

Interfacing Techniques for Simulation Tools

IEEE Task Force on Interfacing Techniques for Simulation Tools
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Abstract— This panel paper presents an overview of techniques to address: (a) the interfacing of an electromagnetic transient simulation program with a transient stability simulation program, (b) interfacing of an electromagnetic transient simulation program with an electromagnetic field simulation program, and (c) interfacing issues of a real-time digital simulator. The salient features of each type of simulation program are discussed with the highlights on technical challenges for interfacing, and the classification of the various interfacing methods available in the literature is presented.

Index Terms— Electromagnetic transient analysis, Electromagnetic fields, Interfacing, Transient stability, Real-time systems.

I. INTRODUCTION

Power system studies are numerous such as load flow, short-circuit, harmonic, transient stability, and electromagnetic transient studies. Each of these types of studies has its own modeling requirement and solution technique. Over the years several computer simulation programs were developed to satisfy the individual modeling needs of different studies. A need was, however, quickly recognized to interface various programs to exploit their complementary strengths for model validation and to exchange data between different simulation tools [1], [2]. Recent advances in commercial math software has also encouraged the need to interface them with power system software to exploit the advanced toolboxes for power system applications. Several papers have been published on interfacing techniques, but there is no systematic collection of all the available information. The mandate of the IEEE Task Force on Interfacing Techniques for Simulation Tools is to collect the published literature on interfacing techniques to help fuel further research in developing better tools and techniques. This panel paper gives a summary of techniques used to address: (a) the interfacing of electromagnetic transient simulation (EMT) programs with transient stability (TS) simulation program, (b) interfacing of circuit simulation program with an electromagnetic field simulation program, and (c) interfacing issues of a real-time digital simulator.

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II. INTERFACING OF EMT AND TS SIMULATORS

A. Competing modeling requirements of TS and EMT simulators

The power system model for transient stability analysis can be described by a set of differential algebraic equations. The differential equations model dynamics of the rotating machines while the algebraic equations represent the transmission system, loads, and the connecting network. These equations are nonlinear, and the typical solution approach is to use a discretization method such as the Trapezoidal rule followed by an iterative solver such as Newton-Raphson. A time-step in the range of milliseconds is chosen for the TS simulation. It is assumed that voltage and current waveforms more or less remain at power frequency (60 or 50 Hz). Thus, phasor modeling is used for various power system components. Moreover, transient stability study is a positive-sequence single-phase type of analysis [3], [5]. A large integration time-step of the transient stability programs is the main restriction for the detailed representation of nonlinear elements (such as power electronic apparatus) and dynamically fast events (such as line energization).

Electromagnetic transient study requires detailed modeling and therefore a much smaller time-step than in the transient stability study. Depending on the type of transient and the highest frequency involved, the required step-size can vary in the range of a few nanoseconds for very fast transients, to a few hundred microseconds [4], [6] for slower transients. Electromagnetic transients are fast phenomena for which power-frequency phasor modeling is not valid. In contrast with transient stability analysis, instantaneous values need to be used. In addition, electromagnetic transient phenomenon is not a symmetric event that could be studied on the single-phase basis, but requires a full three-phase simulation.

Practically it is inefficient to perform electromagnetic transient analysis for a large network where all of the components are represented using detailed models. Usually some form of network partitioning and model reduction are required to reduce computational burden.

Both the TS and EMT simulators have merits and drawbacks. Developing a simulator with TS-type speed and EMT-type accuracy is essential for power system studies, and this necessity led researchers to generate a hybrid simulation tool. The main objective of hybrid simulation is to split the original network into two parts, and based on the required modeling accuracy the TS or the EMT simulator is used for each zone. EMT is used for the smaller part in which more detailed and accurate results are needed. This part may comprise HVDC links, FACTS devices, closed-loop controlled devices for real-time simulations such as relays or controllers, parts of the

