Simulation Tools for Electromagnetic Transients in Power Systems: Overview and Challenges

IEEE PES Task Force on Portable Data and Modeling Methods for Electromagnetic Transient Analysis Programs

Jean Mahseredjian, *Senior Member, IEEE*, Venkata Dinavahi, *Member, IEEE*, and Juan A. Martinez, *Member, IEEE*

***Abstract*—This paper presents an overview on available tools and methods for the simulation of electromagnetic transients in power systems. Both off-line and real-time simulation tools are presented and discussed. The first objective is to give the reader an overview on the modeling and simulation capabilities in currently available state-of-the-art tools. The second objective is to provide perspectives on research topics and needed enhancements.**

***Index Terms*—Electromagnetic transients, EMTP, power system models, real-time digital simulation.**

I. Introduction

SIMULATION of electromagnetic transients in modern power systems is widely used for the determination of component ratings such as insulation levels and energy absorption capabilities, in the design and optimization process, for testing control and protection systems and for analyzing power systems in general.

The targeted application field is electromagnetic transients. With the increasing speed of computers and improvements in computational methods, the computation of electromagnetic transients is now overlapping with electromechanical transients. The ultimate objectives are set to maximize computational speed and modeling precision. An additional objective is the development of unique environments that can handle a variety of studies from load-flow to time-domain. This implies wideband models and methods.

The simulation tools or methods for electromagnetic transients fall into the category of EMT-type (or EMTP-type) tools. Such tools are designed to study the power system at a very high precision level by trying to reproduce the actual time-domain waveforms of state variables at any location in the system. The power system is modeled at the circuit level in phase domain and with the representation of all wires and all required components. As for control systems, they are usually represented using block-diagrams. In the time-domain approach there are no inherent limitations in studying harmonics, nonlinear effects and balanced or unbalanced networks.

EMT-type simulation tools are classified into two main categories (families): off-line and real-time. The purpose of an off-line simulation tool is to conduct simulations on a generic computer. Although an off-line tool must be designed to be highly efficient using powerful numerical methods and programming techniques, it does not have any time constraints and can be made as precise as possible within the available data, models, and related mathematics.

Real-time simulation tools are capable of generating results in synchronism with a real-time clock. Such tools have the advantage of being capable of interfacing with physical devices and maintaining data exchanges within the real-time clock. The capability to compute and interface within real-time, imposes important restrictions on the design of such tools.

The objective of this paper is to provide an overview of simulation tools and methods for the computation and analysis of electromagnetic transients. The number of variants in available methods and programs can become very high. This paper concentrates only on the most widely recognized and available groups. Generic and proven methods are mostly considered. Examples are used to demonstrate what is feasible. In addition to presenting current achievements, this paper also discusses limitations and research topics for practical simulation needs. This paper follows the initial work presented in [1] and [2] with the difference of contributing a large amount of details and comprehensive coverage of more topics.

II. Applications

A. Range of Applications

The main and initial application of EMT-type tools is the computation of overvoltages in power systems. There are four main categories of overvoltages: very fast front, fast front, slow front and temporary. The very fast front category is related mainly to restrikes in gas insulated substations. The frequencies range from 100 kHz to 50 MHz. The lightning overvoltages fall into the fast front category, their typical frequency content is from 10 kHz to 3 MHz. The switching overvoltages fall into the slow front category with the frequencies ranging from fundamental frequency to 20 kHz. Switching events are internal controlled or uncontrolled events. For example, controlled events are line switching actions. Faults on buses or in transmission lines fall into the list of uncontrolled events. As for the temporary overvoltages the typical causes for such overvoltages

Manuscript received August 08, 2008. First published May 02, 2009; current version published June 24, 2009. Paper no. TWPRD-00597-2008.

J. Mahseredjian is with École Polytechnique de Montréal, Campus Université de Montréal, 2900 Édouard-Montpetit, Montréal, QC, H3T 1J4 Canada (e-mail: jeanm@polymtl.ca).

V. Dinavahi is with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB T6G 2V4 Canada (e-mail: dinavahi@ece.ualberta.ca).

J. A. Martinez is with the Departament d'Enginyeria Elèctrica of the Universitat Politècnica de Catalunya, Catalunya, Spain (e-mail: martinez@ee.upc.edu).

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Digital Object Identifier 10.1109/TPWRD.2008.2008480

are: single-line-to-ground faults causing overvoltages on live phases, open line energization and load-shedding. In some cases temporary overvoltages are combined with ferroresonance. The frequency content for temporary overvoltages is typically from 0.1 to 1 kHz.

Frequencies above the fundamental frequency usually involve electromagnetic phenomena. Frequencies below the fundamental frequency may also include electromechanical modes (synchronous or asynchronous machines).

The above categories can be expanded to list specific important study topics in power systems:

- switchgear, TRV, shunt compensation, current chopping, delayed-current zero conditions;
- insulation coordination;
- saturation and surge arrester influences;
- harmonic propagation, power quality;
- interaction between compensation and control;
- wind generation, distributed generation;
- precise determination of short-circuit currents;
- detailed behavior of synchronous machines and related controls, auto-excitation, subsynchronous resonance, power oscillations;
- protection systems;
- HVDC systems, power electronics, FACTS and Custom Power controllers.

These applications are in a wideband range of frequencies, from dc to 50 MHz. This range is different from the classical studies of electromechanical transients performed using transient stability (stability-type) programs. Although separate and more widely used packages are available for studying electromechanical transients (from 0 to 10 Hz), it is feasible to apply EMT-type programs to study transient stability or even small signal stability problems. EMT-type programs can produce more precise simulation results for such studies due to inherent modeling capabilities to account for network nonlinearities and unbalanced conditions. Frequency dependent and voltage dependent load models can be also incorporated. The main disadvantages, especially in off-line tools, remain the computational speed and requirements for data. In EMT-type programs the network equations are solved in time-domain and not with phasors as in transient stability solution methods, which is the main explanation for reduced computational speed.

Since EMT-type programs are able to represent the actual phase-domain circuits of a network, they are much more general than traditional power system analysis tools. It is important to emphasize that some traditional power system analysis tools may encounter important limitations for studying practical network problems through sequence networks. In the case of short-circuit programs, the presence of an arrester in parallel with a series compensation capacitor may cause coupling between sequence networks for a fault near the capacitor bank. Such a condition is not acceptable for a traditional short-circuit package. This is not a problem when studied with an EMT-type application.

