus a TSA can accommodate power system models containing 1000s of buses [5]. Combining the TSA and EMT algorithm in one simulation is often referred to as co-simulation or hybrid simulation. The full network of the external system is modelled using a TSA and hence any topology changes can be easily accounted for. References [6], [7], [8] and [9] highlight some of the methods used to interface EMT and TSA models. Interfacing TSA to an EMT model can be challenging. Interfaces that introduce delays are susceptible to numerical instability due to the negative damping associated with the delay. Interfacing between EMT and TSA is particularly susceptible to numerical instability due to their large difference in simulation time-steps [6]. EMT and TSA models represent different frequency bands and direct interface could add inaccuracies to the co-simulation.

This paper addresses the above challenges by using an interface module based on Dynamic Phasors (DP). The DP interface module consists of the transmission line/s connecting EMT and TSA models. Interfacing EMT and TSA models using DP was originally suggested in [9] and [10]. Dynamic phasors are phasor models like TSA, but the network dynamics are accurately represented by modeling capacitor voltages and inductor currents using differential equations. Therefore, the frequency bandwidth of a DP model is wider compared to a TSA [11], [12]. In terms of the complexity of the network models, the EMT models all three phasors using differential equations, the DP model uses a balanced network with differential equations, and the TSA model uses a balanced network with no differential equations. Therefore, the complexity of the DP network model is in between the complexities of EMT and TSA network models. Hence, the DP transmission line in the interface allows smooth integration of EMT and TSA models. The time-step delay between EMT and TSA models is avoided by modeling the DP interface transmission lines using a Bergeron line model. However, direct decoupling of EMT and TSA models requires a transmission line with a propagation wave delay corresponding to the TSA time-step. Since the TSA time-step is significantly large, the required length would be correspondingly long and finding such a line in a practical power system will become difficult. As a solution, an additional calculation step is added to the DP interface module to calculate the DP-TSA interface variables at every EMT time-step. Additional calculation step allows the interface variables at the TSA end of the transmission line to get updated at every EMT time-step and thus the propagation delay in the line corresponds only to the EMT time-step. The transmission line interface with the boundary variables updated at every EMT time-step is the main contribution of this paper which allows integration of large TSA model to an EMT model with a transmission line length corresponds to the EMT model time-step. As an example, for an EMT time-step of $50\mu s$ and a TSA time-step of $1ms$, the interface transmission line length has to be longer than $15km$. If the additional calculation step is not used the transmission line length has to be longer than $300km$ which is hard to find in a practical power system. Reference [10] uses a similar boundary update on the TSA interface to overcome the negative effects of using a larger time-step in the TSA model. A buffer region in between the TSA boundary and the region of interest is considered to reduce the errors due to high-frequency transients entering the TSA model [8], [10]. Both EMT network and DP interface model contribute to the buffer region.

References [6] and [10] also provide an implementation of a real-time EMT-TSA interface through a DP buffer zone. In [6], the negative effects due to the time-step delay is addressed by using an extrapolation method. The extrapolation method introduces inaccuracies to the simulation and the level of inaccuracies become significant when there is a disturbance in the system. The proposed co-simulation approach addresses the above problem and improves [6] for a more robust, stable, and accurate simulation by using the delay in the interface transmission lines. The co-simulation method in [6] has three network models; EMT, DP and TSA resulting two interfaces. Two interfaces result in two time-step delays. The proposed method results in only one time-step delay which is easier to handle compared to two.

The proposed EMT-TSA interface is numerically stable, and it is possible to have multiple interface nodes between EMT and TSA models. In the proposed co-simulation model, faults can be applied in both internal and external systems, as well as, in the boundary region without causing numerical instabilities. The effectiveness of the co-simulation model is demonstrated for IEEE 39 bus power system [13] and a 500-bus power system [14].

II. Background

A. Interfacing three-phase EMT model to phasor model

The voltages and currents in the EMT internal system are in three-phase quantities whereas DP and TSA are in the complex phasor domain. EMT three-phase quantities can be converted into the phasor domain by using an alpha-beta transformation [6]. The alpha beta components ($v_{\alpha\beta}$) for a given three-phase voltage v_{abc} can be calculated as shown in (1) and (2).

$$T_{\alpha\beta} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \quad (1)$$

$$v_{\alpha\beta} = T_{\alpha\beta} v_{abc} \quad (2)$$

In order to calculate the phasors using the alpha-beta transformation, the power system should be a three wire balanced system. Unbalanced three-phase voltages and currents result in inaccuracies.

