# An Implicitly-Coupled Solution Approach for Combined Electromechanical and Electromagnetic Transients Simulation

Shrirang Abhyankar, Alexander J. Flueck, *Senior Member, IEEE*

***Abstract*—This paper presents a novel implicitly-coupled solution approach for the combined electromechanical and electromagnetic transients simulation. Unlike the existing hybrid simulators that use an explicit approach to interface separate transient stability (TS) and electromagnetic transients (EMT) programs, the authors propose combining the equations of the two simulators and solving them simultaneously by an implicit approach. To combine the two sets of equations with their different time steps, and ensure that the TS and EMT solutions are consistent, the equations for TS and coupled-in-time EMT equations are solved simultaneously, referred to as TSEMT simulation. The simulation results for the proposed implicitly-coupled solution approach on the WECC 9-bus system are discussed. Along with the implicitly-coupled solution approach, a novel strategy, referred to as TS3ph-TSEMT, based on difference between the phasor boundary bus voltages of the detailed and external systems is also proposed to terminate the implicitly-coupled TSEMT simulation and continue with only the TS simulation. The computational efficiency of the proposed TS3ph-TSEMT approach is presented for the 9-bus and 118-bus systems.**

***Index Terms*—Hybrid simulator, Implicitly-coupled solution approach, Transient stability, Electromagnetic transients.**

## I. INTRODUCTION

THE simulation of electrical power system dynamic behavior is done using transient stability simulators (TS) and electromagnetic transient simulators (EMT). A Transient Stability simulator, running at large time steps, is used for studying relatively slower dynamics e.g., electromechanical interactions among generators, and can be used for simulating large-scale power systems. In contrast, an electromagnetic transient simulator models the same components in finer detail and uses a smaller time step for studying fast dynamics e.g. electromagnetic interactions among power electronics devices. Simulating large-scale power systems with an electromagnetic transient simulator is computationally inefficient due to the small time step size involved. A hybrid simulator attempts to interface the TS and EMT simulators which are running at different time steps. By modeling the bulk of the large-scale power system in a transient stability simulator and a small portion of the system in an electromagnetic transient simulator, the fast dynamics of the smaller area could be studied in detail, while providing a global picture of the slower dynamics for the rest of power system.

In the existing hybrid simulation interaction protocols, the two simulators run independently, exchanging solutions at regular intervals. However, the exchanged data is accepted without any evaluation, so errors may be introduced. While such an explicit approach may be a good strategy for systems in steady state or having slow variations, it is not an optimal or robust strategy if the voltages and currents are varying rapidly, like in the case of a voltage collapse scenario.

This paper proposes an implicitly coupled solution approach for the combined transient stability and electromagnetic transient simulation. To combine the two sets of equations with their different time steps, and ensure that the TS and EMT solutions are consistent, the equations for TS and coupled-in-time EMT equations are solved simultaneously. While computing a single time step of the TS equations, a simultaneous calculation of several time steps of the EMT equations is proposed.

## II. HYBRID SIMULATORS

A hybrid simulator connects a transient stability simulator and an electromagnetic transient simulator, running separately at different time steps, with an interface or sequence of actions to exchange data as well as reduced circuitry. The need for the interface protocol and the associated circuitry is due to the differences in TS and EMT as shown in Table I.

TABLE I
DIFFERENCES BETWEEN TS AND EMT

| Property | TS | EMT |
|---|---|---|
| Time step | Milliseconds | Microseconds |
| Network Modeling | Balanced positive sequence | Three phase unbalanced |
| Voltages and currents | Phasor | Instantaneous |

The idea of hybrid simulation was first proposed by Hefernan, et. al., in [2] to simulate combined HVAC-HVDC systems. They modeled a HVDC link in detail within a stability based AC system framework, thus exploiting the advantages of both EMT and TS. They achieved this by executing TS and EMT alternately with periodic coordination of the results. Reference [4] proposed that the boundary of the interface should be extended into the AC network further for taking into consideration the effect of harmonics generated by power electronics on the AC network.

Shrirang Abhyankar (e-mail: abhyshr@mcs.anl.gov) is with the Mathematics and Computer Science Division, Argonne National Laboratory, Argonne, IL 60439.

A. J. Flueck (e-mail: flueck@iit.edu) is with the Department of Electrical and Computer Engineering, Illinois Institute of Technology, Chicago,IL, 60616 USA.

Reference [5] presented another approach to take the harmonics into account. In the EMT program, the network equivalent for the TS network is represented by a frequency-dependent equivalent, instead of a simple fundamental frequency equivalent circuit used by Heffernan and Reeve. Reference [7] basically adopted the approaches described above, i.e., extending the interface location into the AC network to some extent, and at the same time, having a frequency-dependent TS network equivalent. Kasztenny, et. al.,[8] have also discussed a general method for linking different modeling techniques such as waveform-type, phasor-type, and algebraic-type simulation techniques into one complete model.

In the hybrid simulator, the power system network is partitioned into two sub networks; a large network (TS domain of operation) and a smaller network run with EMT. The large network has been called external system [3]-[5], electromechanical transient network [6], TS-program subsystem [9], while the smaller system has been called detailed system [3]-[5], EMT network[6], instantaneous network [10]. In this paper, the larger network will be called the external system and the smaller system will be called the detailed system. To connect the external system simulated with TS and the detailed system simulated with EMT, an interface is required over space, time and waveform. Reference [1] is an excellent reference for the state of the art in hybrid simulators and provides a very good overview of the space, time, and waveform interfaces.