B. Modeling Guidelines

As it became apparent in the previous section, in EMT-type programs it is necessary to model network components for the entire range of frequencies. In many cases it is neither simple nor practical to develop and maintain unique models for the entire range of frequencies. The main reason is available data and computer timings. It is thus necessary to select models adapted to the simulation type and frequency content of the studied phenomenon. Studies are performed in a layered approach. It is emphasized however that the greater availability of wideband models and data has contributed to the reduction in the number of layers. But even if all data layers are conveniently available in a graphical user interface, the engineering approach may still be to use the required layer for the given study.

Several publications ([3]–[6], for example) are available to help users of EMT-type programs on the correct representation of power system components according to the studied phenomenon. Other publications, such as [7] (see also its references) are available for providing guidelines on needed and typical data.

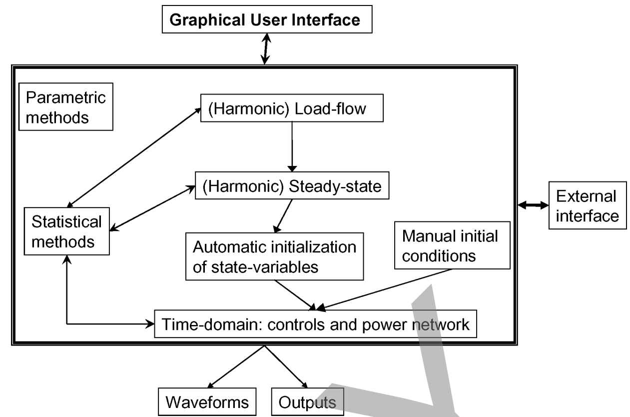

Fig. 1. Ultimate building blocks of an EMT-type simulation tool.

III. Generalities

The scope of this section is to provide a high level view on the most important computational modules currently available in EMT-type tools. Modules that require further research for generalization and implementation in industrial grade applications are also identified.

The building blocks that constitute an EMT-type program are shown in Fig. 1. This figure is labeled as “ultimate” since some of the presented modules or internal features are still at the research stage.

Generally speaking, the simulation of a given electrical network is based on the solution of a system of equations

$$\mathbf{A}\mathbf{x} = \mathbf{b}. \tag{1}$$

The unknown variables found in the vector $\mathbf{x}$ are usually voltages and currents. Matrix $\mathbf{A}$ is used to express topological constraints and component equations, and vector $\mathbf{b}$ represents known quantities. All network component models must participate in matrix $\mathbf{A}$ and vector $\mathbf{b}$. Although there are several methods for the solution of nonlinear models, the most generic approach is to convert matrix $\mathbf{A}$ into a Jacobian and solve (1) through an iterative process. Equation (1) is solved using sparse matrices which provide the capability to solve very large systems efficiently.

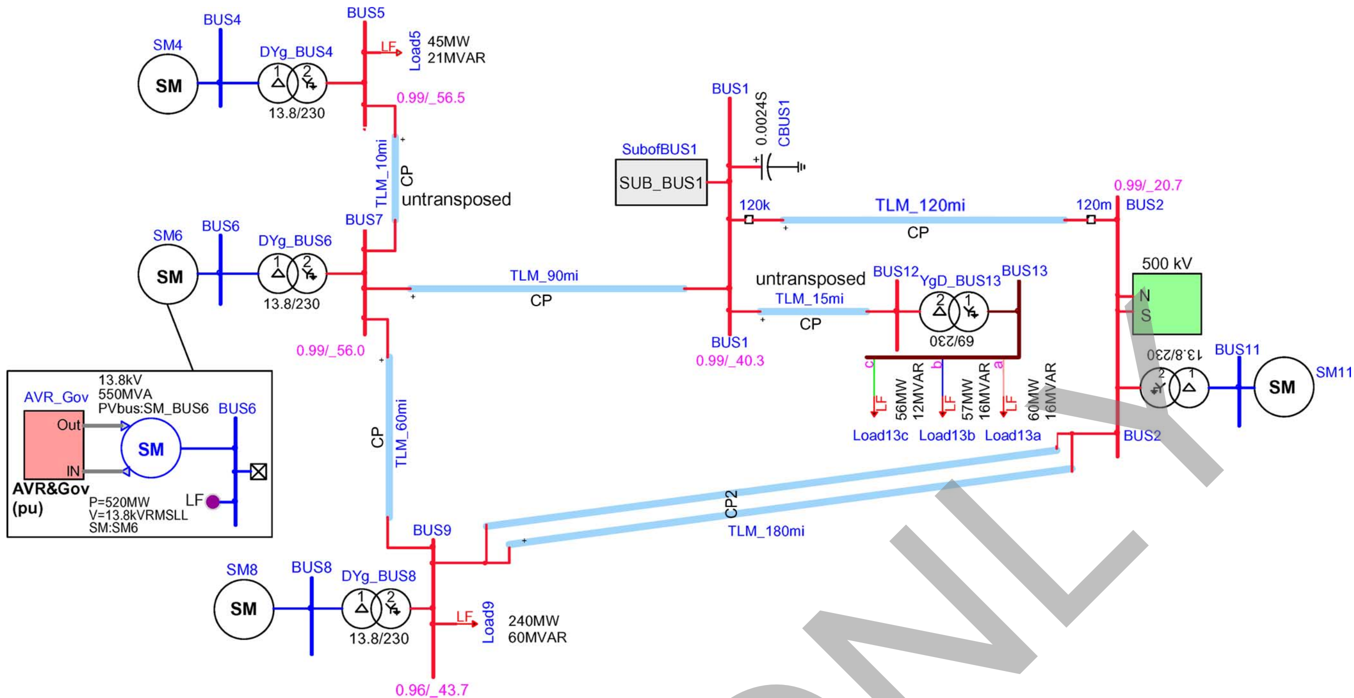

Fig. 2. Sample 230-kV network study case.

A. Graphical User Interface (GUI)

The first entry level to the simulation process is the graphical user interface or data input. Graphical user interfaces with various levels of flexibility and visualization capabilities allow basically drawing the circuit diagram of the simulated system and entering all the appropriate data for selected models.