Conversion from phasor to three-phase quantities is straightforward and done using the equations: $v_a = V_m sin(\omega_0 t + \theta)$, $v_b = V_m sin(\omega_0 t + \theta - 2\pi/3)$ and $v_c = V_m sin(\omega_0 t + \theta + 2\pi/3)$. Here, V_m, θ and ω_0 are the magnitude of the phasor signal, angle of the phasor signal and angular speed corresponding to base frequency respectively. The magnitude V_m and the angle θ are calculated using the phasors.

B. DP model

DP is also a phasor model like TSA where a three phase signal is represented using its magnitude and angle. Let us say that the DP of the three-phase balanced signal $u(t)$ is represented using $U(t)$. The phasor transformation of the derivative of $u(t)$ can be expressed as (3) [11].

$$\frac{d}{dt}u(t) = \frac{d}{dt}U(t) + j\omega_0 U(t) \quad (3)$$

DP equations for an inductor L and a capacitor C can be expressed using (4) and (5).

$$V_L(t) = L\frac{d}{dt}I_L(t) + j\omega_0 L I_L(t) \quad (4)$$

$$I_C(t) = C\frac{d}{dt}V_C(t) + j\omega_0 C V_C(t) \quad (5)$$

Capacitor and inductor equations of DP contain derivative terms to model the capacitor voltages and inductor currents compared to TSA [11]. Hence, in DP, the dynamics associated with inductors and capacitors can be accurately captured. The loads and the PI section model of transmission lines can be modeled using the capacitor and inductor equations. The traveling wave line model offers advantages over PI section models. Most importantly, it allows decoupling of the network into subsystems. Since the DP model is used as the interface between the EMT and TSA, a traveling wave line model is a good way to overcome the time-step delay in the co-simulation. In the work reported herein, the DP model of the Bergeron line is used which has been derived using the EMT model [15]. Figure 1 shows the equivalent model for a

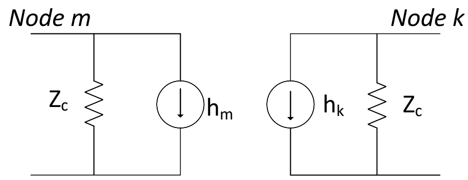

Fig. 1. Bergeron model of the transmission line

transmission line between nodes m and k. In the EMT model, the current source values are defined as follows [1]

$$h_k = -v_m(t-\tau)Z_c - hi_m(t-\tau) \tag{6}$$

$$h_m = -v_k(t-\tau)Z_c - hi_k(t-\tau) \tag{7}$$

where, $Z_c = {}^{1}/_{(Z_0 + R/4)}$ and $h = {}^{(Z_0 - R/4)}/_{(Z_0 + R/4)}$ Here, τ is the traveling wave delay, Z_0 is the characteristic impedance, R is the line resistance, v_m is the voltage at node m, v_k is the voltage at node k, i_m is the current at node m, and i_k is the current at node k. The voltages and the currents used for calculating the current source values (h_m and h_k) has a time-shift (τ) corresponding to the traveling wave delay from node m to k. In DP, time-shift τ results in an additional phase shift of $e^{-j\tau\omega_0}$. Therefore, (1) and (2) can be converted to DP domain as in (3) and (4), where V_m, V_k, I_m and I_k are DP voltages and currents.

$$H_k = e^{-j\tau\omega_0}\left(-V_m(t-\tau)Z_c - hI_m(t-\tau)\right) \tag{8}$$

$$H_m = e^{-j\tau\omega_0}\left(-V_k(t-\tau)Z_c - hI_k(t-\tau)\right) \tag{9}$$

III. Implementing TSA model in Real-Time

In this section, practical challenges of implementing a TSA model in real-time are discussed. The characteristics that are essential in the proposed TSA model for interfacing it to the EMT model are also discussed.

