Practical Challenges of Hybrid Simulations Interfacing with Real-Time Digital Simulators

P. Zadkhast, X. Lin, F. Howell, B. Ko, K. Hur

***Abstract*--This paper discusses practical challenges encountered when interfacing Transient Stability Analysis (TSA) packages and Real-Time Digital Simulators for hybrid simulation studies. Various interfacing approaches are examined and single-port Thevenin equivalent is proposed as a suitable and practical solution to represent the TSA-side system in Electro-Magnetic Transient (EMT) simulation. The shortcomings of this representation are discussed and a quantitative measure is proposed to evaluate validity of the interface, which helps capturing the cases where the simulation may run into numerical instability due to simple representation of the external system. The effectiveness of the proposed technique is demonstrated using a practical power system with over 5,600 buses.**

***Keywords*: Hybrid Simulation, Interfacing Techniques, Real-Time Digital Simulation, Transient Stability Analysis.**

I. Introduction

HYBRID simulation or Co-Simulation has been the subject of research for decades and it aims at improving accuracy and efficiency of simulation studies by separating the electrical system into two parts. The region of focus which is also called internal system is simulated in an Electro-Magnetic Transient (EMT) package while the rest of system that is typically much larger and commonly referred to as external system is represented in positive sequence and phasor domain, simulated in a Transient Stability Analysis (TSA) tool.

The efforts in developing a hybrid simulator dates back to early 1980's [1], [2] where a detailed EMT type HVDC model was used inside an AC system simulated by a TSA package. In recent years, most of studies have focused on the representation of TSA-side system in internal model. In this regard, [3]-[6] used Frequency Dependent Network Equivalent (FDNE) technique to have a detailed representation of external system. While FDNE provides a detailed picture of the transient response of the external system, it typically needs to use a high degree transfer function that might become numerically unstable during a simulation. Moreover, FDNE is built in advance and it cannot be changed once the simulation starts, making it difficult to apply a disturbance in the external system. To address these challenged, a multi-port Thevenin equivalent was proposed in [7]-[10] where external system is represented by a set of Norton sources and Thevenin impedances, connected through mutual-impedances. The multi-port Thevenin equivalent maintains simplicity and passivity of the interface between internal and external systems and its parameters are easy to calculate. However, since this is a simple representation of external system, a buffer region needs to be considered between interface and core part of internal system where a disturbance may be applied or harmonic sources are available. This ensures that current injections converted from EMT-side to TSA-side remain close to sinusoidal waves.

Various methods proposed in the literature are mainly developed to interface offline EMT tools with the TSA packages. In the recent years, real-time simulators have become popular in testing protective relays, control logic of various devices, etc., and they are now widely available at power system labs around the globe. As a result, there is a growing need to interface the real-time simulators with transient stability simulation tools to help engineers retaining larger portion of the electrical system in designing damping control, testing Phasor Measurement Units (PMUs), testing out-of-step relays, detailed analysis of renewable generator control system, and similar studies that require modeling of low-frequency electro-mechanical oscillations of power systems as well as the detailed electro-magnetic transients of the devices/region of interest. While real-time simulators and offline EMT tools share many features and most of theoretical foundations of the developed interfacing techniques still apply to the hybrid simulation study with a real-time simulator, there are a number of practical limitations that need to be addressed. In particular, the type of interface being used, location of interfaces in the model and the required computational resource may become limiting factors in hybrid simulation studies. To this end, this paper continues the previous work to discuss practical challenges in interfacing TSA with real-time simulator. The main features and contributions of this paper are summarized below:

1. The challenges in using FDNE and multi-port Thevenin equivalent in a hybrid simulation study in the presence of real-time simulators are discussed.
2. It is proposed to use a single-port Thevenin equivalent in such hybrid simulation studies and a quantitative measure is proposed to evaluate the validity of the interface.
3. A practical power system with over 5,600 buses is used to demonstrate accuracy and effectiveness of the propose approach.

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II. BACKGROUND

In a hybrid simulation study, the power system is divided into two regions, which are connected to each other through a set of boundaries a shown in Fig. 1. Typically, the small region of system is simulated in EMT package and the larger section is handled by TSA simulator. In hybrid simulation study with real-time simulators, the TSA simulation runs in real-time (may be intentionally slowed down if necessary) and at the end of each TSA's integration time-step, the boundary injections are updated and passed to the other tool as shown in Fig. 2.

