Real-time Electromagnetic and Transient Stability Simulations for Active Distribution Networks

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Abstract**-- This paper presents the solutions of a real-time parallel-processing based simulator, e*MEGA*sim, to perform electromagnetic transient and transient stability simulations for distribution power networks. The electromagnetic transient simulation can be distributed into several processors without adding an artificial delay, and the transient stability simulation tool can model three-phase unbalance systems. The simulator provides a flexible environment to interface discrete-time and phasor domains to create a hybrid simulation.**

Keywords**: real-time simulation, distribution power system, electromagnetic transient, transient stability, hybrid simulation.**

I. INTRODUCTION

THE distribution power systems were traditionally considered as passive networks that only involved end-users and loads. The simple topology of these systems and the utilization of cables instead of overhead lines made it less sensitive to transient stability phenomena. Distribution systems are usually coupled in a common bus with a strong transmission system. Therefore, disturbances such as short circuits in distribution networks were considered as localized phenomena without significant impact on the stability of the overall power system.

However, the integration of several types of energy resources has transformed the nature of distribution systems from passive to active. Currently, a large number of wind turbines, micro-turbine generators, and photovoltaic panels are connected to distribution networks. The massive penetration of small but geographically distributed generators (DG) has changed the operation of distribution networks during the steady and dynamic states. From the dynamic state viewpoint, the disturbance in the advanced distribution systems cannot be considered anymore an insignificant local event. First, each type of DG unit presents a different behavior during transients in the system. Second, a disturbance in the transmission system can easily lead to the tripping of the DG units in the distribution system, and in return the disconnection of DG units increases the chance of load-shedding due to the lack of generation. Therefore, the overall stability of power systems is affected from both the transmission and the distribution networks.

This paper presents the application of real-time simulation for transient stability (TS) and electromagnetic transient (EMT) study of distribution systems. The real-time simulation for distribution systems facilitates the design, test, and analysis of control devices and their interactions with the power system. These devices can be either mathematically modeled or actually connected to the simulator (hardware-in-the-loop). Moreover, since advanced distribution systems include both generators and loads, their operation becomes more complicated than the operation of the traditional systems; thus, the real-time simulation of these systems is also beneficial for operator training purposes. Three subjects are addressed in this paper for distribution power networks: (1) utilizing parallel processors for EMT-type simulation, (2) three-phase TS-type simulation, and (3) hybrid TS-EMT simulation.

The paper is organized as follows. In Section II. the real-time EMT-type simulation and its parallelization approaches will be described. The real-time TS-type simulation and existing library for distribution systems are presented in Section III. The potential of the simulator to link EMT and TS solutions will be revealed in Sections IV. Experimental real-time simulation results, accuracy validation, and a discussion of the results are shown in Section V. Concluding remarks are presented in Section VI.

II. REAL-TIME ELECTROMAGNETIC TRANSIENT SIMULATION

A. Overview

In a typical Electromagnetic Transient (EMT) simulation algorithm, each element in the network is replaced by an equivalent circuit consisting of conductances and current sources [1]. The next step for EMT computation is to establish the nodal equations for the substituted network:

$$[G][v(t)] = [i(t)] - [I] \quad (1)$$

where $[G]$ is the nodal conductance matrix, $[v(t)]$ is the node voltage vector, $[i(t)]$ is the injected current source vector and $[I]$ is the known history current vector. The elements of $[G]$ and $[I]$ in (1) directly depend on the components in the power system (e.g., inductance, capacitance, transmission lines, etc.) and the numerical method (e.g., Trapezoidal rule) chosen for discretization of differential equations which describe the behaviour of the elements.

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It is a common practice with EMT simulators to use a simulation time-step of 30 to 50 us to provide acceptable results for transients up to 2 kHz. Since greater precision can be achieved with smaller time-steps, simulation of transient phenomena with frequency content up to 10 kHz typically require a simulation time-step of approximately 10 us.

The computation resource for real-time EMT type simulation is critical where the system is large-scale or it includes a big number of switches whose status can change during the simulation. Therefore, to keep the real-time performance with a time-step in the range of few microseconds it is unavoidable to exploit parallel processing techniques to distribute the computation load into multi processors.