A. *TSA network model*

TSA models use a constant admittance to model the network. To model dynamic devices (such as generators) differential equations are used resulting in a set of Differential and Algebraic Equations (DAE) [5]. The DAE model can be solved by using either a partitioned or a simultaneous approach [5]. In partitioned solution, differential equations of each non-linear device are solved separately using an explicit integration method and represented in the network as a Norton or Thevenin equivalent. The partitioned solution provides advantages such as simplicity, programming flexibility, reliability, and robustness but could result in numerical instability in stiff systems. The stiffness of the system relates to the difference in time constants of different models in the simulation. In the simultaneous solution, implicit integration methods are used to solve the differential equations. The state equations and network equations are solved simultaneously. The resulting equations are non-linear and therefore requires an iterative solution like the Newton method. A simultaneous solution approach allows for larger time-steps (e.g., 10ms) compared to the partitioned solution for handling stiff differential equations. However, more iterations are required in some scenarios (e.g., when applying a fault) resulting longer CPU time which can make the real-time simulation challenging. In the proposed method, the partitioned solution approach is used within the TSA model. It is recommended to use a time-step of less than 4ms in the TSA model for numerical stability and accuracy [8], [16].

The TSA model is implemented using only the positive sequence voltages and currents. Therefore, in the proposed method the unbalances in the external system are not modeled. the equation for the conversion from three phase to phasor (1) is also valid for a balanced three phase system. Therefore, the proposed co-simulation model is recommended to be used in analyzing a balanced system.

B. *Interfacing TSA model running in a larger time-step*

In the proposed approach, DP and EMT models are simulated using the same time-step and the TSA model is simulated using a larger time-step. As discussed in [10], interfacing a TSA model running in a larger time-step into a DP/EMT model can cause numerical instability. The impedance of the two network models decides the stability of the system. In [10], the transient stability boundary bus voltage inside the DP model is updated at every DP time-step to overcome the instability issue. A similar update is done in the work presented herein to make the minimum length requirement of the interface transmission line/s to be proportional to the EMT time-step.

Consider a TSA model with "n" number of dynamic nodes (i.e., nodes where a generator or another dynamic device is connected), "m" number of internal nodes (TSA nodes that are not dynamic nodes or interface nodes) and "k" number of DP interface nodes. The network solution of the $n + m + k$ system can be written as (10). The inverse of the admittance matrix can be partitioned into 9 parts as (10) considering the above three types. The subscripts, "dy", "in" and "DP" in the current and voltage variables denote dynamic nodes, internal nodes, and interface nodes correspondingly.

$$\begin{bmatrix} \underline{V}_{dy} \\ \underline{V}_{in} \\ \underline{V}_{DP} \end{bmatrix} = \begin{bmatrix} Z_{pp} & Z_{pq} & Z_{pr} \\ Z_{qp} & Z_{qq} & Z_{qr} \\ Z_{rp} & Z_{rq} & Z_{rr} \end{bmatrix} \begin{bmatrix} \underline{I}_{dy} \\ \underline{I}_{in} \\ \underline{I}_{DP} \end{bmatrix} \tag{10}$$

where,
$\underline{V}_{dy} = [V_{dy1}V_{dy2}\cdots V_{dyn}]$, $\underline{V}_{in} = [V_{in1}V_{in2}\cdots V_{inm}]$, $\underline{V}_{DP} = [V_{DP1}V_{DP2}\cdots V_{DPk}]$, $\underline{I}_{dy} = [I_{dy1}I_{dy2}\cdots I_{dyn}]$, $\underline{I}_{in} = [I_{in1}I_{in2}\cdots I_{inm}]$, $\underline{I}_{DP} = [I_{DP1}I_{DP2}\cdots I_{DPk}]$.

In (10), the vector $\underline{I}_{DP}$ consists of the current injections from the DP model and is updated at every EMT time-step. The intention is to calculate voltage vector $\underline{V}_{DP}$, at every EMT time-step so the TSA boundary of the DP model is updated at every EMT time-step. The voltage vector at the DP boundary of the TSA model is given in (11).

$$V_{DP} = Z_{rp}I_{dy} + Z_{rq}I_{in} + Z_{rr}I_{DP} \tag{11}$$

$$V_{DP} = V_{tsa} + V_{dp} \tag{12}$$

where,

$$V_{tsa} = Z_{rp}I_{dy} + Z_{rq}I_{in} \tag{13}$$

$$V_{dp} = Z_{rr}I_{DP} \tag{14}$$

The TSA model computes V_{tsa} using (13) at every TSA time-step and sends it to the DP model. In (13), the internal current injection vector I_{in} equals to zero. The current injections vector for dynamic nodes (I_{dy}) varies slowly since it depicts only the electromechanical transients. The DP interface model computes (14) using I_{DP} and Z_{rr} at every DP time-step. In between TSA time-steps, the DP model uses the previous value of V_{tsa} to calculate V_{DP}. The Z_{rr} matrix (size equals to number of DP interface buses) has to be sent to the DP model from the TSA model before the simulation starts in order to calculate V_{dp}. It should be noted that the calculation burden of V_{dp} ($Z_{rr}I_{DP}$) is negligible since the number of DP-TSA interface buses is much less compared to the size of the TSA network.