The quantities in internal system are three-phase that needs to be converted to an equivalent positive sequence, phasor domain signal to be used as an injection signal on the TSA-side. Likewise, phasor-domain injections calculated by TSA package need to be transformed into the equivalent three-phase signals. Conversion of phasor-domain to three-phase quantities is straightforward and no information is lost during this process. Let $\vec{I}_{TSA} = I\measuredangle\theta$ represents the phasor-domain injection at one of boundaries between internal and external systems that needs to be converted into an equivalent three-phase injection signal. Then, the equivalent three-phase quantities can be written as:

$$\begin{aligned} \alpha(t) &= 2\pi f_0 t + \theta \\ i_A(t) &= \sqrt{2}.I.sin\big(\alpha(t)\big) \\ i_B(t) &= \sqrt{2}.I.sin\left(\alpha(t) - \frac{2}{3}\pi\right) \\ i_C(t) &= \sqrt{2}.I.sin\left(\alpha(t) + \frac{2}{3}\pi\right) \end{aligned} \tag{1}$$

where f_0 represents base system frequency of TSA-side system, and i_A, i_B, and i_C represent three-phase components of the current that are injected into corresponding boundary in the internal system.

Conversion of three-phase quantities to phasor domain is more challenging and some information will be lost during the conversion process. In this paper, an energy-based technique [11] is used to perform the conversion. In this approach, total energy absorbed from internal system is calculated at each boundary and the equivalent phasor-domain current that injects the same amount of energy into external system is calculated, which helps improving passivity of interface. To this end, let P_B and Q_B represent active and reactive power flowing through one of boundaries on EMT-side of the simulation calculated as:

$$\begin{aligned} P_B &= v_A i_A + v_B i_B + v_C i_C \\ Q_B &= v_A i_B + v_B i_C + v_C i_A \end{aligned} \tag{2}$$

where v and i represent the voltage and current at the boundary on the EMT-side. Since instantaneous powers can

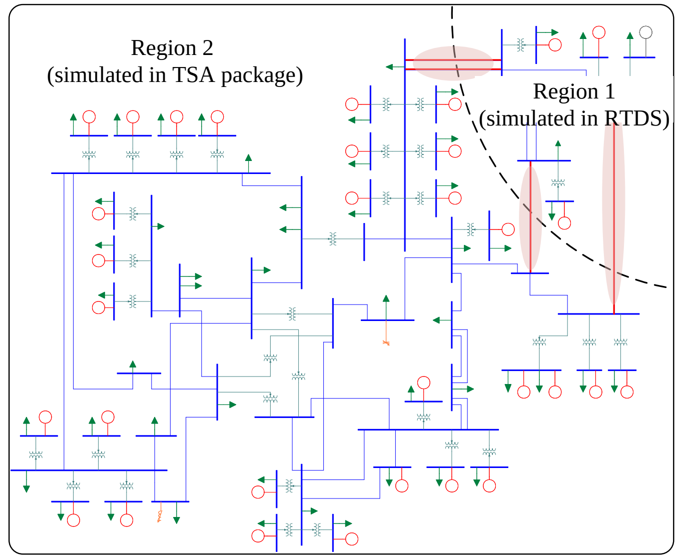

Fig. 1. Dividing power system by a set of boundaries (shaded areas) into two regions to be simulated in EMT and TSA packages separately.

show fast transients, they need to be smoothed out before being used in calculation of equivalent injection phasor to avoid numerical issue on TSA-side. Let $\tilde{P}_B$ and $\tilde{Q}_B$ be averaged power calculated by passing P_B and Q_B through a low-pass filter with a small time-constant (~10ms). Using averaged power flowing through the boundary and by calculating the boundary voltage phasor $\vec{V}_B$ as in [11], phasor of boundary current flowing into TSA-side is calculated as:

$$\vec{I}_B = \left(\frac{\tilde{P}_B + j\tilde{Q}_B}{\vec{V}_B}\right)^* \tag{3}$$