An example of GUI based design is shown in Fig. 2. Modern GUIs are based on the hierarchical design approach with subnetworks and masking. Subnetworks allow simplifying the drawing and hiding details while masking provides data encapsulation. The design of Fig. 2 is using several subnetworks. The 230-kV network is interconnected with a 500-kV network evacuated with all its details into the subnetwork shown in Fig. 2. In a hierarchical design, subnetworks can also contain other subnetworks. Subnetworks can be also used to develop models. The 3-phase transformers shown in Fig. 2 are based on the interconnection of single-phase units. The synchronous machine symbols are also subnetworks containing the load-flow constraints, machine data and also voltage regulator and governor controls subnetwork, as shown in Fig. 2.

Although several advanced GUIs are currently available, there are no interoperability standards between various software applications. There are no applicable standards for transient data fields which complicates even manual copying of models between GUIs. In some cases, the standardization problem is directly linked to the complexity of models and solution methods for electromagnetic transients.

The lack of standardization is also an important issue when different applications are used in one or more collaborating organizations. Some applications provide external access functions and might be called directly from other applications for performing simulations on assembled networks. The programming aspects of such applications are not complex, but interfacing networks solved in different computational engines may become error prone or create numerical divergence due to inherent lack of simultaneous solution capability.

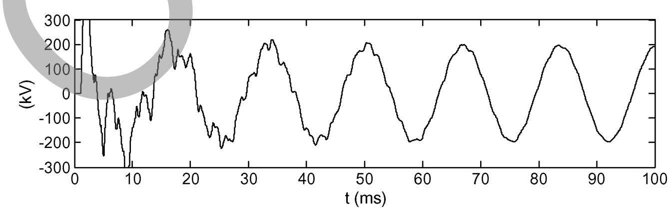

Fig. 3. Transmission line voltage at the receiving end: with (dashed line) and without (solid line) initialization.

A possible solution to data portability between applications is the utilization of the CIM (Common Information Model [8]) format into the simulation of electromagnetic transients. The CIM format is an open standard for representing power system components. It could be used for electromagnetic transients if augmented with many data fields related to such models.

Standardization can also help solving the data exchange problems [9] with conventional power system applications and result into significant benefits to the power industry.

B. Initialization

The importance of initialization can be illustrated through the simple example of Fig. 3. The presented waveforms are the voltages at the receiving end of an arrester protected transmission line for two simulation cases. The first case is without any initial conditions and second case is with automatic initialization from steady-state solution. Even if frequency dependent line models (increased damping over constant parameter models) are used, the transients without initialization require more than 100 ms for attaining the actual steady-state response. This will have dramatic computing time consequences on large systems.

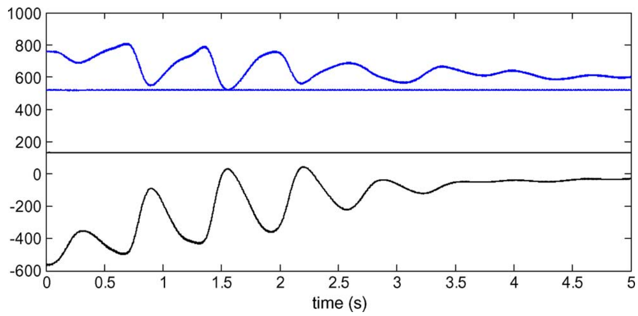

Fig. 4. Two synchronous machine powers in MW, with (straight lines) and without initialization.

In most cases the study of transients is conducted from a given steady-state condition in the network.

The problem becomes more complex in the presence of synchronous or asynchronous machines within multiple generator networks. Machine phasors can be made available from an external load-flow program, but since the actual network may be unbalanced or use models specific to the simulation of transients, the best approach is the implementation of a load-flow method directly before the steady-state solution and within the same simulation tool [10].

As demonstrated in Fig. 4 (test case of Fig. 2, machines SM6 and SM3 in SubofBUS1), without automatic initialization and even after 5 s of simulation the shown machines do not reach steady-state, whereas the automatic initialization starts from the load-flow solution where the machines are given PV constraints. In some cases, if no proper initialization is applied the simulation may reach abnormal operating modes for otherwise obtainable load-flow solution.

The Load-flow module shown in Fig. 1 is used to compute the operating conditions of the power system. It must employ a multiphase solution since the objective is to use the same network data and initialize the time-domain network. The load-flow solution replaces all load-flow constraints (PQ, PV and slack buses) by equations in a Newton solution method. Upon convergence of the load-flow solution, all steady-state phasors become available. The synchronous machine phasors are used to calculate internal state variables. The asynchronous machine requires the calculation of slip for a given mechanical power or torque. The load-flow solution remains optional since in some study cases the source phasors maybe available from existing system data.

The steady-state module follows the load-flow solution and replaces all devices by lumped equivalents to proceed with a phasor solution. Phasors are used for initializing all state-variables at the time-point $\mathrm{t} = 0$. The solution at $\mathrm{t} = 0$ is only from the steady-state and all history terms for all devices are initialized for the first solution time-point.

In some cases the network may contain harmonic sources or nonlinearities in which cases it is necessary to perform a harmonic load-flow. Although is it feasible to program such a method [11], it has a narrower application field.

When the solved network is linear or in linear operating conditions, then the initialization with harmonics method in the Steady-state module constitutes a simple superposition of all harmonic solutions. In some special conditions such as different rotor frequencies, initialization is still possible by solving the rotor networks independently. A more significant programming effort is needed to account for nonlinearities using an iterative Newton method. It can have a significant impact on computing time under some particular conditions [12] or when analyzing multiple harmonic sources.

If there is no calculated steady-state solution there could be manual initial conditions, such as trapped charge or all variables can be at 0-state. Manual initial conditions are also useful for reproducing complex conditions such as ferroresonance.

A complex subject in automatic initialization is the initialization of systems with power electronics switching devices (see also [13]). It is not obvious to automatically predict commutation patterns in a given operating mode and initialize state-variables for harmonic waveforms. A programmed initialization method should find steady-state conditions in significantly less computing time that the brute force approach. In some cases, such as wind generation installations with power electronics devices connected on the rotor side, the best approach is to start with mean-value models or tricked equivalents and to switch onto actual commutating functions after establishing steady-state operation.