The EMT simulator tool used in this paper is e*MEGA*sim based on the ARTEMiS sets of EMT solvers from Opal-RT [2]. ARTEMiS solves electric circuits using the state-space method. However, when the topology of the circuit changes (e.g. status of one breaker change) a new state-space matrix needs to be calculated. Two techniques are designed in ARTEMiS solvers to take advantage of parallel processing computation:

- Fully state-space solver
- State-space combination with nodal solver

B. Fully state-space solver

ARTEMiS comes with a library of decoupling elements to help parallelize network state-space equations. This decoupling can be natural, as with Bergeron traveling-wave power lines that have inherent delays built into their model. Due to the length and characteristic impedance, electrical signals sent from one end of a transmission line will be received at the other end with a time delay τ. Because of this delay the transmission line can be used as a decoupling point. The shunt capacitor of the stubline (C) is calculated based on the characteristic impedance of the line to create one time-step delay based on the following equilibrium:

$$h = \sqrt{LC} \quad (2)$$

where h is the time-step and L is the line's inductance. The advantage of this technique is that the decoupling stubline can be placed any location in the system which there is significant series impedance, such as in transformers, to introduce a time delay.

In transmission systems with long lines the calculated capacitor can be interpreted as line's capacitor while in distribution power systems lines are short (normally in the range of few km) and it is a common practice to ignore line's capacitor. Thus, the limitation of this method for distribution power systems is that the calculated capacitor is large when the time-step is small. In other words, this decoupling method introduces parasitic capacitors to the model which are not realistic.

The impact of the parasitic capacitor in case of short lines or transformers can be compensated by adding a shunt reactor so that:

$$Q_C + Q_L = 0 \quad (3)$$

where Q_C and Q_L are reactive power of parasitic capacitor and shunt reactor:

$$Q_C = Y_C \times V^2 \text{, and } Y_C = j\omega C \quad (4)$$

$$Q_L = Y_L \times V^2 \text{, and } Y_L = 1/(j\omega L)$$

where Y_C and Y_L are admittance of parasitic capacitor and its shunt reactor, and V is the nominal voltage of the transmission line or transformer. From (3) and (4) the value of shunt reactor in H is:

$$L = 1/(\omega^2 C) \quad (5)$$

C. State-Space Nodal (SSN) solver

The SSN solver in ARTEMiS library allows for direct and delay-free parallelisation [3]. The key idea of SSN is to split the state-space equation of the system into several *groups* linked by *nodes*. These groups are described by local state-space systems, including switch permutations which are also decoupled. Each node contains the nodal current or voltage of the decoupling point. Fig. 1 demonstrates the concept of SSN nodes and groups. In Fig. 1.a the state-space equations of the circuit is given while in Fig. 1.b it is shown that a SSN node, i.e. v(nodal), is placed in the circuit to split it into two groups (Gr1 and Gr2). The entire circuit now can be modeled by two sets of state-space equation (i.e. [A1], [B1] and [A2], [B2]) and one extra nodal sets of equation as the interface. Once each SSN group have been iterated, the common point solution v_{n+1}*(nodal)* is found using a nodal method with a nodal matrix

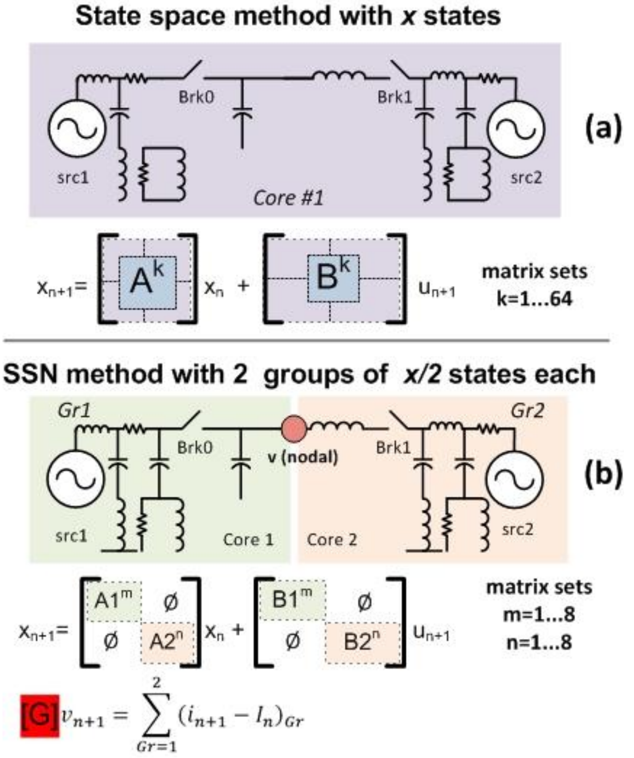

Fig. 1.Virtual group separation in SSN: (a) entire circuit, (b) decoupled circuit

G and history sources i_{n+1}-I_n computed from all groups.