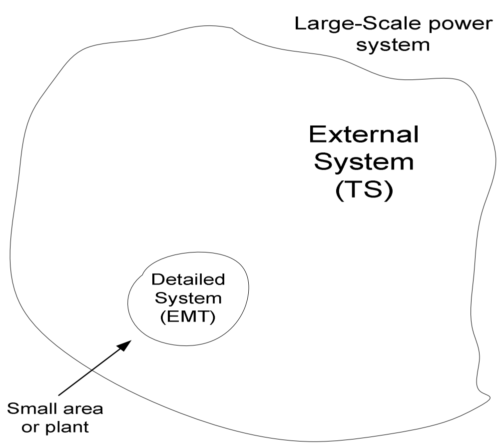


Fig. 1. Detailed and external system

### A. Hybrid simulator interaction protocols

Since the TS and EMT run at different time steps, synchronization of these simulators is required for data exchange. This synchronization is done through predefined sequential actions which coordinate the data exchange between TS and EMT simulators [1]. Both serial and parallel [3],[13] interaction protocols have been proposed so far. In serial protocols, only one simulator either TS or EMT, runs while the other is idle. In parallel protocols, both simulators run at the same time. Fig. 2 describes the data exchange between the TS and EMT simulators, for one TS time step, in a serial interaction protocol.

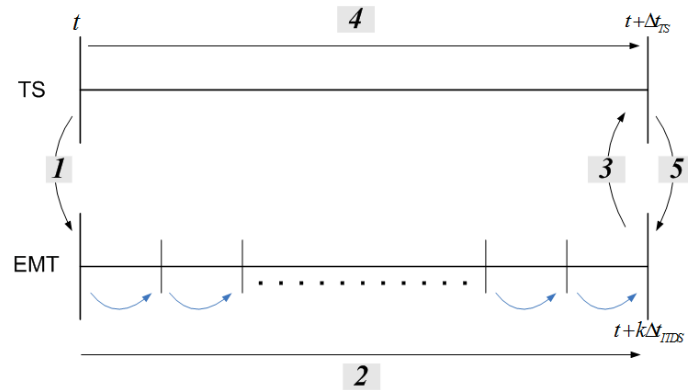


Fig. 2. Serial interaction protocol for one TS time step

The sequence of actions taken in a serial interaction protocol are as follows:

1) TS passes the external system equivalent to EMT at time $t$.
2) EMT solves the detailed system equations at $t+\Delta t_{EMT}$. Once it computes the solution, it proceeds to compute the solution for $t+2\Delta t_{EMT}$ and so on, till it computes the solution at time $t+k\Delta t_{EMT}$ which is equal to $t+\Delta t_{TS}$.
3) At this point, EMT computes the equivalent of the detailed system and passes it to TS.
4) The TS simulator, which is still at time t, solves the external system for the next TS time step solution at time $t+\Delta t_{TS}$.

This completes one time step of the hybrid simulator and steps 1-4 are repeated for future time steps.

It is to be noted here that the external system equivalent is not updated when EMT is running, i.e., it is held constant for all the EMT time steps within a TS time step. This equivalent can be also derived from some extrapolated history data, but either way, it may not accurately predict the conditions at the next TS time step. While such an approach would be sufficient if the TS system is evolving slowly, i.e., there is a small difference between the voltages and currents at two consecutive time steps, for large changes this approach may not be suitable.

Another point to note here is that no iterations are done between TS and EMT to check if the solutions at each TS and EMT boundary are consistent. Having no iterations is probably sufficient when the external system equivalent does not change much, and it may be adequate for the gradually changing external system voltage profile. However, for large changes in voltages between consecutive TS time steps, iterations would be needed to update the external system equivalent repeatedly. Due to the explicit coupling, more iterations would be required and the solution still might diverge.

We present simulation results for the serial interaction protocol on the test WECC 9-bus system to justify our argument. The detailed system consists of buses 7, 8, and 9 with two transmission lines 7-8 and 8-9 and a load modeled as constant impedance on bus 8. Buses 7 and 9 form the boundary buses.

As a disturbance scenario, a three phase fault is placed on bus 8 in the interior of the detailed system at 0.1 seconds and removed at 0.2 seconds. The time step for TS is 1 cycle or 16.667 milliseconds and that for the EMT simulator is $1/100^{th}$ of a cycle or 166.67 microseconds. All the generators are in the external system and modeled by fourth-order differential models with an IEEE Type 1 exciter model. The external system equivalent for the EMT simulator is a fundamental frequency Thevenin equivalent. The instantaneous boundary current for Bus 7 phase $a$ is shown in Fig. 4. As seen in Fig. 4, the serial interaction protocol produces incorrect results and fails to converge. The correct Thevenin equivalent for this scenario is not constant when the fault is applied since the generator bus voltages are not constant. However, EMT uses the 'constant pre-fault' Thevenin equivalent voltage for the time steps immediately after the fault is applied. Due to the incorrect Thevenin equivalent voltage, errors are introduced in the EMT solutions which get propagated to TS at the next data exchange. The accumulation of these errors results in the non-convergent behavior at a future time step. The external system in this case can be considered as 'weak' since the fault on bus 8 causes considerable change in the external system voltages resulting in a large change in the Thevenin equivalent voltage.