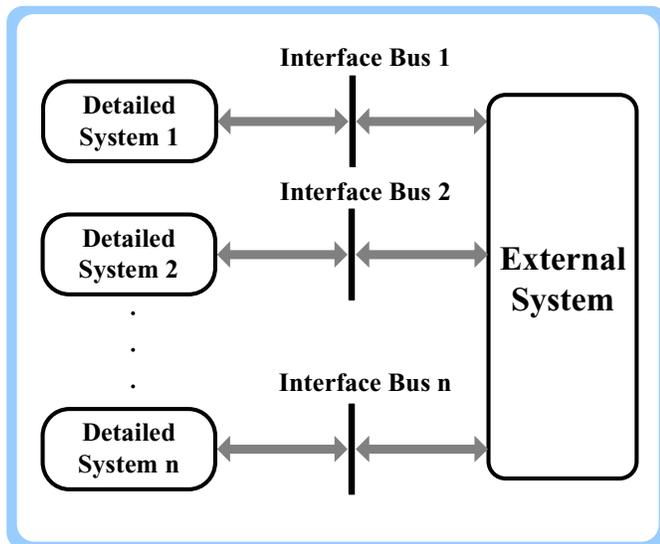


Fig. 1. Interface between detailed and external systems

network vulnerable to a disturbance, or any other elements that need small time-steps for representation. In contrast, the other part that embraces extensive portions of the network is simulated by the TS simulator. Detailed modeling is not required for elements existing in this part, but the capability of the simulator for fast computation is essential here.

B. Hybrid TS-EMT simulator

A hybrid simulator [7]–[13] has the following 4 main features:

- 1) *Detailed System*: It corresponds to one or more portions of the power system having components that need to be modeled at a detailed device level. The detailed system is the area for operation of EMT simulator.
- 2) *External System*: The other part of the power system that includes the remaining elements of the network that need to be modeled on a system wide functional basis. System-level modeling supposes that devices work as designed; any malfunctions in the elements cannot be adequately represented. The external system is the domain of the TS simulator.
- 3) *Interface buses*: Buses through which the detailed and external systems interact and exchange data. Fig. 1 shows the schematic position of the detailed and external systems and the interface buses.
- 4) *Interaction protocol*: Predefined sequential actions which coordinate the data exchange between TS and EMT simulators. Two main categories of interaction protocols exist: serial and parallel. In a serial protocol at each time instant only one of the TS or EMT simulators runs while the other one is idle. In a parallel protocol both simulators run simultaneously.

The main issues in interfacing TS and EMT simulators are as follows:

- Equivalent models of external and detailed systems: In a hybrid simulator, EMT and TS programs are run on

two separate zones. Thus, each program requires a true picture of the other zone which adequately reflects the characteristics of that zone. This picture is referred to as the equivalent model. The validity of the hybrid simulator directly depends on the accuracy of equivalent models.

- Identifying domains of study and locations of interface buses: Earlier approaches for determining domains of study were to simply consider the elements where an accurate result was desired as the detailed system, and their terminals as the location of interface buses. A single frequency Norton equivalent was used for modeling the external system in the EMT simulator. The merit of this form of regionalization is that the size of the detailed system which is computationally burdensome is reduced to a minimum. However, the major drawback of this method is that if there exists waveform distortion or phase imbalance at the interface buses then a simple Norton equivalent would not be valid. One solution is to keep the detailed system to a minimum, while exploiting a full frequency dependent Norton equivalent to model the external system.
- Exchanging data between TS and EMT simulators There are two important considerations for data exchange in a hybrid simulator. First, which variables need to be transferred between the simulators, and second how two types of data must be interpreted for TS and EMT simulators. The interaction of the detailed and external systems is maintained via data interface buses. Parameters that are generally available for measurement include active and reactive power, voltage, current through interface bus, and also phase angle information in the case of using different reference frames. Another major concern in a hybrid simulator is how to pass the interface variables properly between the TS and the EMT programs. As mentioned earlier the TS program is based on the fundamental frequency, positive sequence, 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 programs two data converter blocks are needed: phasor-to-waveform and waveform-to-phasor. Fig. 2 depicts these conversion blocks.
- Organizing interaction protocol between TS and EMT simulators: Since the EMT and the TS programs have a different time-step (microsecond vs. millisecond), an interaction protocol is required to coordinate the information exchange and update the equivalent circuits in the simulators. The step-size of the TS simulator is made an integer multiple of that of the EMT simulator, and exchanging of information occurs at common points in time, which conventionally are the TS simulator time steps. Several serial and parallel protocols have been proposed in the literature.