In contrast to the stubline technique, in SSN technique the decupling will not introduce an artificial delay into the system. Thus, the technique is flexible and there is no restriction for placing the SSN nodes in the network. The SSN groups can be assigned to parallel CPU cores to solve simultaneously. The only rule is to split the system as such the computation load, in terms of number of switches and states, is distributed evenly among the parallel processors.

The limitation of the SSN technique is the nodal solver part that computes the injected current at interfacing node which is not parallelized, as shown in Fig. 2. Therefore, to keep the real-time performance with a small time-step it is required to limit the number of SSN groups that are linked by the nodal solver. The size of nodal matrix (G) must be small enough that the nodal equation can be solved in one time-step.

D. EMT simulations in distribution systems

The advantages and limitations of two parallel processing based techniques explained in the previous sections imply to combine these two methods to perform real-time EMT type simulations for distribution power systems. In these types of networks with short lines and cables the transformers at substations or ones along the feeders are potential candidates to split the system by the stubline decoupling points. However, the number of transformers is limited; in addition they require compensation for the inserted parasitic capacitors. Consequently, it is not always feasible to split the system only with stubline technique. On the other hand, splitting the system by many SSN nodes will increase the size of nodal solver and have impacts on the real-time performance.

The proposed approach is to use stublines to tear the system into subsystems and then utilize SSN nodes to split each subsystem to a few SSN groups. This makes the size of the SSN nodal solver at each subsystem be limited only to the groups existed in that subsystem while the entire system can be distributed into multiple CPU cores. Fig. 3 demonstrates the proposed approach. It shows the one-line-diagram of a one feeder in a distribution network. There are three transformers along the feeder, with two of them used to tear the entire system into three subsystems. Each subsystem is also split into several SSN groups.

III. REAL-TIME TRANSIENT STABILITY SIMULATION

A. Overview

From the system theory viewpoint, power systems transient stability (TS) is a strongly nonlinear problem. To assess it accurately, first it should be mathematically described by a set of differential-algebraic equations (DAEs) as follows [4]:

$$\dot{x}(t) = f(x,V) \qquad (6)$$

$$YV = I(x,V) \qquad (7)$$

$$x(t_0) = x_0 \qquad (8)$$

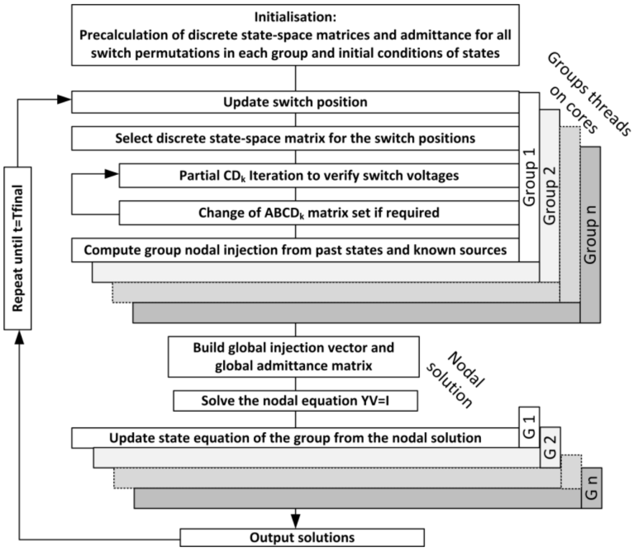

Fig. 2. Parallel SSN algorithm

where *x* is the vector of state variables, *V* and *I* are the vector of bus voltages and currents, *Y* is the nodal admittance matrix of the network, and x_0 is the initial values of state variables. For transient stability simulation the system is modeled in the main frequency phasor domain, and the dynamics of the system only depend on rotating machines and control devices. Therefore, a simulation time-step in the order of few milliseconds to half of a cycle is sufficient. Equation (6) describes the dynamic behaviour of the system, while equation (7) describes the network constraints on (6).