To complete the picture, it is important to mention that initialization concerns also the control system diagrams. It is usually a more complex, but essential feature, since, for example, initialization of synchronous machine variables without initialization of its controls can become worthless. Fully automatic methods do not yet exist, but backward propagation of variables in control blocks from specified initial condition variables is a practical option.

In the lack of an automatic initialization, some programs are based on blocking the machine speed for forcing the steady-state, but such methods require additional knowledge on operating conditions and extra user intervention. Some programs also offer a snap-shot feature which allows preserving the steady-state solution conditions (after all time-domain transients have decayed) for successive studies. This option assumes that there are no changes in the saved case.

C. Statistical and Parametric Methods

The Statistical methods are for simulating with random data and evaluating worst case overvoltages or other probabilities for network variables. A new trend in power system applications is to provide Parametric study options. These options can incorporate arbitrary solution search rules through statistical and/or systematic data laws. Such methods are capable to modify and manipulate data using data scripting languages with full access to visualization and analysis functions. Parametric and statistical studies are particularly useful for estimating failure risks due to lightning and switching events or for evaluating performance limits for controllers.

D. External Interface

Modern applications have some means of interfacing with external packages or code. The interfacing methods are either object oriented or capable of calling Dynamic Link Libraries (DLLs) or both. Such interfaces are important since they provide a simple interoperability and expandability path. An important user-defined type modeling application is the connection of advanced controllers or relay models available in actual programming language codes.

E. Time-Domain Module

The time-domain module is the heart of an EMT-type program. It starts from 0-state (all devices are initially deenergized) or from given automatic or manual initial conditions and computes all variables as a function of time.

Since component models may have differential equations, it is needed to select and apply a numerical integration technique for their solution. Since many electrical circuits result in a stiff system of equations, the chosen numerical integration method must be stiffly-stable. Such a need excludes explicit methods. In the list of implicit numerical integration methods, the most popular method in industrial applications remains the trapezoidal integration method. It is a polynomial method that can be programmed very efficiently. If an ordinary differential equation is written as

$$\frac{\mathrm{dx}}{\mathrm{dt}} = \mathrm{f}(\mathrm{x},\mathrm{t}) \\ \mathrm{x}(0) = \mathrm{x}_0 \tag{2}$$

then the trapezoidal integration solution is given by

$$\mathrm{x}_\mathrm{t} = \frac{\Delta\mathrm{t}}{2}\mathrm{f}_\mathrm{t} + \frac{\Delta\mathrm{t}}{2}\mathrm{f}_{\mathrm{t}-\Delta\mathrm{t}} + \mathrm{x}_{\mathrm{t}-\Delta\mathrm{t}}. \tag{3}$$

The terms found at $\mathrm{t}-\Delta\mathrm{t}$ constitute history terms and all quantities at time-point t are also related through network equations. The integration time-step $\Delta\mathrm{t}$ can be fixed or variable. The fixed (set by the user) approach has several advantages in power systems. It avoids the time consuming reformulation of system equations and programming issues related to the models. In the case of transmission line models, for example, it is necessary to maintain history buffers for interpolating for propagation delays. The time-step variability will affect the buffer sizes continuously thus slowing down the computations. Fixing the size for the smallest time-step will create memory problems for large cases.

The automatic computation of time-steps can be based on the local truncation error [2]. The variable time-step approach provides an important advantage for riding through various system time-constants with the required precision. Another advantage is for the solution of nonlinear functions. Reducing the time-step may help convergence. It also provides more precise function fitting in time-domain. Changing the time-step can however become significantly time-consuming as explained above. An alternative applicable specifically to the stiffest problems is to use a set of predefined time-steps. The breaker arc model is an extremely nonlinear function that requires using time-steps in the range of nanoseconds. Since the breaker arc acts only for a short duration of the entire simulation period, the simulation method could revert only temporarily to a reduced time-step. This will not affect overall efficiency since the time-steps will be user-defined and two or three system matrices can be precalculated.

Using a variable time-step does not fix the numerical oscillation problems (see references in [14]), but it can minimize them. It will also minimize errors related to interpolation issues (see [14] and its references), but may become extremely time-consuming for such problems. A complete solution for numerical oscillations due to discontinuities and interpolation for events occurring within the fixed time-step, must be able to correctly account for nonlinear functions and distributed parameter models. The efficient and precise treatment of discontinuities remains an ongoing research topic.

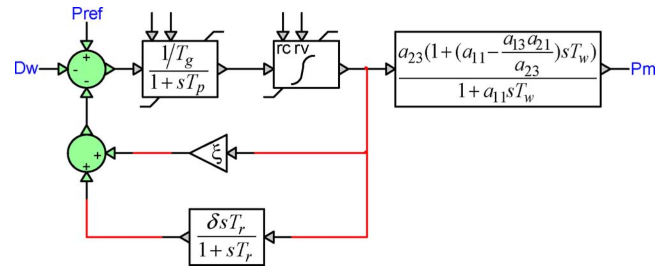

Fig. 5. Typical control system diagram.

There are other numerical integration methods, such as multistep methods and the backward-differentiation formula [15]. Some of these methods can be more precise or provide other advantages over the trapezoidal method for a given integration time-step. The backward-differentiation formula, for example, has the advantage of providing an extremely simple equation for evaluating the local truncation error. The polynomial Gear methods can be used in a variable order setup to increase the integration time-step. It must be however restarted at each breakpoint and requires the maintenance of more history terms. The difficulty is with the added computational burden due to added number of coefficients, history terms and restarting procedures. The theoretical advantages become overshadowed by the computational overhead specially since lowering the integration time-step in the trapezoidal method allows attaining similar precision while still remaining more efficient in most cases.

F. Control Systems

The simulation of control system dynamics is fundamental for studying power system transients. The development of control system solution algorithms based on the block-diagram approach has been initially triggered by the modeling of synchronous machine exciter systems. It was then extensively used in HVDC applications. Control elements can be transfer functions, limiters, gains, summers, integrators and many other mathematical functions. In many applications the block-diagram approach is also used to build and interface user-defined models with the built-in power system components.

A typical control diagram taken from the AVR_Gov block shown in Fig. 2 is shown in Fig. 5. Such diagrams are drawn in the GUI and solved directly. The GUI must allow drawing arbitrary control systems. Several commonly required functions may be available through GUI libraries.