Let us consider (12). If the voltage V_{tsa} of V_{DP} is updated only at every TSA time-step, chatter can be generated in the EMT waveforms. The magnitude and the frequency of the chatter depend on the time-step of TSA. According to the methodology presented above, in between EMT time-steps, V_{tsa} in (12) remains a constant until the new voltage is received from the TSA side. Therefore, in every TSA time-step, DP model sees a sudden change in V_{tsa} which can produce chatter when large time-steps are used in TSA. As a solution, V_{tsa} is ramped up using the voltages at previous time steps as shown in (15) and (16).

$$\Delta V_{tsa} = V_{tsa}(t) - V_{tsa}(t - \Delta T) \tag{15}$$

$$V_{tsa}(t + k\Delta t) = V_{tsa}(t - \Delta T) + k\frac{\Delta t}{\Delta T}\Delta V_{tsa} \tag{16}$$

where, ΔT = TSA time-step and Δt = DP time-step. The variable k corresponds to current number of the DP time-step within a TSA time-step.

IV. Implementing Co-simulation Model in Real-Time

In the proposed method, every transmission line connecting the EMT model to the TSA model is modeled using DP. The interface results in only one time-step delay, which comes from the EMT-TSA interface. To overcome the time-step delay between EMT and TSA models, the Bergeron model discussed in Section II-B is used to model the transmission line/s. One end of the Bergeron model is modeled inside the EMT model and the other end is modeled inside the DP model with the reduced boundary matrix corresponding to the TSA boundary (Z_{rr}). The propagation delay of waves through the DP lines should be greater than the EMT time-step of the simulation. Finding a transmission line with a length corresponding to the EMT time-step is much easier since the EMT time-step is typically in the microseconds range. It should be noted that major transmission systems more commonly have transposed lines and are generally balanced. The method is not targeted at distribution feeder simulation where long lines are not common and where unbalance operation is more prevalent. The diagram in Figure 2 illustrates the proposed interface for an interface through a single transmission line.

It is recommended to keep some buffer region in between the region of interest (e.g., bus where a fault may be applied) within EMT model and the TSA boundary for accuracy. The buffer region will dampen out the high frequency components of waveform entering the TSA boundary. The size of the buffer zone depends on the system parameters, but two transmission lines would be typically sufficient to separate the TSA interface from the area of interest. In the proposed method, the interface region at the DP model contributes to the buffer region. Consider Figure 3 as an example for an interface network. The electromagnetic transients in bus 1 are focused on the interface network. Let us call the EMT end of the interface DP transmission line as EMT-DP interface bus and the TSA end as the DP-TSA interface bus. In Figure 3, bus 3 is selected as the EMT-DP interface bus and bus 4 is selected as the DP-TSA interface bus. The dynamic phasor model has one transmission line which is inside the grey color dotted box (T-Line 3). The purple bolded area is the buffer zone for the network which includes three T-Lines: two in the EMT model and one in the DP model.

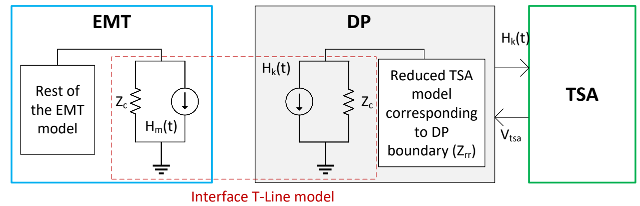

Fig. 2. EMT-TSA interface through a transmission line

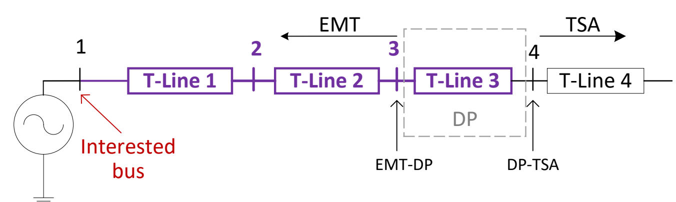

Fig. 3. EMT-TSA buffer region

The TSA and DP parts of the proposed co-simulation model are implemented in Real Time Digital Simulator (RTDS). The EMT part of the proposed co-simulation model is constructed using the library components available in RTDS simulator software; RSCAD.