The transient stability simulation tool used in this paper is e*PHASOR*sim from the family of the e*MEGA*sim real-time simulators [5]. The e*PHASOR*sim is built specifically for phasor domain simulation for both transmission and distribution power systems. Its library involves positive sequence as well as unbalanced three-phase models.

B. TS simulations in distribution systems

The distribution system components in e*PHASOR*sim tool are developed based on multiphase and unbalanced models. Therefore, it can provide a phase-based simulation for both unbalanced systems as well as asymmetric events. The distribution system library contains the following models:

- Voltage sources: The parameters are based either on three-phase and single-phase short circuit levels, or on its zero and positive sequence impedances.
- Load (unbalanced): The constant impedance, constant current, constant power, and complex ZIP load are modeled. Each load can have its own profile to vary during simulation.
- Shunt devices: Capacitor banks can be modeled with these components.
- Current injector: used to externally set the injected current at a specific bus in (7).

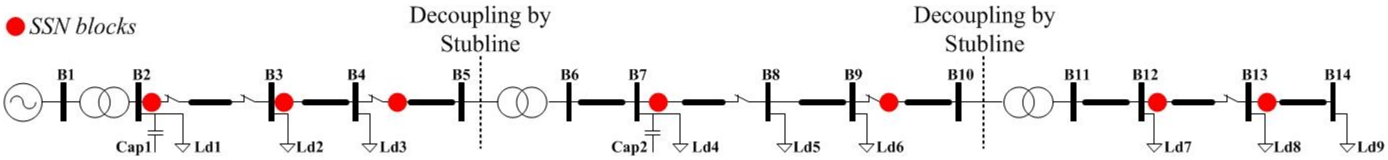

Fig. 3. A distribution system feeder split with stubline and SSN blocks

- Transformer: Three-phase transformer with various types of winding configurations and variable tap-position is modeled [6].
- Line (asymmetric): the model is either based on sequence network parameters or based on predefined configuration types. It encompasses both cables and lines.

IV. HYBRID TS-EMT SIMULATION

Several applications in power systems such as simulation of transient states of the network including power electronic apparatuses require a simulator as fast as the TS and as detailed as the EMT simulator. Many attempts were made towards that end, such as using parallel processing or simplified models in the form of equivalents [7]–[9]. The idea of a combined TS and EMT simulator was first proposed and implemented by Heffernan [10], in 1981. In [11], the authors proposed a method to directly link frequency domain component models inside the TS to the EMT program by means of Fourier transforms.

As mentioned earlier the TS program is based on the fundamental frequency, phasor-type data, while the EMT program is based on the three-phase instantaneous waveform data which includes several frequency components. Thus, to connect these two types of solutions two data converter blocks are needed: phasor-to-waveform and waveform-to-phasor. Fig. 4 depicts these conversion blocks. One of the main challenges in hybrid simulation is how to establish an interface between two different types of solution methodologies which are running in different time-steps. Several types of serial and parallel protocols are proposed in literature to coordinate the data exchange and update the equivalent circuits in TS and EMT domains [12].

The e*MEGA*sim simulator can integrate TS and EMT domain solutions in one working model. This capability creates a flexible environment that facilitates to:

- Develop, test, and validate various interaction protocols between TS and EMT domains
- Examine strategies to choose the domain of study and interface location between TS and EMT domains
- Choose the interface variables that need to be exchanged between two domains

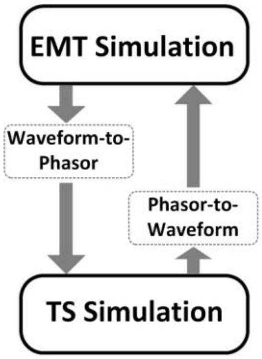

Fig. 4. Data converting to interface TS and EMT simulations

The idea of the hybrid simulation with e*MEGA*sim solutions will be disclosed more in the next section along with an experimental test case for a distribution level power system.

V. EXPERIMENTAL RESULTS

This section describes test cases to demonstrate simulation methods presented in the paper. All the real-time simulations in these experiments are performed on an e*MEGA*sim real-time digital simulator (Linux RTOS, 3.4GHz Intel processor). The case study for EMT-type simulation and TS-type simulation are identical, while for the hybrid simulation a simple test case will be used.