III. CHALLENGES IN IMPLEMENTING HYBRID SIMULATOR

A. *Representation of TSA-Side System in Real-Time Simulator*

EMT-side system is typically represented as a current source on TSA-Side. At the end of each TSA's integration step, current phasor (3) is updated and passed to TSA program which is used to represent internal system as a set of constant current sources. On the other hand, there are two different methods to represent TSA-side system in EMT model: Frequency Dependent Network Equivalent [FDNE] [3]-[6] and multi-port Thevenin equivalent [7]-[11]. In addition to shortcomings discussed in section I, FDNE may need significant computational resources especially when number of boundaries is large, which typically happens when a central or meshed region of electrical grid is selected as internal system. As a result, the FDNE component can occupy a considerable loading portion of a real-time simulator that degrades overall performance of the simulator as parallel computation will not be efficiently manipulated. Moreover, one FDNE block is constructed to represent the whole external system and therefore, it should run purely on one subsystem with many connections to the rest of internal system. This scheme can technically become challenging to be implemented as a real-time simulator case.

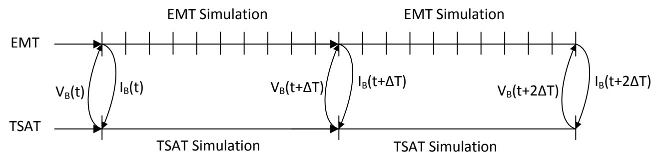

Fig. 2. Exchanging boundary injections at the end of each TSA integration step.

Multi-port Thevenin equivalent is another approach to represent TSA-side system which has been of interest when interfacing with offline EMT packages such as PSCAD. On the other hand, real-time simulator breaks the system into multiple subsystems to be simulated on different computational processors. The subsystems need to be connected only via distributed transmission line models, making it difficult to interconnect all boundaries that might have been placed in different subsystems. Moreover, having coupling impedance between each pair of boundaries can significantly increase computation burden of processors without noticeably improving simulation accuracy.

Due to these limitations, using single-port Thevenin equivalent have been identified as the most practical option in hybrid simulation studies involving real-time simulators. In this approach, the equivalent impedance of the TSA-side system is calculated at each boundary and it is used along with a Norton source to represent the TSA-side system as shown in Fig. 3. When using a simple Norton equivalent, the TSA-side system should show low frequency dynamics at the boundaries so that the external system can be represented by an equivalent Norton source during one integration step. This can be achieved if boundaries on TSA-side are sufficiently far apart (so that there is no strong coupling between boundaries) and if integration step-size on TSA-side of simulation is small enough. A value of 4ms is typically sufficient to meet the integration step-size requirement.

IV. Electrical Distance Between Boundaries

One of fundamental assumptions in hybrid simulation studies is that EMT-side system is well damped around the boundaries to demonstrate only electromechanical oscillations at the boundaries. If this condition is not satisfied, the conversion made to transform three-phase quantities into phasor domain will have high frequency components and fast transients that can cause numerical issue for TSA package. For example, if a harmonic or unbalanced source in EMT-side system is too close to boundary, the transformed phasor-domain injections will have components with f_0, $2f_0$, etc. Considering that integration step-size used in TSA-side system is suitable to capture only low frequency transients, such fast dynamics may lead to numerical instability. In this situation, using higher order integration techniques such as fourth-order Runge-Kutta may help to improve robustness of TSA-side simulation but still the simulation will remain vulnerable to numerical instability. As a result, the injections at the EMT-side boundaries should be close to sinusoidal signal, which is partially achieved by maintaining a buffer zone between harmonic/unbalanced sources and boundaries.

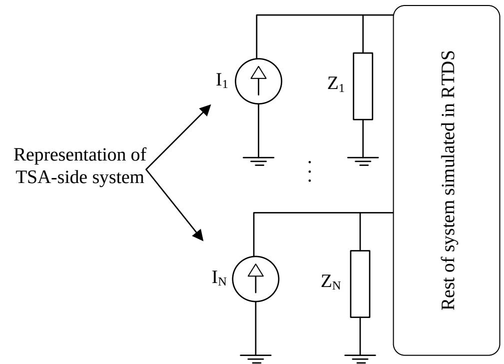

Fig. 3. Representing TSA-side system as a set of Norton equivalents in EMT-side system.