C. Integrated TS-EMT simulation

Recent research has focused on the integrative modeling of EMT and TS as an alternative interfacing method. Rather

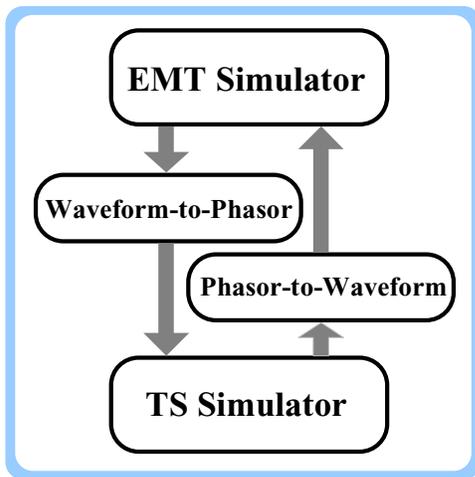


Fig. 2. Interfacing the EMT and TS programs

than coupling two existing programs, the underlying models are represented based on the concept of frequency adaptive simulation of transients (FAST) [14] to cover the application spectrum of typical TS and EMT programs. The method relies on the introduction of the shift frequency as a novel simulation parameter in addition to the time-step size.

III. INTERFACING OF ELECTROMAGNETIC FIELD AND CIRCUIT SIMULATORS

Over the years, circuit simulation of electrical systems has evolved to a mature and well-established field. Several techniques such as Loop Current Method, Nodal Analysis, Modified Nodal Analysis (MNA), and State-Variable Approach [15] are widely used in different circuit simulators including emt-type programs such as ATP, PSCAD/EMTDC, EMTP-RV, the SPICE family programs, and the MATLAB/SIMULINK. All of these simulators are able to solve circuit equations for lumped and distributed elements in both steady-state and transient regimes, handle the nonlinear behavior of circuit elements and employ different techniques to discretize the temporal derivatives during the transient simulation.

The field analysis of electromagnetic apparatus, with the aid of numerical techniques, has been used as the most accurate and detailed method of predicting the magnetic behavior of such systems under various operating conditions. Several effects such as space harmonics, slotting, and saturation which are usually present in different types of electric machines, transformers and other magnetic apparatus could be readily included in the field equations. The Finite Element Method (FEM) is usually the method of choice for modeling low frequency phenomena of power apparatus because of its flexibility and accuracy.

While one of the main source terms in the FEM equations are the winding currents, electromagnetic apparatus are usually connected to linear and nonlinear voltage sources [2]. Thus to have a precise simulation of the system, one needs to solve the FEM equations in conjunction with the circuit equations relating the voltages and currents. The coupling between field and circuit equations becomes more prominent when neither

currents, nor voltages at the output terminals of the apparatus are known a priori.

The main applications of these techniques include simulation of electrical drives, transformers, actuators and individual conductors connected to circuit elements, and the interaction phenomena between rotating machines and the network (e.g. SSR and fault studies). The main techniques for coupling 2D FEM equations with circuit equations at low frequencies (up to a few kHz) can be classified into two broad categories of *Direct* or *Indirect* methods. In direct methods, FEM equations and circuit equations of a system are combined and solved simultaneously. In indirect methods, the FEM-based part is handled as a separate subsystem which communicates with the circuit model through coupling coefficients.

A. Direct Methods

The direct method of coupling field and circuit simulation programs can be classified [2], [16]–[26] into 4 categories based on (a) simple circuit equations, (b) the loop (mesh) current method, (c) the nodal or modified nodal approach (MNA), and (d) the state-space (SS) approach. All these circuit analysis methods have been used successfully in coupled field-circuit problems. However, implementing the loop current method in the existing finite element codes is rather difficult as compared to the MNA. Furthermore, in a circuit with a large number of branches and complicated topology, the MNA provides a more systematic process to build the circuit equations. For example, transient analysis of coupled systems based on the nodal approach is described in [21] where a symmetrical matrix equation is obtained and solved by a step-by-step integration technique.