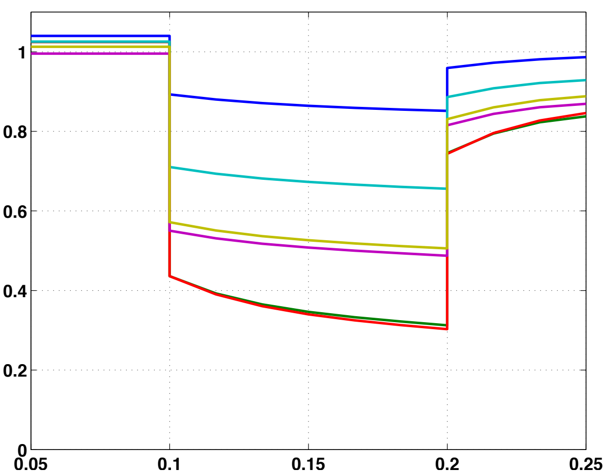

Fig. 3. Positive sequence voltage profile for the external systems buses

Fig. 5 shows the zoomed-in plot of the serial interaction protocol for time steps immediately following the fault. The boundary current in figure 5 for the immediate cycle after the fault is the same as that obtained in the previous test case, which is incorrect. As such, errors are introduced in the EMT solutions which get passed to TS at the next interchange and eventually lead to the non-convergence behavior.

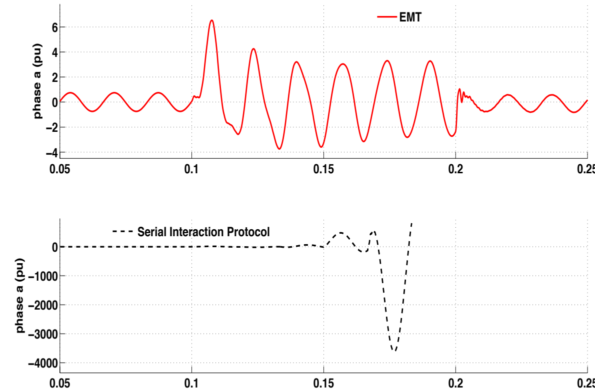


Fig. 4. Bus 7 phase $a$ instantaneous current: Non-convergent behavior of the serial interaction protocol

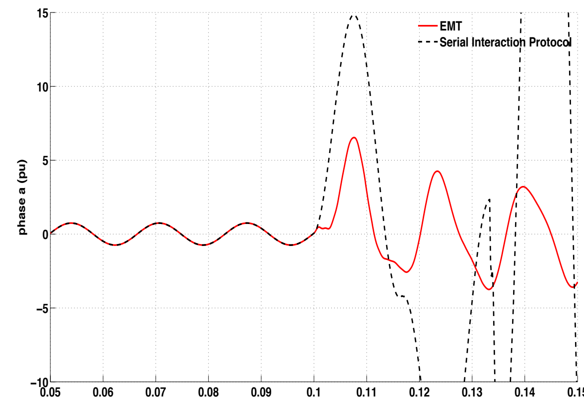


Fig. 5. Zoomed-in plot of the serial interaction protocol for non-convergent behavior

## III. Proposed implicitly-coupled simulator (TSEMT)

Instead of coupling TS and EMT at the application level, we propose to couple these two at the equation solution level. To combine the two sets of equations with their different time steps, and ensure that the TS and EMT solutions are consistent, the equations for TS and coupled-in-time EMT equations are solved simultaneously in a single large system of equations. While computing a single time step of the TS equations, a simultaneous calculation of several time steps of the EMT equations is undertaken. For the remainder of this document, this implicitly-coupled combined TS and EMT simulator will be referred to as TSEMT.

One of the major assumptions in TS is that the transmission network is always balanced. Hence a positive sequence network suffices for the analysis. For the hybrid simulators, such an assumption results in using only a balanced external system equivalent for EMT. We also propose using a full three-phase phasor model of the external system. The proposed three-phase TS simulator, TS3ph, modeling is used for the external system in the implicitly-coupled TSEMT simulator. Its details are described in [14].

### A. Network equivalents and waveform conversion

Network equivalents and waveform conversion form the coupling between TS3ph and EMT in the proposed TSEMT simulator. The equations for these are included in the overall system of equations and form the implicit-coupling between the TS3ph and EMT equations. For the proposed TSEMT simulator, we use a Thevenin equivalent of the external system and fundamental frequency phasor current source injection as the coupling between TS3ph and EMT. The Thevenin equivalent connects the EMT to TS3ph and the fundamental frequency phasor current source injection connects TS3ph to EMT as shown in Fig. 6. The Thevenin impedance is kept

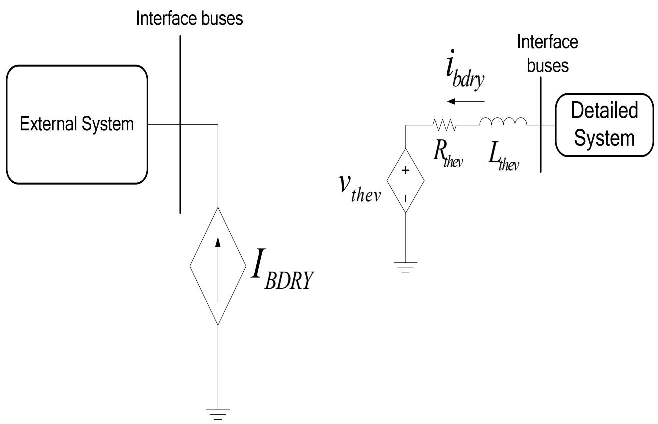


Fig. 6. Equivalent networks for detailed and external system

constant throughout the simulation, unless there is a topological change in the external system. Only the Thevenin voltage $V_{thev}$ needs to be updated at each time step. Since EMT uses instantaneous voltages, phasor voltage $V_{thev}$ needs to be converted to instantaneous waveform $v_{thev}$. This conversion is done by a fundamental frequency sine wave generator.