A complicated problem in oriented-graph systems is the capability to solve the complete system simultaneously without inserting artificial (one time-step) delays in feedback loops. A solution to this problem is available in some applications [16], [17].

In most applications the control system diagram equations are solved separately from network equations. The control system uses its own set of equations similar to (1). Although this is not a significant source of errors in most cases, it can become an important drawback for user-defined network models and in the simulation of power electronic systems. The combination of both systems into a unique system of iteratively solved equations is complex. A fixed-point approach where both systems are solved sequentially is more efficient and acceptable in many cases [16].

IV. Off-Line Simulation Tools

Off-line simulation tools are available on generic computer systems on which they can be easily installed and integrated within the working environment and operating system of the user computer.

A. Nodal Analysis Type Tools: Power Systems

The first nodal analysis tool used for power systems was named Electromagnetic Transients Program (EMTP) [18]. For historical reasons, the programs available in this category are called EMTP-type tools.

The nodal analysis method simply accounts for the equilibrium of current injections at each node by using the nodal admittance matrix $\mathbf{Y}$

$$\mathbf{Y}\mathbf{v} = \mathbf{i}. \tag{4}$$

The vector of unknown voltage is $\mathbf{v}(t)$ and the vector of current injections is $\mathbf{i}(t)$. The nodal admittance matrix is also time-dependent since most applications model ideal switches which require inserting or deleting rows and columns. The fact that (4) is real means that it contains only resistances in the symmetrical admittance matrix $\mathbf{Y}$. This is achieved by applying the trapezoidal integration method of (3) through which all branch models with differential equations are given the Norton equivalent resistive companion model for a given integration time-step. The time-step can be fixed or variable. It becomes embedded in $\mathbf{Y}$ and each change of time-step requires the complete reformulation of $\mathbf{Y}$.

The most widely used and available packages in power system applications are: ATP, EMTDC [19] and EMTP-RV [10]. These tools are all based on the fixed time-step trapezoidal integration method using (4). EMTP-RV has introduced the non-symmetric and modified-augmented version of (4), which can be expressed as (1).

In addition to the power network the above applications provide a block-diagram approach for the simulation of control systems. This feature and the usage of black-box type devices is also part of the user-defined modeling approach. In most software packages it is also possible to link with external codes using various complexity levels and accessibility to program features. The external code can be a DLL or a generic object. Its creation requires a compiler. It can be also used for interfacing with other applications. It is the most efficient and the most powerful approach for user-defined modeling.

The electromechanical modeling aspect is covered in most EMTP-type packages through multimass machine models. More complexity might be added by interfacing with external packages specific to the simulation of mechanical motion or torque computation problems, such as in wind generator modeling [20].

The main advantage in EMTP-type tools is the availability of a large number of validated models specific to power system studies. The most complex models are machine models, frequency-dependent transmission line models and transformer models. The models are designed for a wide range of frequencies. Built-in models can be used as building blocks for elaborate modeling of complex installations. EMTP-type tools are also given a distinctive advantage for high-voltage modeling capabilities.

B. Nodal Analysis: Electronic Circuits

There are many simulation tools used for simulating electronic or power electronic circuits. It will be difficult to enumerate all such tools in this paper, but the most powerful and popular tools are based on the original algorithms of SPICE [21]. SPICE is using the modified version of (4), which is called modified-nodal analysis. It is also using the trapezoidal integration method, but with a variable time-step algorithm for controlling truncation error [2]. Some versions may provide extra integration techniques, but the trapezoidal method remains the most popular choice.

SPICE-type (used hereinafter to regroup such tools) packages are not designed for power system applications but for elaborate electronic switching device models and electronic circuits. Such models must account much more precisely for the stresses and losses in semiconductor devices. In EMTP-type solution methods, devices such as thyristors or transistors can be modeled as ideal switches with extra components included externally for adding losses. Although it is also possible to include nonlinear behavior, the level of model sophistication is limited since the target is the study of surrounding circuit system behavior. SPICE-type applications are targeting the detailed analysis of the semiconductor device behavior in the simulated circuits. In some versions of SPICE-type programs it is possible to access directly semiconductor device libraries from various manufacturers providing data for all model parameters including even temperature effects.

In SPICE-type programs, it is usually possible to use a variable integration time-step which can have important advantages for solving nonlinearities. The inconvenience however is that changing the time-step requires reformulation and may become extremely demanding in computer time. It is possible to fix the time-step by fixing its limits, but this may affect the behavior of the nonlinear solver.

In EMTP-type applications, the built-in nonlinearities are monotonically increasing and crossing zero. In SPICE-type applications it is possible to use non-monotonically increasing characteristics and search for multiple solutions.

Most SPICE-type programs allow finding the dc polarization conditions. Ac initialization remains limited.

Although it is feasible to use SPICE (or SPICE-type) for the computation of power system transients, it is not designed for this field of applications. The readily available models for transmission lines and rotating machines are usually much less sophisticated. Many specialized fields, such as lightning transients and switching transients benefit from advanced modeling capabilities available only in EMTP-type applications.

Contrary to power systems in the case of electronic circuits and microchips it is easier to obtain data and maintain advanced databases of models from various manufacturers. Advanced packages such as SABER [22] are used for analog, digital, mixed-signal, and mixed-technology simulations. A specialized language named MAST is used to model complex electrical circuits. It is capable of interfacing with Fortran and C++ code and reuse existing models. MAST is a hierarchical language.

The industry uses Very High Speed Integrated Circuit Hardware Description Language (VHDL) [23] for the purpose of synthesizing and simulating digital circuit designs. VHDL designs can be simulated and translated into a form suitable for hardware implementation. There are several IEEE standard extensions to VHDL for analog, mixed signals and mathematics. VHDL borrows heavily from the Ada (programming language) in both concepts and syntax. VHDL has constructs to handle the parallelism inherent in hardware designs.

It is urgent and important to develop a similar standard for the power system industry.