V. Simulation Results

The proposed co-simulation approach is validated using three test cases. The three test cases include 1) IEEE 39 bus system, 2) modified IEEE 39 bus system with an HVDC in-feed and 3) a 500 bus system. The test systems 1 and 2 are used to validate the accuracy of the co-simulation model. It is recognized that the IEEE 39 bus system is not a practical power system and not large enough to demonstrate proposed co-simulation model's capability on simulating large power systems. IEEE 39 bus system is used to validate the principles used in implementing the co-simulation model. Also, it can be completely simulated using only EMT components in RTDS and therefore the co-simulation model can be validated against the EMT model for accuracy. The complete EMT model used for the validation is built using the RSCAD library components in RTDS. The typical detailed models of power system components (such as synchronous machine model with stator winding dynamics and Bergeron model of transmission line) are used in the EMT simulation [1]. The 500 bus system is used to validate the performance of the co-simulation model when simulating large power systems. In the co-simulation, a time-step of $50\mu s$ is used in the EMT model and a time-step of $1ms$ is used in the TSA model.

A. Validation of the co-simulation model using IEEE 39 bus system

The IEEE 39 bus system is used to validate the co-simulation model (Figure 4). For validation, the entire IEEE 39 bus system is modeled using a complete EMT model and a complete TSA model (using commercially available software). The co-simulation model results are compared against both models. Figure 4 shows the boundaries of EMT and TSA models in the IEEE 39 bus system. Here, buses 28, 29, 38 (shown in red), the connecting transmission lines and shunt devices are modeled using an EMT model. Bus 26 is selected as EMT-DP bus and buses 25 and 27 are selected as DP-TSA interface buses. The transmission lines shown using dotted boxes are modeled using DP. The rest of the 39-bus system is modeled using the TSA model. Case 1 and 2 show the results when faults are applied in the internal and external systems of the power system.

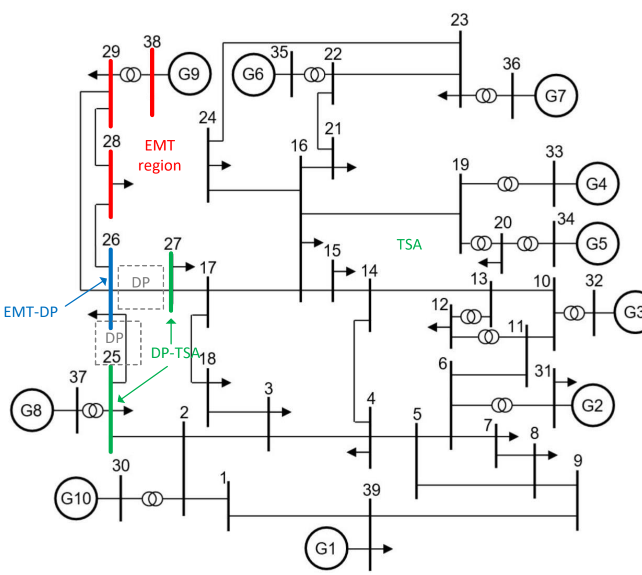

Fig. 4. IEEE 39 bus system

1) Case 1: three-phase fault in the internal system: A three-phase fault is applied at bus 29 for a duration of $0.1s$. The variables of generator 9 are shown in Figure 5. The results show that the co-simulation results closely follow the complete EMT simulation results. The high-frequency content of the waveform is accurately captured by the co-simulation model similar to the EMT model. The pure TSA model does not capture the high-frequency content of the transient.