Having boundaries that are electrically close to each other on TSA-side is another common source of numerical instability in hybrid simulation studies. The reason is that electrical network is modeled algebraically in TSA studies and having two or multiple boundaries with strong coupling can effectively create an algebraic loop, especially when there is a weak connection between boundaries and the rest of external system. In hybrid simulation analysis, such algebraic loop is being observed on the EMT-side system, which causes fast dynamic interaction between the boundaries on both sides of simulation. Due to relatively large integration step-size used in TSA package, such fast transients can cause numerical instability. To avoid such situation, a quantitative measure of the electrical distance between boundaries is needed to evaluate possibility of numerical instability.

To this end, let B_i and B_j represent two boundaries on TSA-side. Assuming that electrical distance between these boundaries and other boundaries is much larger than the distance between B_i and B_j, the equivalent circuit shown in Fig. 4 demonstrates how boundaries B_i and B_j affect each other. To calculate a quantitative measure for impact of B_j on B_i, the change in equivalent Norton current source of B_i is considered:

$$\Delta\vec{I}_{Ni} = \frac{1}{Z_{ii}}\Delta\vec{V}_i - \Delta\vec{I}_j \tag{4}$$

where ΔV_i represent the change in the voltage of B_j; ΔI_j is the change in current injected at B_j at the end of a TSA's integration step; ΔI_{Ni} is the change in equivalent Norton source current of B_i that is sent to EMT-side system; and Z_{ii} is the equivalent Thevenin impedance seen at B_i as:

$$\vec{Z}_{ii} = \frac{Z_1(Z_2+Z_3)}{Z_1+Z_2+Z_3} \tag{5}$$

Using Fig. 4, ΔV_i can be written as:

$$\Delta\vec{V}_i = \vec{Z}_{ii}\Delta\vec{I}_i - \frac{Z_1 Z_2}{Z_1+Z_2+Z_3}\Delta\vec{I}_j \tag{6}$$

Replacing (5) and (6) in (4) results in:

$$\Delta\vec{I}_{Ni} = \Delta\vec{I}_i - \frac{Z_1 Z_2}{Z_{ii}(Z_1 + Z_2 + Z_3)}\Delta\vec{I}_j \quad (7)$$

From Fig. 4, it can be seen that the cross-impedance between B_i and B_j can be formulated as:

$$\vec{Z}_{ji} = \left.\frac{\Delta\vec{V}_j}{\Delta\vec{I}_i}\right|_{\Delta\vec{I}_j=0} = \frac{Z_1 Z_2}{Z_1 + Z_2 + Z_3} \quad (8)$$

and therefore, the change in $\Delta\vec{I}_{Ni}$ can be written as:

$$\Delta\vec{I}_{Ni} = \Delta\vec{I}_i - \frac{\vec{Z}_{ji}}{\vec{Z}_{ii}}\Delta\vec{I}_j \quad (9)$$

Eq. (9) shows that the ratio between cross-impedance between B_i and B_j and the Thevenin impedance at B_i determines the level of impact that current injection at B_j can have on B_i. Typically, $\vec{Z}_{ii}$ is much larger than $\vec{Z}_{ji}$ and this makes $\Delta\vec{I}_{Ni}$ mainly dependent on the current injected at B_i. However, when boundaries are electrically close, $\vec{Z}_{ji}$ becomes comparable to $\vec{Z}_{ii}$ and any small change in $\Delta\vec{I}_j$ will be reflected in equivalent Norton current of B_i.

Based on (9), boundaries that are electrically close can be captured using by calculating an impedance ratio between B_i and B_j as:

$$Z_r^{(i,j)} = \left|\frac{\vec{Z}_{ji}}{\vec{Z}_{ii}}\right| \times 100 \quad (10)$$

If boundaries are identified efficiently, impedance ratio will be insignificant. However, for boundaries that are electrically close, the impedance ratio will be close to 100, indicating that numerical instability may be observed in simulation. Based on authors' experience, any value larger than 85% can indicate a potential numerical instability in the problem. It should be noted that this value has been derived based on working with various practical power systems and it may be different in special circumstances. Also, having a large impedance ratio does not necessarily lead to numerical instability and other factors such as strength of electrical system along with network configuration play an important role in stability of hybrid simulations. Nonetheless, in cases where numerical instability is observed, the impedance ratio (10) provides a measurable quantity to identify source of issue.