C. General Purpose Modeling Environments

The most popular general purpose modeling environment is MATLAB/Simulink. There are no built-in stand-alone programs in MATLAB for simulating transients, but its programming language has advanced functions for solving large scale linear systems, which allows programming complete solvers [24]. There are many advantages in such codes since they provide a completely open and high-level architecture which can be used for rapid testing of new solution methods and prototyping of new models. The programming environment of MATLAB can be used as a laboratory for programming compiled code applications using standard computer languages. It also offers many advantages for programming and compiling visualization and analysis tools [25].

Simulink [17] is a block-diagram based package available in MATLAB. It is a general purpose application, widely used for simulating control systems in time-domain. Simulink offers many advantages with a large library of control blocks and various design functions. Both fixed time-step and variable time-step integration methods are available. The state-space block can be used for entering electrical network equations in state-space format

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{5}$$

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} \tag{6}$$

where $\mathbf{x}$ is the vector of states and $\mathbf{u}$ is the vector of inputs. The $\mathbf{C}$ and $\mathbf{D}$ matrices are used to obtain the vector of outputs $\mathbf{y}$. This is the main concept behind the development of a specialized tool named SimPowerSystems [26] for the simulation of power systems transients. This tool offers advanced flexibility for customization and definition of user-defined models.

Such tools are adequate for designing and testing control systems. The drawbacks are in the usage of the state-space formulation for network equations. The computer time required for the formulation of (5) can become unaffordable for larger systems. This is not the case with nodal analysis where the assembly of $\mathbf{Y}$ is a straightforward process and requires minimum computer time. Another drawback is in the representation of nonlinearities. It is not simple to include them directly and simultaneously in (5) and that is why they must be modeled externally through feedback loops which can, in some cases, create numerical problems.

Other implementation methods are also available [27].

D. Hybrid Methods

The term hybrid is used for designating simulation tools or methods based on the following combinations: different types of solution methods and different simulation environments.

A typical example for different types of solution methods is when a frequency domain solution for the network equations is combined with a time-domain solution. Such an approach offers many advantages in modeling and computational speed. In some cases hybrid methods are used for initialization purposes. A frequency-domain solution of the network in the steady-state module is set to call the time-domain solution of a nonlinear component. The time-domain solution generates harmonics which are sent back to the network solution in the form of a Fourier series [12].

For "different simulation environments" the meaning is the simulation of physical problems in different engineering domains. Packages such as [17] and [22] fall into this category. In [22], for example, it is possible to simulate hydraulic, electronic and thermal effects. The ultimate objective is to reduce the need for physical prototypes.

As explained before, hybrid methods can be also established by connecting and interfacing specialized applications from different domains. In [28] an EMTP-type program is linked with an external package based on the finite element method (FEM) for detailed transformer energization studies. In the FEM-based software it is possible to use a highly precise model to account for the material nonlinearity, winding connections and anisotropy. Such software, however, does not offer advanced power system models which become available on the EMTP-type application side.

Another application example is shown in [29], where the CIGRE HVDC benchmark is modeled using an interface between EMTDC and MATLAB/Simulink. Such an approach also allows creating model portability between applications [30].

Interfacing has also been used to incorporate optimization when multiple simulations are involved in design applications in power electronics or simulation of transients. References [31], [32] provide examples of interfacing the SABER and the PSCAD/EMTDC respectively, with optimization routines.

As explained in a previous section, the time-domain approach for solving network equations is more precise, but offers a significantly reduced performance. To provide significant acceleration in the solution of large networks or to combine with solvers for electromechanical transients (lower frequency oscillations), a given network can be separated into fast (precise) and slow areas. Relaxation methods or stability time-frame methods can be applied in the slower regions. The main difficulty is related to the interfacing of methods between regions (see [33], [34] and related references). In some applications [35], it is possible to solve the same system separately in both frequency and time-domain.

E. Frequency-Domain Methods

Although time-domain techniques have been usually preferred for calculation of electromagnetic transients, frequency-domain (FD) techniques have some advantages that can be considered in some applications; e.g. modeling and calculations can be more rigorous with frequency-dependent distributed-parameter elements, and numerical errors can be better determined and controlled.

There are many examples of cases where FD analysis has been instrumental for advancing time-domain techniques; some of these are the development of: full frequency dependent line and cable models, convolution techniques, rational fitting and network equivalent synthesis.

Several frequency-domain techniques have been developed over the years; they are based on the Fourier Transform, the Numerical Laplace Transform or the Z-Transform. The comprehensive coverage of this topic is beyond the scope of this paper. The reader can also consult the partial list of [36]–[41].

V. Case Study: Off-Line Simulation Example From a 230 kV Network

The simulations presented in this section are based on the 230-kV network shown in Fig. 2 and performed using [10]. Various types of studies can be conducted for this network from design and operational point of views. It is demonstrated here that it is now feasible to perform such studies from the same data set and environment.

A typical study type is the computation of overvoltages on transmission lines for switching transients. Such studies can result into the selection of line arresters or usage of pre-insertion resistors during the line energization. Such studies require statistical analysis for the determination of worst overvorltage conditions.

The network of Fig. 2 contains complete data with synchronous machines and related controls. In the case of line energization it is sufficient to model the network with simple equivalents: ideal sources with Thevenin impedances followed by transmission lines up to the substation where energization is performed. The amount of details will improve the precision in the computation of overvoltage waveforms. Inclusion of load and transformer models will improve the precision on damping. It is also more precise to select frequency dependent models for transmission lines. The waveforms shown in Fig. 6 are from the energization study of the transmission line TLM_120mi shown in Fig. 2. The line is protected with surge arresters at both ends. Trapped charge conditions capable of causing worst overvoltages are imitated by opening the line from steady-state conditions at 2 ms and reclosing at 13 ms. Since there is coupling in the line, its phase voltages continue changing until all phases are isolated. The overvoltages are effectively limited using arresters.

The voltage waveforms in Fig. 7 result from the tripping of the transmission line TLM_180mi. The BUS9 side breaker is opened first followed by the opening of the breaker near BUS2. The line has shunt reactors modeled with their nonlinear characteristics. It appears to enter a ferroresonnant state and discharges after being completely isolated.