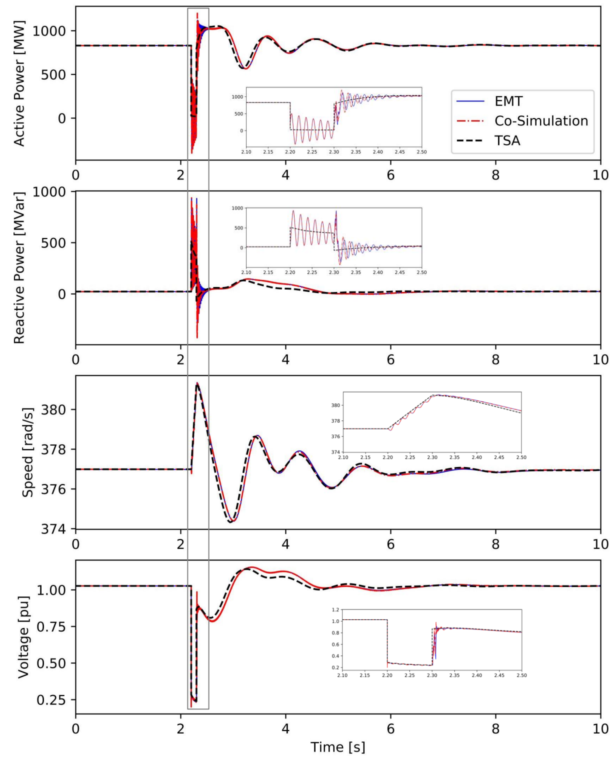

Fig. 5. Generator 9 variables for a fault in the internal system

2) Case 2: three-phase fault in the external system: A three-phase fault is applied at bus 2 in the external system modeled using the TSA model. The variables of generator 1 are shown in Figure 6. The results closely match with the commercial TSA program results. Therefore, it can be concluded that the co-simulation model performs well even under a fault in the external system.

B. Validation of the co-simulation model using IEEE 39 bus system with an HVDC in-feed

In standard IEEE 39 bus power system, generation at bus 38 (generator 9) was replaced using an HVDC in-feed [17] (Figure 7) to validate the performances of the co-simulation model in the presence of high frequency transients in the system. Same interface configuration used in Section V-A is used to prepare the co-simulation model. The co-simulation model results are validated using a complete EMT simulation results. A three-phase fault is applied at bus 29 for a duration of $0.1s$. The dc link current and bus 29 voltage are shown in Figure 8. The results are compared against a complete EMT simulation results. It can be seen that the proposed co-simulation model results closely match with the complete EMT simulation results. The proposed model accurately captures the high frequency transients in the HVDC system and its surrounding area.

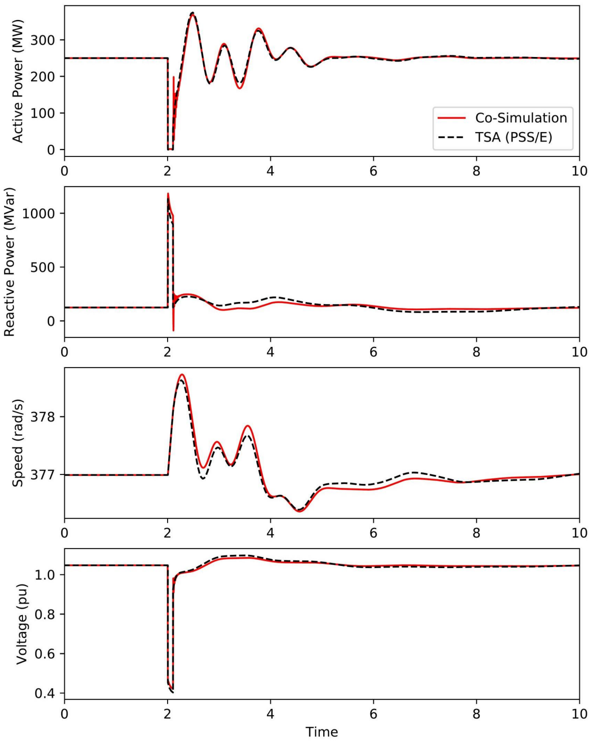

Fig. 6. Generator 1 variables for a fault in the external system

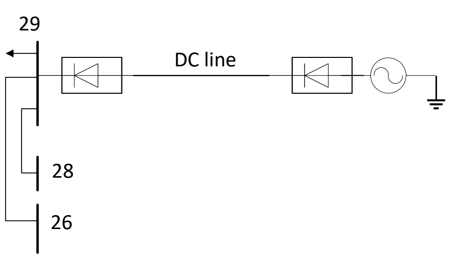

Fig. 7. Modified portion of the IEEE 39 bus system with the HVDC in-feed

C. *Performance of the co-simulation model for a large power system*

The proposed co-simulation model is used to simulate a power system with 500 buses and 90 generators to demonstrate its capability in simulating large power systems. A small part of the 500-bus system (containing buses 3, 4, 63, 64, 354, 355, 422, 479, 480, 481, 482, 483 and 484) is selected and modeled using an EMT model. Buses 62 and 421 are selected as the EMT-DP interface buses and buses 1, 287, 457 are selected as the DP-TSA interface buses. The EMT region and the interface buses are shown in Figure 9. Only one RTDS processor core is used to model the TSA part of the 500-bus system. A three-phase fault is applied at bus 479 for $0.1s$ duration. The results of the co-simulation model are compared against the results obtained from a pure TSA model using a commercially available TSA software. The variables of the generator connected to the bus 480 are