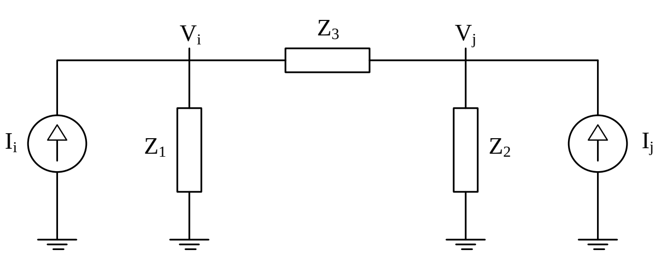

Fig. 4. Approximate electrical circuit between boundaries B_i and B_j.

V. Simulation Studies

A practical power system with 5,619 buses and 854 generators is used here to demonstrate effectiveness of the proposed approach. Due to confidentiality agreement, details of the system cannot be disclosed. The internal system represented in EMT is shown by shaded area in Fig. 5. This system has 25 buses and 11 generators with a total of ~4.5GW output. There are 7 boundaries between internal and external systems that are highlighted in red in Fig. 5. It should be noted that external system expands on the right side but the expansion it is not shown in this figure.

The internal system is simulated on 1 real-time simulator rack with 50μs step-size and external system is simulated in TSAT with a 4ms time-step. The TSAT-RTDS Interface (TRI) is used to provide a communication interface between TSA and EMT simulation tools. This application provides a custom component on the EMT-side that represents each boundary as a single-port Thevenin equivalent. The equivalent impedance is calculated by the TSAT and passed to this custom component at the start of simulation. Also, the Norton source current at each boundary is calculated at the end of each integration step and sent to the EMT-side. Likewise, the boundary injection in the EMT program is converted to an equivalent phasor-domain signal and sent back to TSAT. A VC707 FPGA board from Xilinx is used to exchange signals between real-time simulator rack and the PC that hosts TSAT.

A fault is applied 10 seconds after starting hybrid simulation at high tension bus of one of generators and cleared in 0.1 seconds. Fault location is shown with a red arrow in Fig. 5. Also, in the first 10 seconds system runs without any disturbance to ensure that the simulation remains stable and any mismatch due to difference between EMT model and powerflow solution dies out. The generator in internal system that is the closest unit to the fault is monitored and results are compared with pure TSA study. The generator speed, active,

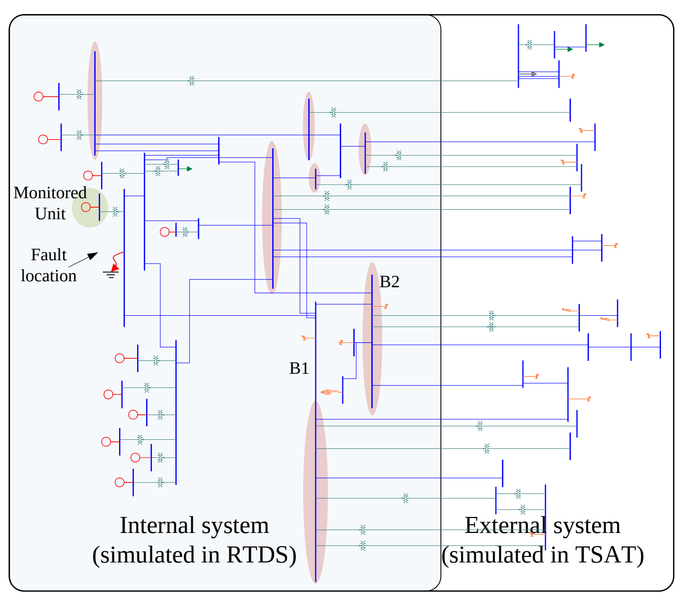

Fig. 5. The test system used in section V to perform hybrid simulation studies.

and reactive powers are shown in Fig. 6 to Fig. 8, where it can be seen that hybrid simulation study results match pure TSA and this verifies that using single-port Thevenin equivalent does not affect have adverse impact on simulation results.