The inclusion of the external system equivalent in EMT introduces an additional set of differential equations

$$L_{thev}\frac{di_{bdry}}{dt} = v_{thev} - R_{thev}i_{bdry} - v_{bdry} \qquad (1)$$

where $v_{thev}$ is the instantaneous Thevenin voltage, $i_{bdry}$ is the current flowing out through the detailed system boundary buses, and $v_{bdry}$ is the instantaneous boundary bus voltage.

The detailed system equivalent used by the TS portion of our proposed TSEMT simulator is a fundamental frequency phasor current injection at the boundary buses. This phasor current injection is computed via a Fourier analysis of EMT boundary bus currents $i_{bdry}$ over a running window of one cycle of fundamental frequency.

The phasor current injections, $I_{BDRY}$, at the external system boundary buses expressed in rectangular form can be related to the instantaneous current, $i_{bdry}$, flowing through the detailed system boundary buses by Fourier analysis as follows:

$$\begin{aligned} I_{BDRY,D}(t+\Delta t_{TS}) &= \frac{2}{T}\int_{\tau=t}^{t+\Delta t_{TS}} i_{bdry}(\tau)\sin(\omega\tau)d\tau \\ I_{BDRY,Q}(t+\Delta t_{TS}) &= \frac{2}{T}\int_{\tau=t}^{t+\Delta t_{TS}} i_{bdry}(\tau)\cos(\omega\tau)d\tau \end{aligned} \qquad (2)$$

## B. *Implicitly coupled solution approach*

In compact form, the TS3ph system DAE model equations are

$$\begin{aligned} \frac{dX_{TS}}{dt} &= F(X_{TS}, V_{TS}) \\ 0 &= G(X_{TS}, V_{TS}) \end{aligned} \qquad (3)$$

In (3), $X_{TS}$ represents the dynamic variables for the synchronous generators and the associated control circuitry, i.e., exciters, voltage regulators, turbine governors etc. while $V_{TS}$ are the network phasor bus voltages. The differential equations for EMT are described by (4).

$$\frac{dx_{EMT}}{dt} = f(x_{EMT}) \qquad (4)$$

Note here that the differential model for EMT is due to using a state variable analysis scheme and the transmission lines modeled as equivalent $\pi$ models. If distributed-parameter transmission line models and a numerical integration substitution solution scheme is used then the EMT model would be described by algebraic equations with history terms instead.

Adding the coupling, the equations for TS3ph and EMT in compact form are

$$\begin{aligned} \frac{dX_{TS}}{dt} &= F(X_{TS}, V_{TS}) \\ 0 &= G(X_{TS}, V_{TS}, I_{BDRY}) \\ \frac{dx_{EMT}}{dt} &= f_1(x_{EMT}, i_{bdry}) \\ \frac{di_{bdry}}{dt} &= f_2(x_{EMT}, i_{bdry}, v_{thev}) \end{aligned} \qquad (5)$$

Discretizing the TS equations with the TS time step, $\Delta t_{TS}$, and EMT equations with EMT time step, $\Delta t_{EMT}$, and using an implicit trapezoidal integration scheme, the complete set of equations to solve at each TS time step is given by (6)-(13). Equations (6) and (7) represent the equations for the external system for one TS time step while (8)-(13) are the coupled-in-time EMT equations. Equations (6)-(13) are solved simultaneously using Newton's method at each TS time step.

Fig. 7-9 show the comparison of the instantaneous boundary bus currents and voltages using the implicitly-coupled solution approach with the EMT simulator. These results are for the same fault scenario which causes the serial interaction protocol to diverge. As seen from these figures, the implicitly-coupled solution approach is able to qualitatively follow the instantaneous voltages and currents. The network equivalent for the external system used in this work is a Thevenin equivalent of the external system derived at fundamental frequency. Research in the area of network equivalents has shown that frequency dependent network equivalents present a better picture of the external system to the EMT simulator [15], [1] ,[5] and thus allow the detailed system can be kept at minimum. In the future, we plan to explore frequency dependent equivalents to simulate more accurate harmonic waveforms.

$$
\begin{aligned}
&X_{TS}(t_{N+1}) - X_{TS}(t_N) - \\
&\quad \frac{\Delta t_{TS}}{2}(F(t_{N+1}) + F(t_N)) = 0 && (6)\\
&G(t_{N+1}) = 0 && (7)\\
&x_{EMT}(t_{n+1}) - x_{EMT}(t_n) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_1(t_{n+1}) + f_1(t_n)) = 0 && (8)\\
&i_{bdry}(t_{n+1}) - i_{bdry}(t_n) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_2(t_{n+1}) + f_2(t_n)) = 0 && (9)\\
&x_{EMT}(t_{n+2}) - x_{EMT}(t_{n+1}) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_1(t_{n+2}) + f_1(t_{n+1})) = 0 && (10)\\
&i_{bdry}(t_{n+2}) - i_{bdry}(t_{n+1}) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_2(t_{n+2}) + f_2(t_{n+1})) = 0 && (11)\\
&\quad \vdots \\
&\quad \vdots \\
&x_{EMT}(t_{n+k}) - x_{EMT}(t_{n+k-1}) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_1(t_{n+k}) + f_1(t_{n+k-1})) = 0 && (12)\\
&i_{bdry}(t_{n+k}) - i_{bdry}(t_{n+k-1}) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_2(t_{n+k}) + f_2(t_{n+k-1})) = 0 && (13)
\end{aligned}
$$

where

$$
\begin{aligned}
&I_{BDRY}(t_{N+1}) = h_{EMT->TS3ph}(i_{bdry}(t_{n+1}), \\
&\qquad i_{bdry}(t_{n+2}), \ldots, i_{bdry}(t_{n+k})) \\
&(v_{thev}(t_{n+1}), v_{thev}(t_{n+2}), \ldots, v_{thev}(t_{n+k})) \\
&\qquad = h_{TS3ph->EMT}(V_{thev,TS}(t_N), V_{thev,TS}(t_{N+1}))
\end{aligned}
$$

represents the coupling between TS3ph and EMT.