A. EMT-type simulation

Fig. 5 depicts the one-line-diagram of a 3-phase distribution feeder that includes 28 single-phase switches, constant power and constant impedance loads, as well as capacitor banks. The test case is built with Matlab's SimPowerSystems (SPS) toolbox, and Fig. 6 demonstrates few cycles of voltage waveform at bus B2 just after a disturbance happens in the system. It can be observed from this figure that the numerical oscillations in the SPS model with the time-step of 50µs do not exist if the time-step is reduced to 1µs. Therefore, the SPS model with the time-step of 1us is the reference to validate the multi-processor based simulation results with the SSN solution.

Fig. 7 shows the test case that is split into seven groups with SSN blocks. Therefore, the system can be simulated on parallel CPUs without adding any artificial delay. The integration method used in SSN solver is the implicit backward Euler. Fig. 8 shows the voltage of phase A at bus B2 for the steady state, transient, and after transient states. The time-step for simulation is 50µs, and the result is compared with reference (i.e. Simulink's 1µs time-step). It is obvious from this figure that results of SSN solver match well with the aforementioned reference.

B. TS-type simulation

The system in Fig. 5 has been modeled with e*PHASOR*sim which is the TS solver of e*MEGA*sim simulator. The time-step in this case is set to 10 ms, and the outputs of the solver are the RMS values and angle. Although the e*PHASOR*sim solver is identical for transmission and distribution systems, the accuracy of the solver is evaluated separately with different simulation tools. For transmission systems, PTI's PSS/E is used as the validation tool, while for distribution system CYMEDIST (CYME), SimPowerSystems toolbox (Simulink/Matlab) in phasor mode, and OpenDSS (EPRI [13]) have been utilized. The maximum discrepancy that is found with the test cases in the RMS values is 0.08% for distribution systems, and for angles is less than 0.1 degree.

C. Hybrid simulation

The objective of this experiment is to show the concept of co-simulating the TS and EMT solutions on one working model with the e*MEGA*sim simulator. The test case is shown in Fig. 9. The line between buses B4 and B5 is a distributed parameter line model with a length of 100km. This line and the load Ld3 (connected to bus B5) are in the EMT mode and all other parts of the system are in TS mode. Thus, bus B4 is chosen to be the interface bus. As shown in Fig. 10, the simulation time-step for Phasor domain, which will be modeled by e*PHASOR*sim, is 10ms, and the time-step for EMT part which will use the SSN solver is 50µs.

Although the outputs of the e*PHASOR*sim solver are in the phasor domain (i.e. RMS value and angle), it is still possible to represent them as the sinusoidal waveforms (with no DC offset). The signal generation can be done in a separate CPU core running with a faster time-step (e.g. 50µs) in parallel with the e*PHASOR*sim solver which is running with a slower time-step (e.g. 10ms). The sinusoidal waveform for the voltage measurement can be represented as:

$$v(t) = \sqrt{2}\, V_{rms} \sin(2\pi f t + \varphi_V) \qquad (8)$$

where f is the nominal frequency of the power system (60 Hz), and V_{rms} and φ_V are the outputs of the e*PHASOR*sim solver. These calculations are done for all three phases of bus B4, and they are passed to the SSN block, as demonstrated in Fig. 11.

The output of the EMT domain is the three-phase current flow in the discrete time-domain that must be injected into the phasor domain with a reversed direction. The e*PHASOR*sim models the current injector to externally set the injected current at a specific bus in (7). The RMS and angle of the fundamental frequency of the current measurements in EMT domain are computed based on a running window of one cycle of main frequency, as illustrated in Fig. 11.

The communication between the TS and EMT solutions is established based on a basic protocol that is illustrated in Fig. 12. The data exchange occurs at each time-step of the phasor domain.