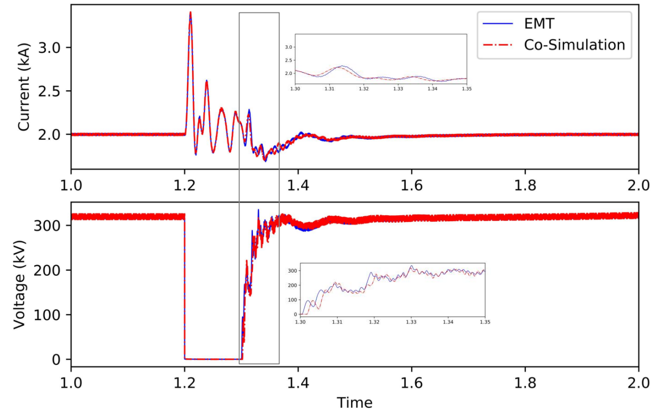

Fig. 8. DC line current and bus 29 voltage for a fault at bus 29

shown in Figure 10 for both co-simulation and pure TSA models. The electromechanical response of the two models is similar however only the co-simulation model captures the high-frequency content of the dynamic response.

If the TSA part of the 500 bus system is simulated using an EMT model, at least 14 times more computational resources (cores) are required compared to the proposed co-simulation model.

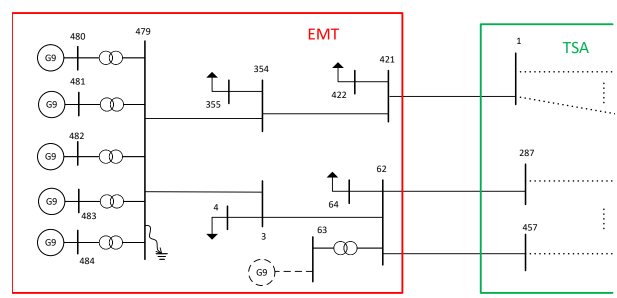

Fig. 9. The EMT region and the interface buses of the 500-bus system

VI. Conclusions

An EMT-TSA co-simulation model has been presented in this paper. The interface between the EMT model and the TSA model has been done using the delay in transmission line connecting EMT and TSA models. The interface transmission line has been modeled using DP. The length of the transmission line is determined according to the time-step of the EMT model, although the TSA model is simulated using a much larger time-step. The co-simulation model has been validated using the IEEE 39 bus system. It has been demonstrated that a 500-bus system can be simulated in real-time using significantly less computing resources.

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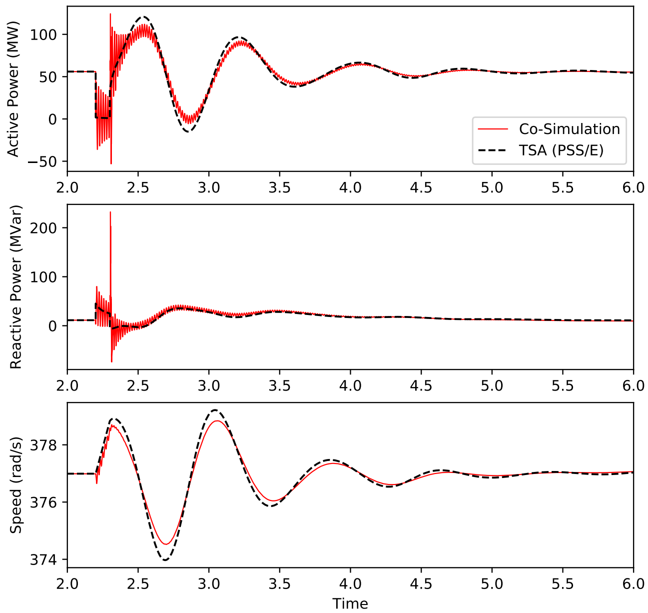

Fig. 10. Generator variables at bus 480 for a fault in the EMT network

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