## IV. Proposed Electromechanical and Electromagnetic Transients Simulation Strategy TS3ph-TSEMT

The proposed implicitly coupled simulator, TSEMT, can by itself be used for a combined electromechanical and electromagnetic transients simulation. If the fast dynamics, harmonic voltages and currents, in the detailed system are of prime importance then the TSEMT simulator could be used for the entire simulation time length. Our interest in the TSEMT simulator is for analyzing the fast dynamics following disturbances only. Disturbances typically cause the generation of harmonic voltages and currents and the TSEMT simulator can be used only when harmonics are present. When there are no harmonics, a transient stability simulator is sufficient to simulate fundamental frequency, or relatively slow, dynamics and hence it should be used.

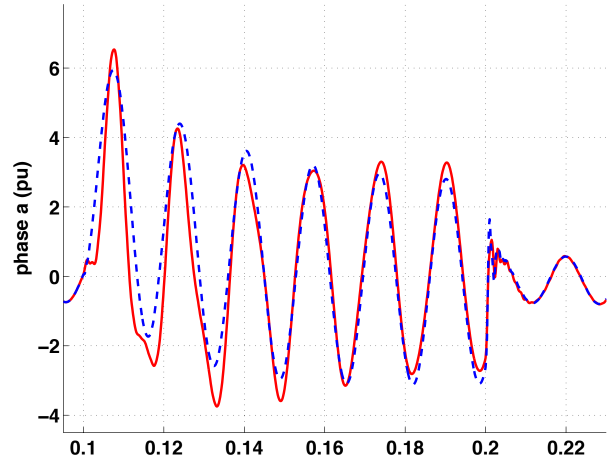


Fig. 7. Bus 7 phase a boundary currents using the implicitly-coupled solution approach ( — EMT - - - TSEMT)

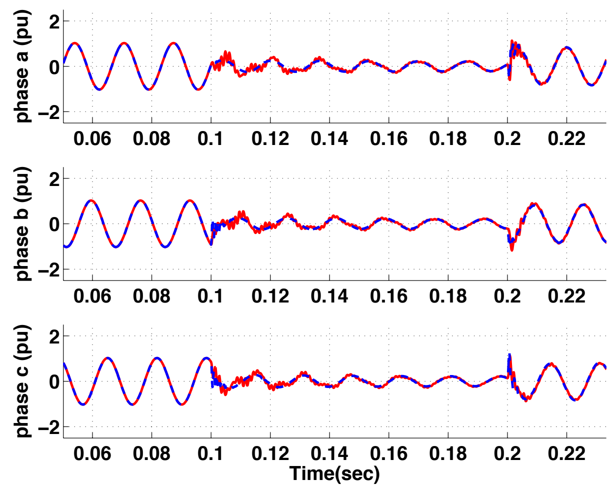


Fig. 8. Boundary bus 7 three-phase instantaneous voltages using the implicitly- coupled solution approach ( — EMT - - - TSEMT)

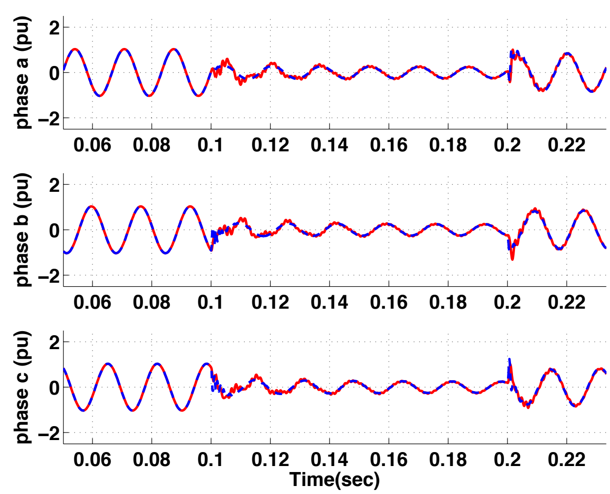


Fig. 9. Boundary bus 9 three-phase instantaneous voltages using the implicitly- coupled solution approach ( — EMT - - - TSEMT)

Hence the electromechanical and electromagnetic transients simulation strategy presented here is to use TSEMT selectively whenever there are harmonics and use TS3ph for the rest of the time frame. Such a strategy will be referred to as TS3ph-TSEMT for the remainder of this document. The TS3ph-TSEMT simulation strategy for a disturbance scenario, shown in Fig. 10, is as follows:

1) TS3ph is run initially on the complete network during the pre-disturbance period.
2) At time $t_1$, a disturbance occurs and the complete network is split into a detailed system for EMT and an external system for TS3ph. The Thevenin equivalent for EMT is set up.
3) The combined set of TS3ph and coupled-in-time EMT equations for each TS3ph time step are solved using the proposed implicit coupled solution approach.
4) At time $t_2$, if the fast dynamics in the detailed system have died down then TSEMT is terminated, the network is merged again, and the relevant EMT variables are passed to the TS3ph simulator.
5) TS3ph is run on the entire network until end time.