To analyze the accuracy of the hybrid simulation the entire system is built in EMT domain with a time-step of 50µs. Two disturbances are applying in the system:

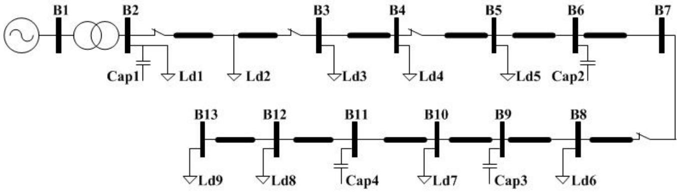

Fig. 5. The test case for distribution feeder

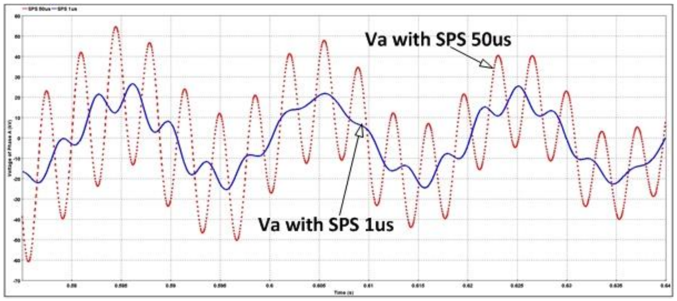

Fig. 6. Simulink's voltage of bus B2 phase A: time-step of 50us vs. 1us.

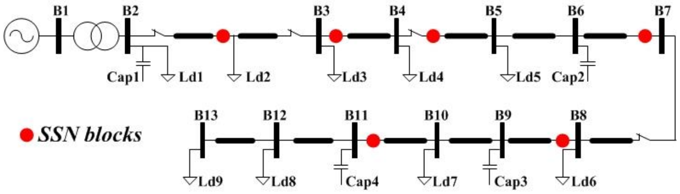

Fig. 7. Splitting the system with SSN blocks.

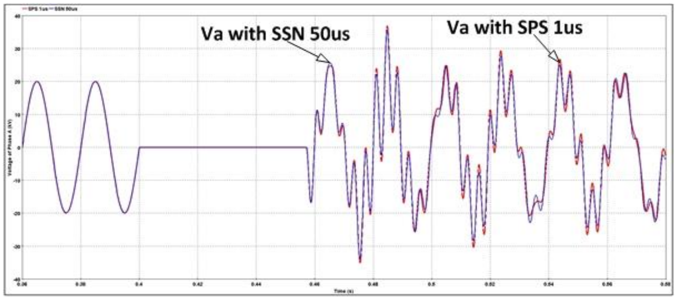

Fig. 8. Comparison the SSN results with the reference values.