In the following study the objective is to evaluate the stability of the network and it is mandatory to use the actual machine models with field voltage and mechanical power controls. In this case the controls included also a stabilizer. The event is a single-phase-to-ground fault occurring on the transmission line TLM_120mi at 100 ms. The fault is cleared at 0.2 s and the line is reclosed at about 0.5 s. It appears that the system is able to regain stability (see 3-phase powers in Fig. 8) after reclosing into the line. The first step in this study is a load-flow solution that establishes the machine phasors and thus all power transfers. The second step is the steady-state solution where loads and load-flow constraints are replaced by

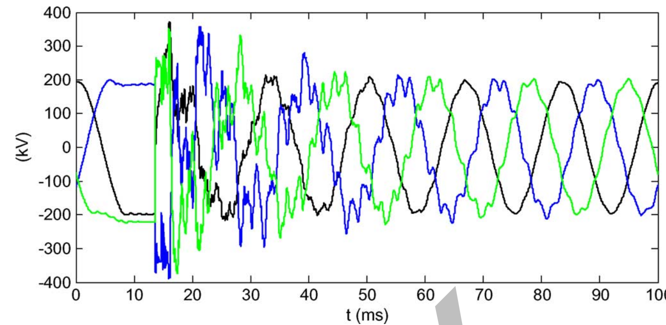

Fig. 6. Transmission line overvoltages at receiving end phases.

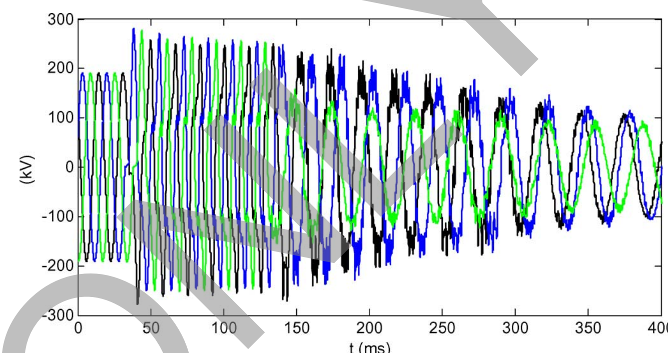

Fig. 7. Overvoltages on shunt reactor of tripped line.

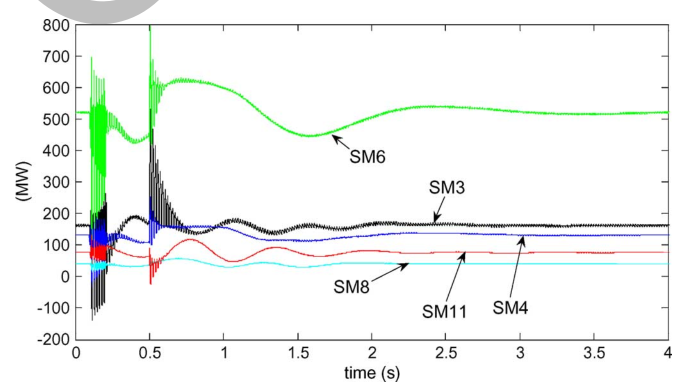

Fig. 8. Synchronous machines, 3-phase powers.

actual equivalents. This step is used to initialize all network variables including internal machine variables and related controls. Controls are initialized by propagating variables backward from the machine field voltage and mechanical power computations in steady-state. Since the time-domain waveforms start in steady-state, it is feasible to quickly simulate the fault condition.

The integration time-step for the case of Fig. 8 was chosen as 50 μs. Although it was possible to select larger time-steps for the machine models, the limiting factor was the propagation delay on the short transmission line TLM_120mi. In classical stability studies, propagation delays are not modeled since the line is a simple pi section. The CPU time for 5 s of simulation time is approximately 18 s on a 2 GHz processor. This is a low number considering the detailed models of machines and transmission lines and that the transformers are modeled including a nonlinear inductance branch which requires iterations. The single-mass synchronous machine models are also solved simultaneously with network equations. If saturation is excluded, which is less precise, but acceptable in this type of stability study, then the CPU time reduces to 12 s.

VI. Real-Time Simulation Tools

In contrast to off-line transient simulation tools, real-time simulators are useful for testing hardware equipment by interfacing them to the simulator. 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. The following sections describe three main types of simulators: the Transient Network Analyzers (TNA), the Real-Time Digital Simulators, and the Real-Time Playback Systems.

A. Transient Network Analyzers (TNAs)

A TNA is an assemblage of scaled down models of physical equipment. It is an analog power system transient simulator. The main strength of a TNA, as with any analog set-up, lies in its real-time capability thus allowing a comprehensive hardware-in-the-loop testing of control and protection equipment. However, TNAs suffer from several drawbacks which have limited their application. Firstly, they require significant resources and time to build and maintain which is why they are owned and operated by large utilities. Once a transient study has been completed and the setup disassembled, it can take several days to prepare the TNA for another test scenario by reconfiguring various components and rewiring the connections between them. Thirdly, TNAs generally lack the scalability for an accurate system representation. Traveling wave effects cannot be reproduced faithfully using only a few pi segments to model a long line. Some of these drawbacks can be overcome by using a *hybrid* simulator which is a combination of analog components and digital computer models.

B. Real-Time Digital Simulators

The best alternative to an analog TNA is a digital simulator that can solve the system equations in real-time. Due to rapid advances in digital processor and parallel processing technology in the last two decades, real-time digital transient simulators are increasingly popular. Real-time digital simulators are required to solve the system differential equations within the time-step selected for simulation. For example, if a transient event happens in 50 μs in the actual system, the real-time simulator should be able to perform the necessary computations for the transient and output the results within 50 μs. It is not sufficient for the end of the simulation run to coincide with the real-time clock. Instead, the computation of every time-step must be executed within the same corresponding interval of real-time. The reason for this stringent requirement is that the simulator must be able to interface and synchronize with actual external control or protection hardware.

There are several industrial grade real-time digital simulators such as HYPERSIM [42], RT-LAB [43] and RTDS [44]. These simulators are based on various types of digital processors such as DSPs, RISC processors, and general-purpose processor based PC-Clusters. Currently 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. Other applications are: harmonics and power quality evaluation [45], [46].

Although earlier efforts at real-time simulation [47], were more or less an extension of the off-line simulators such as EMTP, 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 simulations. There are several important issues that need to be addressed regarding the interfacing of real-time digital simulators and external hardware such as digital controllers for power electronic apparatus [48]. 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 [49], [50]. There are also several commercially available packages such as ARTEMIS [51] that address this issue. The fixing of interpolated signals within fixed time-step simulations is an ongoing research topic (see also references in [14]).