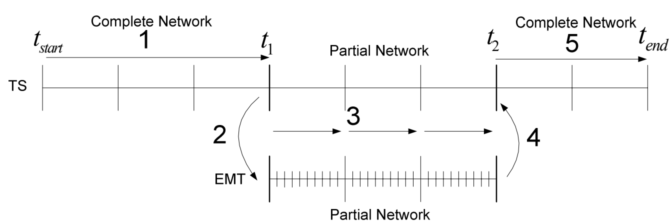


Fig. 10. Combined TS3ph-TSEMT simulation strategy

### A. Criterion for merging to TS3ph

We propose a merging criterion based on boundary bus voltage difference. The detailed system boundary bus phasor voltages, from Fourier analysis, are monitored to check if they are close enough to the external system boundary bus phasor voltages. If the difference is within an acceptable tolerance, then TSEMT is terminated and the control is passed to TS3ph. This strategy ensures that the non-fundamental frequency harmonics in the detailed system are negligible, so that TS3ph continues for the rest of the simulation period. The criterion used for terminating TSEMT is given by (14).

$$||V_{bdry,EMT} - V_{bdry,TS}|| < \epsilon \tag{14}$$

where $V_{bdry,EMT}$ is the vector of detailed system boundary bus phasor voltages computed using Fourier analysis and $V_{bdry,TS}$ is the vector of the external system boundary bus voltage phasors. Furthermore, if the boundary bus voltage magnitudes are found to be low, such as during a fault, then the merging is avoided.

Fig. 11 and Fig. 12 show the comparison of generator speeds and the external system boundary bus 7 phasor voltages for the TS3ph-TSEMT simulator with the full TS3ph and the EMT simulator while Fig. 13 shows the comparison of the boundary bus instantaneous voltages when TSEMT simulator is running. The fault scenario is the same as previously described, i.e., a three-phase solid fault applied on Bus 8, in the interior of the detailed system, at 0.1 seconds and removed at 0.2 seconds. TS3ph runs initially on the complete network till 0.05 seconds, at which time the system is split into an external and detailed system. The TSEMT simulator commences and runs past the fault clearing until 0.233 seconds, at which time the merging algorithm detects that the fundamental frequency phasor boundary voltages for TS and EMT are close enough to each other, and the system can be merged. The tolerance used for the merging algorithm was 0.01 pu. At 0.233 seconds, the TSEMT simulator is terminated and TS3ph continues for rest of the simulation period on the complete network.

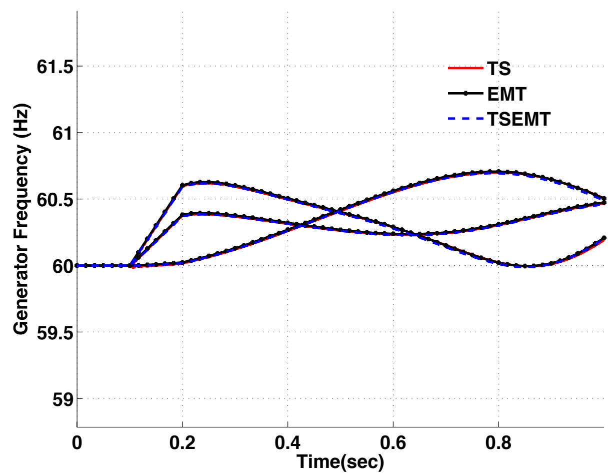


Fig. 11. Generator frequency comparison for TS, EMT, and TSEMT

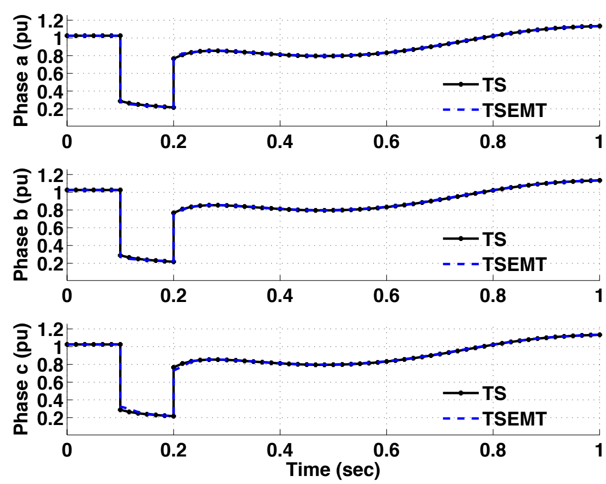


Fig. 12. Three phase boundary bus 7 phasor voltages comparison

### B. Comparison of CPU execution times for different simulators

Table II shows the comparison of the CPU run times for TS, TSEMT, and EMT for a 3 second simulation with a three phase fault. The code for the all the simulators was written in C language and compiled with an optimized compiler version. The computational burden for EMT grows with the system size and for the 118 bus system EMT takes about 30 seconds.