The SS approach has also proved to be effective in handling all types of connections between electromagnetic apparatus and circuit elements. However, choosing the type of circuit analysis in a direct coupling method is still a matter of preference.

B. Indirect Methods

In indirect methods, circuit and field equations of the coupled system are maintained as different subsystems and solved separately. To do this, the coupling coefficients should be exchanged back and forth between the two subsystems. The indirect methods can be divided into two subcategories [2], [27]–[33] according to the type of the coupling coefficients: the current output approach, and the circuit parameter approach. A major step in the coupling method based on the circuit parameter approach is to obtain the coupling coefficients (inductances and/or back EMFs) from the finite element solution. This is usually achieved by calculating the flux linkage of windings from the nodal values of the magnetic vector potential. The coupling based on the current output approach is straightforward because the FEM-based subsystem is represented by voltage-controlled current sources to the external circuit. Furthermore, since voltages and currents are passed directly between the two subsystems, the time consuming procedure of extracting circuit parameters, e.g. inductances and back EMFs calculations, are bypassed during

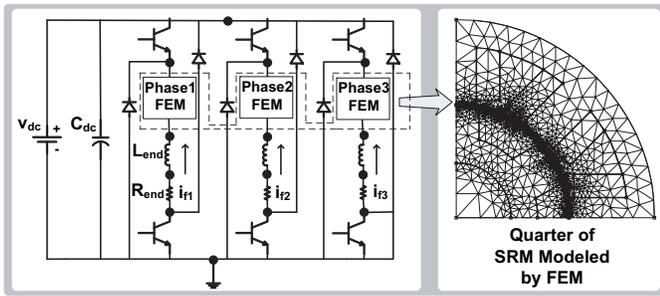


Fig. 3. Electric circuit and finite element mesh of a switched reluctance motor analyzed in [21], based on the nodal approach for coupling.

the simulation. Thus, the computation time is shorter than that of the circuit parameter approach.

C. Comparison of direct and indirect methods

Direct methods are usually more reliable and effective in handling nonlinearities of both the field and the circuit equations by applying multidimensional Newton-Raphson iteration [32]. However, substitution of the dense and usually negative-definite circuit equations in the finite element equations, results in the loss of sparsity, symmetry and positive-definiteness of the final system of coupled equations. These properties are important to solve the large number of finite element equations efficiently using sparse solvers. Thus, an extra step in formulating the direct coupled equations is to modify the equations by multiplying the circuit equations with a coefficient [26], or introducing additional unknowns into the equations [22] to retrieve some of these properties, or to use conventional dense solvers for relatively sparse coupled equations, [?] and [25], which reduce the efficiency.

An advantage of using the indirect coupling method, as described in [31], is that the number of iterations needed for the nonlinear field solution are relatively small compared to that of nonlinear circuit equations. Since the number of field equations are usually much larger than that of circuit equations, this feature results in a considerable time saving. Finally, indirect coupling allows multirate simulation of a coupled system in which the circuit simulation can be performed with a much smaller time-step than that of the FEM-based simulation, as described in [33].

D. Technical challenges of coupled field-circuit simulation

The growing complexity of electromagnetic apparatus and the circuit elements connected to them, as well as the application of advanced control algorithms, is prompting the use of a multi-domain simulation to avoid the costly failure of the whole system after implementation. The main difficulty associated with the use of a coupled field-circuit simulation is the large computational time of the simulation due to the complexity of the field solution. Typical execution time for a few seconds of simulation of a coupled system is in the order of several hours. This is especially troublesome during the design stage when repetitive solutions of the coupled system are necessary. Research is currently ongoing on permeance

network models as an alternative to the FEM-based models for coupled problems due to their relatively fast solution albeit at reduced accuracy. Also, compatibility and synchronization of different field and circuit simulators are important issues which have to be fully examined before successful interfacing of the programs.

IV. INTERFACING ISSUES IN REAL-TIME SIMULATORS

In contrast to off-line transient simulation tools, real-time simulators are useful for testing hardware equipment by interfacing them to the simulator [34]. Real-time simulators can be made up of analog components or digital computers. For over seventy years real-time analog simulators have been used for various applications, but over the last ten years significant advances have been made in real-time digital simulators. Traditionally real-time simulators have been classified as: the transient network analyzers (TNA), real-time playback systems, the real-time digital simulators.