In the next test, impact of boundaries that are electrically close in external system is examined. To this end, the boundaries defined in Fig. 5 are modified to move buses B1 and B2 to the external system. In addition, a few nearby lines are outaged to have a weak connection between B1/B2 and the rest of external system. The impedance ratio (10) calculated for all boundaries are shown in Table 1 where all values are less than 60% except the impedance ration between B1 and B2 that indicates a strong electrical coupling between these boundaries created by the transmission line connecting B1 to B2 that has j0.01pu impedance. This line is highlighted in red in Fig. 9.

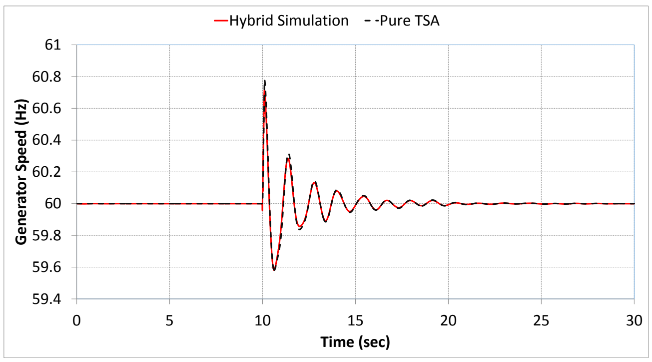

Fig. 6. Speed of generator closest to the fault.

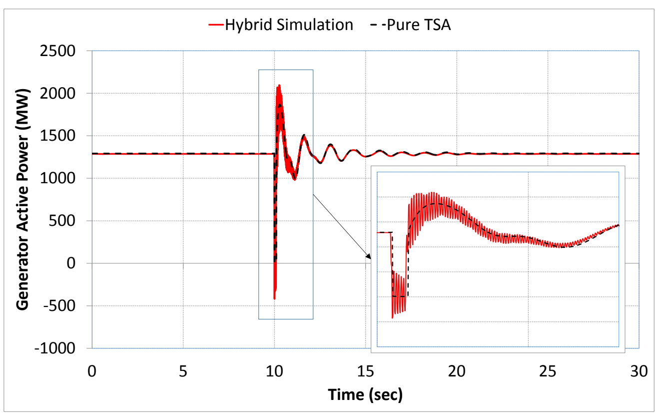

Fig. 7. Active power of the generator closest to the fault.

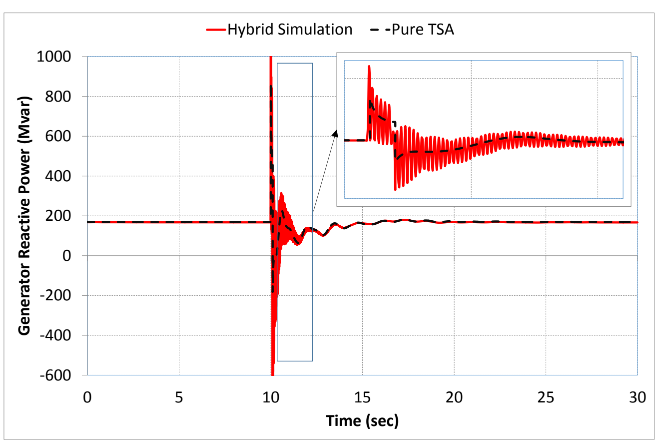

Fig. 8. Reactive power of the generator closest to the fault.

The hybrid simulation case with the modified boundaries is simulated and terminal voltage of the same generator in a no-disturbance test is shown in Fig. 10, where it can be seen that the simulation is numerically unstable. As discussed, the reason for such instability is that electrically close boundaries create a fast and almost algebraic loop that can experience rapid changes. Since, boundaries B1 and B2 are weakly connected to rest of the external system, their voltages become very sensitive to solution of internal system and therefore, high-frequency transients are being transferred to TSA-side of the problem and causes numerical instability.