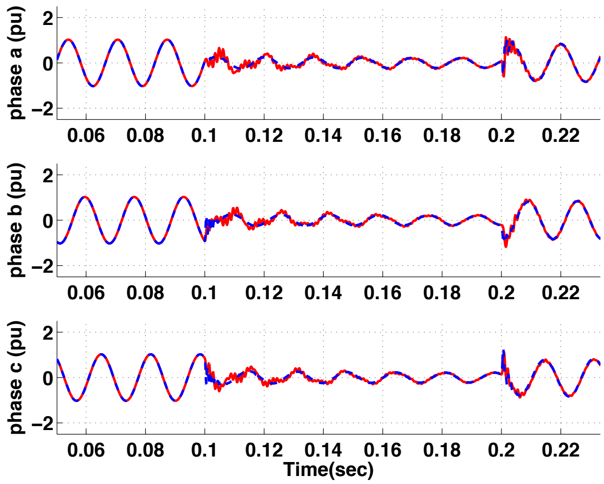


Fig. 13. Boundary bus 7 instantaneous voltages with TSEMT ( — EMT - - - TSEMT)

For TSEMT, the detailed subsystem in the 118 bus system is a radial network consisting of four buses with three transmission lines and a load at each bus. As seen from II, TS3ph is the fastest for both cases while the TS3ph-TSEMT simulator does not lag behind by much.

TABLE II
COMPARISON OF TS3PH, EMT, TSEMT, AND TS3PH-TSEMT RUN TIMES IN SECONDS

| System size | TS3ph | EMT | TSEMT | TS3ph-TSEMT |
|---|---|---|---|---|
| 9 bus | 0.13 | 4.96 | 5.46 | **0.41** |
| 118 bus | 0.36 | 30.1 | 4.87 | **0.53** |

## V. CONCLUSIONS

The proposed implicitly coupled TS3ph-TSEMT simulator is a practical, robust, and computationally efficient tool for simulation of large-scale power systems which require the detailed inspection of the fast dynamics of a critical area and a global view of the slow dynamics over a larger region. Results presented on the WECC-9bus system show the robustness of the proposed approach and also its computational efficiency.

## VI. ACKNOWLEDGEMENTS

This work was supported in part by the Office of Advanced Scientific Computing Research, Office of Science, U.S. Dept. of Energy, under Contract DE-AC02-06CH11357.

## REFERENCES

[1] IEEE Task Force on Interfacing Techniques for Simulation Tools, "Interfacing Techniques for transient stability and electromagnetic transients program," *IEEE Trans. on Power Apparatus Systems*, vol. 8, pp. 2385-2395, Oct. 2009.

[2] Heffernan, M.D., K.S. Turner, J. Arrillaga, and C.P. Arnold, "Computation of AC-DC system disturbances:Part I,II,and III," *IEEE Trans. of Power Apparatus Systems*, vol. 100, pp. 4341-4363, Nov. 1981.

[3] Su, H. T., K. W. Chan, and L. A. Snider,"Parallel interaction protocol for electromagnetic and electromechanical hybrid simulation," *Proceedings of the Institute of Electrical Engineers Conference*, pp. 406-414, May, 2005.

[4] Reeve, J., and R. Adapa., "A new approach to dynamic analysis of ac networks incorporating detailed modeling of dc systems. Part I and II.," *IEEE Trans. on Power Delivery*, vol. 3, pp. 2005-2019, Oct. 1988.

[5] Anderson, G. W., N. R.Watson, C. P. Arnold, and J. Arrillaga., "A new hybrid algorithm for analysis of HVDC and FACTS systems," *Proceedings of IEEE International Conference on Energy Management and Power Delivery*, vol. 2, pp. 462-467, Nov. 1995.

[6] Su, H. T., K. W. Chan, and L. A. Snider., "Investigation of the use of electromagnetic transient models for transient stability simulation," *Proceedings of 6th International Conference on Advances in Power System Control, Operation and Management*, pp. 787-792, Nov. 2003.

[7] Sultan, M., J. Reeve, and R. Adapa., "Combined transient and dynamic analysis of HVDC and FACTS systems," *IEEE Trans. on Power Delivery* vol. 13, pp. 1271-1277, Oct. 1998.

[8] Kasztenny, B., and M. Kezunovic, "A method for linking different modeling techniques for accurate and efficient simulation," *IEEE Trans. on Power Systems*, vol. 15, pp. 65-72, Feb. 2000.

[9] Fang, T., Y. Chengyan, W. Zhongxi, and Z. Xiaoxin., "Realization of electromechanical transient and electromagnetic transient real time hybrid simulation in power system," *Proceedings of IEEE Power Engineering Society Transmission and Distribution Exhibit.: Asia and Pacific*, pp. 16-23, 2005.

[10] Wang, X., P. Wilson, and D. Woodford., "Interfacing transient stability program to EMTDC program," *Proceedings of IEEE International Conference on Power System Technology*, vol. 2, pp. 1264-1269, Oct. 2005.

[11] Su, H., K. K. W. Chan, and L. A. Snider., "Interfacing an electromagnetic SVC model into the transient stability simulation," *Proceedings of International Conference on Power System Technology*, pp. 1568-1572, Oct. 2002.

[12] Su, H., L. A. Snider, K. W. Chan, and B. Zhou., "A new approach for integration of two distinct types of numerical simulator," *Proceedings of International Conference on Power System Transients*, New Orleans, 2003.

[13] Su, H., K. W. Chan, L. A. Snider, and J. C. Soumagne., "Advancement on the integration of electromagnetic transients simulator and transient stability simulator," *Proceedings of International Conference on Power System Transients*, Montreal, Jun. 2005.

[14] Abhyankar, S., A. Flueck, X. Zhang, and H. Zhang., "Development of a parallel three-phase transient stability simulator for power systems," *Proceedings of the $1^{st}$ international conference for high performance computing, networking, and analytics, for the power grid* Seattle, November 2011.