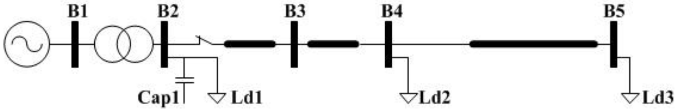

Fig. 9. A small test case for hybrid simulation

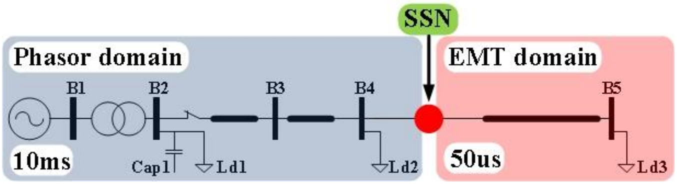

Fig. 10. Defining the phasor and EMT domains

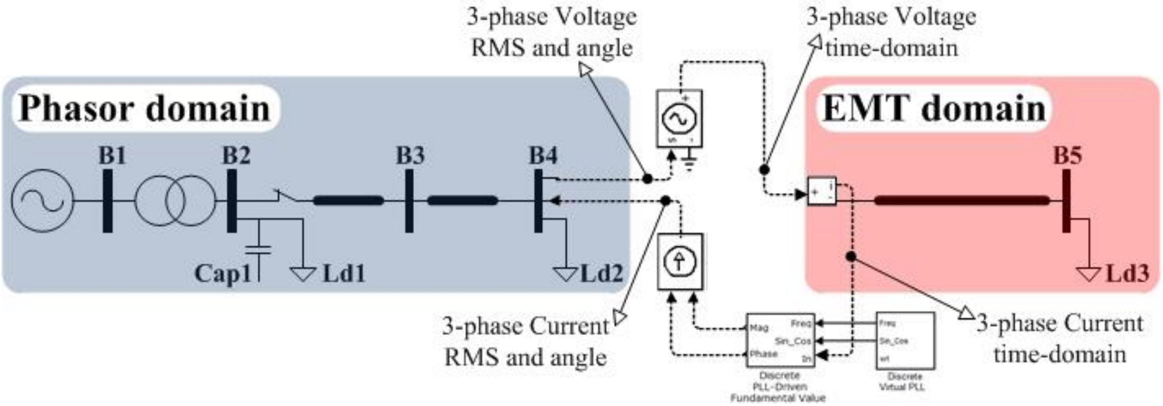

Fig. 11. Interfacing the Phasor and EMT domains

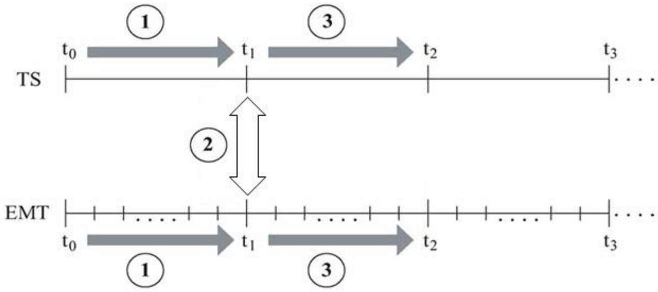

Fig. 12. Communication protocol between TS and EMT solutions

1) Fault in the EMT domain (on bus B5)

The phase A voltage at bus B5 and the current flow between buses B4 and B5 are depicted and compared with the EMT-only simulation in Fig. 13. It can be observed that due to the long length of the line between buses B4 and B5 the impact of phasor domain is negligible.

2) Fault in the Phasor domain (on bus B3)

Fig. 14 shows the phase A voltage at bus B5 and the current flow between buses B4 and B5 where a three-phase-to-ground fault happens in phasor domain. In this case some oscillations exist in the EMT-only simulation, which are not seen in the hybrid simulation.

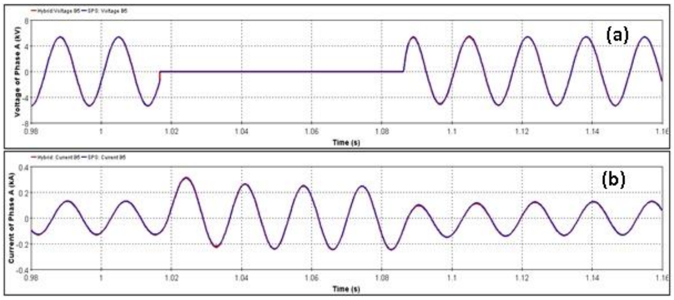

Fig. 13. Fault in the EMT domain: (a) voltage of phase A, (b) current flow of phase A (the results are very close to the reference values)

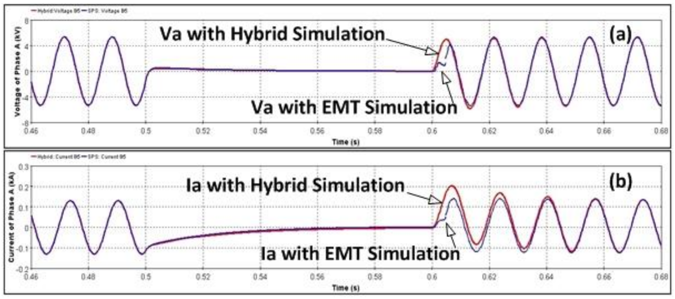

Fig. 14. Fault in the Phasor domain: (a) voltage of phase A, (b) current flow of phase A

VI. CONCLUSIONS

The paper presented the EMT and TS solutions of e*MEGA*sim real-time simulator. Two different parallelization approaches for EMT-type simulations were described. The fully state-space method is more convenient for transmission power systems with long transmission lines; while the SSN method is suitable for both distribution and transmission systems.

For the TS-type simulation the e*PHASOR*sim tool was introduced. The e*PHASOR*sim is a single-processor based simulation tool designed for phasor-domain studies of both transmission and distribution power systems.

The idea of performing a hybrid TS-EMT simulation in e*MEGA*sim environment was discovered. The goal was to reveal the potential of the simulator in interfacing of two different domain simulations in one working model. Although the test system was simple the results were promising to use this simulator to examine other proposed strategies to link TS and EMT solutions in the complex power systems.

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