There are industrial grade real-time digital simulators such as RTDS [35], and RT-LAB [36]. These simulators are based on DSPs, and general-purpose processor based PC-Clusters. Originally the main applications of real-time digital simulators are three-fold: closed-loop testing of digital controllers for power electronic based FACTS and HVDC systems, closed-loop testing of protective relays and simulation of transients specifically for analyzing a large number of operating scenarios and fault conditions. The applications of real-time simulators are widening to include virtually every power system study from steady-state studies such as harmonics and power quality evaluation, and low-frequency dynamics, to high frequency electromagnetic studies [37]–[39]

Although earlier efforts at real-time simulation [40], were more or less an extension of the off-line simulators such as EMTF, the latest developments in real-time simulation have a distinct flavor of their own in terms of newer models and algorithms. This is especially true when performing hardware-in-the loop (HIL) simulations. Two kinds of HIL simulations can be performed: (a) controller hardware-in-the-loop (CHIL), (b) power hardware-in-the-loop (PHIL). There are several important issues that need to be addressed in both these types of simulations. For example, in CHIL simulation, the interfacing of a digital controller with a power electronic system modeled in the real-time simulator has attracted a lot of attention [41]. A real-time digital simulator simulating power electronic systems takes discrete switching signals as external inputs from the digital controller. Digital simulation being itself discrete in nature is unable to cope effectively with switching signals that arrive between two calculation steps of the simulator. The conventional off-line approach of using small step-sizes for simulation to overcome the problem is not a favorable option under real-time conditions. Several algorithms have been proposed for correcting firing errors and extra delays for power electronics in real-time digital simulators [42], [43]. There are also several commercially available packages such as ARTEMIS [44] that address this issue. There are also several issues related to the accuracy and stability of PHIL simulation which is an ongoing research topic [46]–[49].

An upcoming trend in real-time simulator design for HIL simulations is the use of field programmable gate arrays (FPGAs) as the core computational engines. The parallel processing hardware architecture and large resource count of these devices is enabling this development. Time steps of the order of a few nanoseconds is now possible for highly accurate device-level real-time simulation of power electronics and variable-speed motor drives [45].

Another new development is the interfacing of geographically remote simulation facilities to share computational resources in solving multi-domain problems. Such a study is reported in [50] using the virtual test bed (VTB) for fuel cell applications, and in [51] for a thermo-electric co-simulation using RTDS and OPAL-RT real-time simulators.

V. CONCLUSION

Interfacing of various simulation tools is increasingly becoming a necessity for the simulation of complex systems whose modeling requirements cannot be met by a single simulation tool. This paper provides an overview of techniques for three types of interfacing problems.

Issues related to hybrid EMT-TS simulators have been classified in four categories: partitioning the original system, building equivalents for each part, exchanging data, and interaction protocol between the two simulators. In general, the system is split into detailed and external subsystems. Detailed system is the zone of EMT simulation, while the external system is handled by the TS simulator. Equivalent models of each subsystem must be used in order to introduce each subsystem to the other. An integrated EMT-TS simulation is also possible using the concept of Hilbert transform and frequency shifting.

Coupled field-circuit analysis is a major step in accurate design and simulation of electromagnetic devices connected to the complex external circuits. Different direct and indirect methods of coupling for low frequency power apparatus are discussed. It is concluded that direct methods are more efficient with respect to the accuracy and speed of the simulation because they preserve the strong coupling between the equations and avoid the iterative loop between the field and circuit subsystems in each time-step. On the other hand, indirect methods are more suitable for multi-rate simulation and can be easily implemented inside the circuit simulator programs by defining the FEM-based subsystem as a user-defined multipoint element.

It is apparent that there have been significant improvements in the modeling accuracy and efficiency of real-time digital simulators. However, there is still a lot of room for developing of better solutions especially in HIL simulation. Increasing use of parallel reconfigurable hardware in real-time simulators provides newer challenges for HIL simulation.

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