To verify this explanation, two more simulations are performed:

1. The boundaries are changed back to include B1 and B2 in internal system. The result for this test is shown as a dashed, black curve in Fig. 10.
2. Only for boundaries B1 and B2, injection phasor received from internal system is passed through a smoothing filter with 20ms time-constant before being injected into external system. This idea is shown in Fig. 11, where $\vec{I}_{EMT}$ represents injection phasor calculated by TRI on the EMT-side, and $\vec{I}_{TSA}$ represents the current that is actually being injected into the TSA system.

In the second test, smoothing delay adds lag to the fast loop created by B1 and B2 and helps slowing down transients circulating between these two boundaries. As can be seen in Fig. 10, the simulation becomes numerically stable using both tests. These two extra simulations verify that the numerical instability was caused by having strong coupling between B1 and B2, which can be resolved by slighting modifying boundaries between internal and external systems.

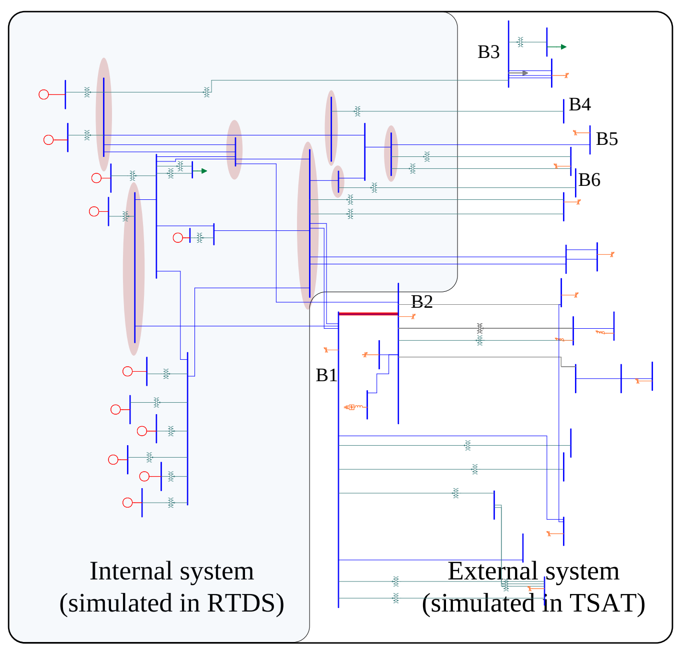

Fig. 9. Modifying boundaries to move buses B1 and B2 to external system.

TABLE 1 - IMPEDANCE RATIO CALCULATED FOR ALL BOUNDARIES

	B1	B2	B3	B4	B5	B6	B7
B1	N/A	97.67	1.65	1.41	2.5	1.9	1.16
B2	93.38	N/A	1.55	1.33	2.35	1.8	1.09
B3	1.75	1.72	N/A	16.6	2.8	17.6	12.9
B4	1.9	1.9	21.68	N/A	5.04	20.47	16.5
B5	10.32	10.1	10.85	14.9	N/A	13.3	9.11
B6	3.06	3.01	26.26	23.4	5.15	N/A	21.16
B7	5.06	4.9	53.02	51.9	9.66	58.18	N/A

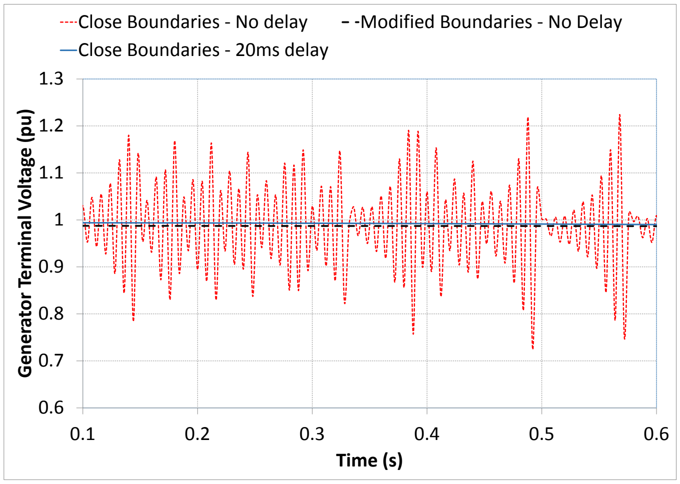

Fig. 10. Numerical instability observed when boundaries are electrically close in external system.