[15] Watson, N., and J. Arrillaga., *Power System Electromagnetic Transients Simulation*. London, UK: The Institution of Electrical Engineers, 2003.

[16] Hydro-Quebec TransEnergie Technolgies,*SimPowerSystems Users Guide*, version. 3, Sep. 2003.

[17] Abhyankar, S. G. *An implicitly coupled electromechanical and electromagnetic transients simulator for power systems*. Ph.D. Dissertation, Illinois Institute of Technology, Dec. 2011.

## APPENDIX A
## COMPUTING $v_{thev}(t)$ FOR EMT TIME STEPS IN-BETWEEN THE TIME BOUNDARY

An important issue for the implicitly-coupled solution approach is computing the instantaneous thevenin equivalent voltage $v_{thev}(t)$ for the EMT time steps that are not on the time boundary, i.e., the EMT time steps in-between two consecutive TS time steps. We experimented with two possible options: (i) a linearly interpolated $v_{thev}(t)$ from $(V_{thev,TS}(t_N), V_{thev,TS}(t_{N+1})$ and (ii) $v_{thev}(t)$ calculated from $V_{thev,TS}(t_{N+1})$ i.e. the Thevenin voltage at the next TS time step. Based on the results from our experimentation, shown in Fig. 14, we found option (ii), i.e. using $V_{thev,TS}(t_{N+1})$ to calculate $v_{thev}(t)$, to be more accurate.

## APPENDIX B
## EMT SIMULATOR USED IN THIS WORK

A three-phase EMT simulator was developed in this research work and benchmarked with the MATLAB-based EMT

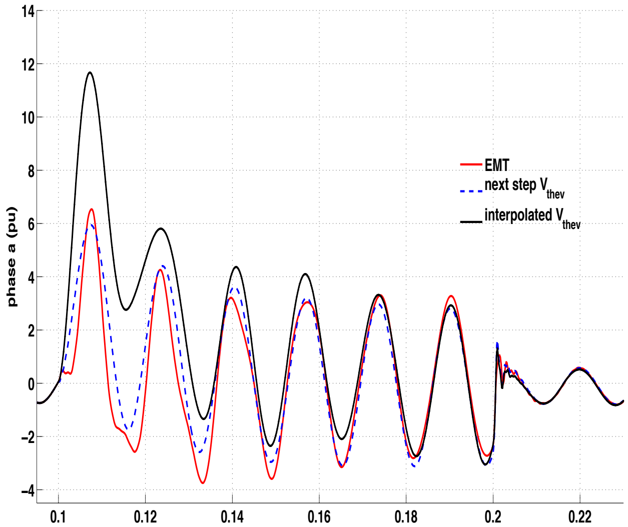


Fig. 14. Comparison of different $v_{thev}(t)$ calculation

package SimPowerSystems [16]. Fig. 15 shows one of the benchmarking results of the developed EMT simulator for a three-phase fault placed on bus 5 in the WECC 9-bus system. The developed EMT simulator uses a state-variable analysis method unlike EMTP which uses a numerical integrator substitution (NIS) scheme [15]. Such a scheme was chosen for simplicity rather than any other reason. We plan to explore the NIS scheme in the future. Currently, all the transmission lines for the EMT simulator are modeled as equivalent $\pi$ circuits resulting in a purely differential EMT model. Distributed-parameter transmission line models are the preferred choice for EMT simulators and we intend to use these models instead of $\pi$ models in the future. The details of this developed EMT simulator, TSEMT, and TS3ph-TSEMT can be found in [17].

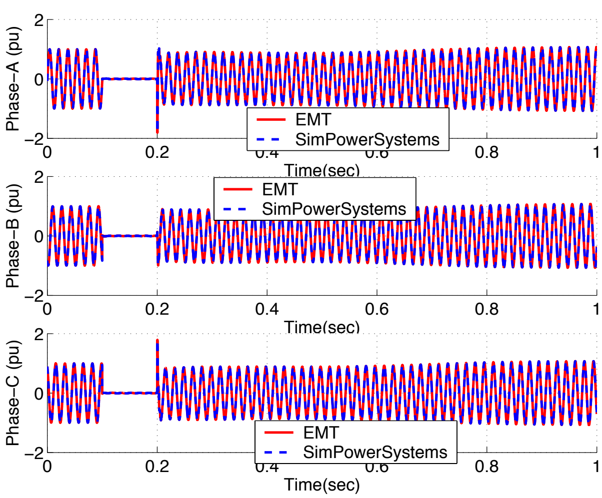


Fig. 15. Comparison of Bus 5 instantaneous voltages for a three phase fault on bus 5 from 0.1 sec to 0.2 sec using the developed EMT simulator with SimPowerSystems

**Shrirang Abhyankar** received the M.S degree (2006) and the Ph.D. degree (2011) in electrical engineering from Illinois Institute of Technology, Chicago. He is currently a Post-Doctoral appointee in the Mathematics and Computer Science Division at Argonne National Laboratory. His research interests include combined electromechanical and electromagnetic simulation, parallel algorithms for large-scale dynamic analysis of power systems.

**Alexander J. Flueck** Alexander J. Flueck received the B.S. degree (1991), the M.Eng. degree (1992) and the Ph.D. degree (1996) in electrical engineering from Cornell University. He is currently an Associate Professor at Illinois Institute of Technology in Chicago. His research interests include three-phase transient stability, electromagnetic transient simulation, autonomous agent applications to power systems, transfer capability of large-scale electric power systems, contingency screening with respect to voltage collapse and parallel simulation of power systems via message-passing techniques on distributed-memory computer clusters.