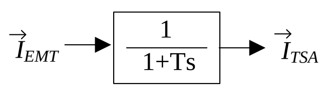

Fig. 11. Passing internal system's injections ($\vec{I}_{EMT}$) through a smoothing filter before being injected into external system.

VI. CONCLUSIONS

This paper discusses practical challenges of developing a hybrid simulator to interface a transient stability simulation package with real-time digital simulators. The main focus of the work is to identify the potential source of numerical instability in simulations and the Impedance Ratio is proposed as a measurable quantity of the coupling between boundaries in external system. This measure helps identifying situations where boundaries are strongly coupled on the TSA-side and they may cause numerical instability in the simulation. A practical power system with over 5,600 buses was used to demonstrate how the proposed technique can be applied to evaluate relative coupling between boundaries and to verify accuracy of the developed method. The simulation results show that the strong coupling between boundaries can lead to numerical instability and the Impedance Ratio helps identifying such boundaries on the TSA-side.

VII. REFERENCES

[1] M. D. Heffernan, K. S. Turner, J. Arrillaga and C. P. Arnold, "Computation of AC-DC System Disturbances, Parts I, II and III", *IEEE Trans on Power Apparatus and systems*, vol. PAS-100, No.11, pp. 4341-4363, Nov. 1981.

[2] J. Reeve and R. Adapa, "A New Approach to Dynamic Analysis of AC Network Incorporating Detailed Modeling of DC Systems, Part I and II", *IEEE Trans on Power Delivery*, vol.3, No.4, pp.2005-2018, Oct. 1988.

[3] A. S. Morched, J. H. Ottevangers, L. Marti, "Multi-Port Frequency Dependent Network Equivalents for the EMTP", *IEEE Trans on Power Delivery*, vol.8, No.3, pp.1402-1412, Oct. 1993.

[4] B. Gustavsen and A. Semlyen, "Rational Approximation of Frequency Domain Responses by Vector Fitting", *IEEE Trans on Power Delivery*, vol.14, No.3,pp.1052-1061, Jul. 1999.

[5] X. Lin, A. Gole and M. Yu, "A wide-band multi-port system equivalent for real-time digital power system simulators," *2009 IEEE Power & Energy Society General Meeting*, Calgary, AB, 2009, pp. 1-1.

[6] Yi. Zhang, A. M. Gole, W. Wu, B. Zhang and H. Sun, "Development and Analysis of Applicability of a Hybrid Transient Simulation Platform Combining TSA and EMT Elements," *Power Systems, IEEE Transactions on*, vol.28, pp. 357-366, 2013.

[7] H. Singh and A. Abur, "Multi-port equivalencing of external systems for simulation of switching transients," *IEEE Trans. Power Del.*, vol. 10, no. 1, pp. 374–382, Jan. 1995.

[8] L. Wen-zhuo, H. Jun-xian, T. Yong, W. Lei, S. Xin-li and F. Sheng-tao, "An electromechanical/electromagnetic transient hybrid simulation method that considers asymmetric faults in an electromechanical network," Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES, Phoenix, AZ, 2011, pp. 1-7.

[9] X. Han and H. Zhang, "Power system electromagnetic transient and electromechanical transient hybrid simulation based on PSCAD," 2015 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), Changsha, 2015, pp. 210-215.

[10] Q. Huang and V. Vittal, "Application of Electromagnetic Transient-Transient Stability Hybrid Simulation to FIDVR Study," in IEEE Transactions on Power Systems, vol. 31, no. 4, pp. 2634-2646, July 2016.

[11] Xi Lin, *System Equivalent for Real Time Digital Simulator*, Ph. D. thesis, University of Manitoba, 2010

[12] Real Time Digital Power Systems Simulator (RTDS), RTDS Technologies Inc. https://www.rtds.com/

[13] Transient Stability Analysis Tool, Powertech Labs Inc., http://www.dsatools.com/tsat/

[14] TSAT-RTDS Interface, Powertech Labs Inc., online: http://www.dsatools.com/wp-content/uploads/2018/04/TRI_brochure.pdf