A combination of rapid advances in PC technology and the development of accurate power system models in mathematical modeling packages such as MATLAB/Simulink are driving the current trend of using PC-clusters for real-time and hardware-in-the-loop simulation which previously could only be implemented by expensive high-end technologies [52]. The PC-cluster based real-time simulator is built entirely from high performance commodity-off-the-shelf (COTS) components to sustain performance at a reasonable cost. Real-time simulation and off-line model preparation are divided between two groups of computers comprising the *target cluster* and *hosts*, as shown in Fig. 9.

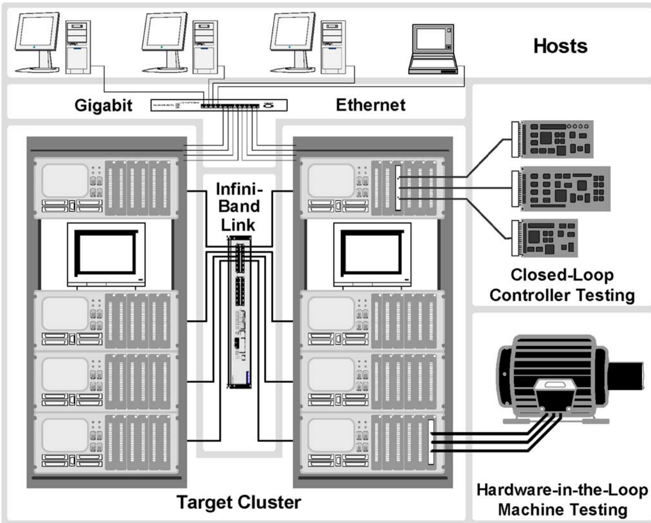

Fig. 9. PC-cluster based real-time digital simulator.

On *target*-side of the gigabit ethernet LAN, the PCs known as *cluster nodes* can be constructed as follows:

- dual 3.0-GHz Intel Xeon processors with double-data-rate (DDR) shared memory providing the CPUs with the raw speed of internal data communication;
- gigabit Network Interface Card (NIC) for fast data transfer between the nodes and hosts; InfiniBand technology is used for inter-node communication at a speed of 30 Gigabit-per-second (Gbps);
- Field Programmable Gate Array (FPGA) based multi-channel I/O module providing 10 ns resolution for various interactions to external hardware;
- dedicated A/D and D/A signal conditioning modules formed the physical connection to the real-world hardware.

The *hosts* are ordinary PCs running on Windows or Linux with sufficient processing power and memory. The real-time model construction and validation is carried out under MATLAB/Simulink with customized toolkits.

The C-code generation is based on MATLAB's Real-Time Workshop (RTW) and the compiled executable is downloaded to the *targets* for real-time simulation.

This *target cluster* and *hosts* configuration is truly flexible and scalable. When more computation power is needed for real-time simulation, additional *cluster nodes* can be added by directly connecting through the InfiniBand switching hub. For more users to share the real-time computation power, properly equipped PCs are simply connected to the gigabit network from the Ethernet switch.

An upcoming hardware trend in real-time simulator design is the use of field programmable gate arrays (FPGAs) as the core computational engines. The parallel processing hardwired architecture and large resource count of these devices is enabling this development. Time steps of the order of a few nanoseconds are now possible for highly accurate real-time simulation of power electronics and variable-speed motor drives [53].

C. Real-Time Playback Simulators

In this type of simulators the transient waveform data is first generated by an off-line EMTP-type program. The stored data is then played back and synchronized in real-time to the device under test. A playback simulator can test the device under open-loop conditions only [54]. This is the main drawback of real-time playback simulators in contrast to an analog TNA or a fully digital real-time simulator.

Real-time playback systems have been used for testing protective relays by subjecting the relay to simulated fault currents and voltages. In addition to simulated waveforms, it is also possible to record field results and play them back in real-time. The main advantage of real-time playback systems lies in the fact that they can utilize the full capabilities of off-line EMTP-type programs. Since the transient data is not collected in the real-time mode, the complexity or the size of the model is not an issue. Multiple test runs can be scheduled in the real-time playback equipment enabling an automated evaluation of the test equipment under a large number of fault scenarios.

VII. Case Study: Real-Time Simulation of 3-Level Vector-Controlled AC Drive

Fig. 10 shows the 3-level 12-pulse vector-controlled variable-speed ac drive system which has been used as a case study for the real-time simulation on the PC-Cluster described in the previous section. The complete system consists of a squirrel-cage induction motor, the drive, and the digital controller. Decoupled vector-control technique has been employed to realize the motor torque/speed control. The electrical system consists of two 3-phase diode rectifier bridges which are connected to the 3-phase ac supply through a 3-winding transformer. After LC filters, the dc sides of the rectifiers are connected to a 3-level 12-pulse IGBT converter which produces the controlled voltages for the induction machine. All parts of the electrical system were first modeled using built-in models in the SimPowerSystems blockset [26]. The system model was then customized for real-time simulation on the PC-Cluster. The power system is modeled in two parts: a state-space (SS) model for the linear circuit and a current injection feedback model for the nonlinear elements. In this case, the electrical model was divided into three parts (Fig. 11). All the linear circuit elements, such as the ac supply, the series filter, the 3-winding transformer, the 3-phase dual rectifier bridge, and the dc filter were modeled by SS equations. The IGBT converter was modeled using a first-level feedback interfacing with the main SS model through the input voltages and output currents. With the output voltages of the converter as inputs, the custom machine model would then generate the stator line currents and feed them back to the converter model.

The objective of the controller (not shown here due to lack of space) is to maintain a constant machine speed ω_{m} while the mechanical torque $\mathrm{T_m}$ is changing. The independent control of ω_{m} is achieved in the synchronously rotating dq frame with the d-axis oriented along the rotating magnetic-flux vector.

The 3-level 12-pulse ac drive and its control system was implemented in real-time using multiple subsystems with multirate sampling as shown in Fig. 12; a *Master* subsystem for the linear part of the electrical system, a *Slave* subsystem for the machine, 12-pulse converter and the controller and a *Console* subsystem for command and monitoring of the various inputs and outputs. Out of these three subsystems, only the *Master*

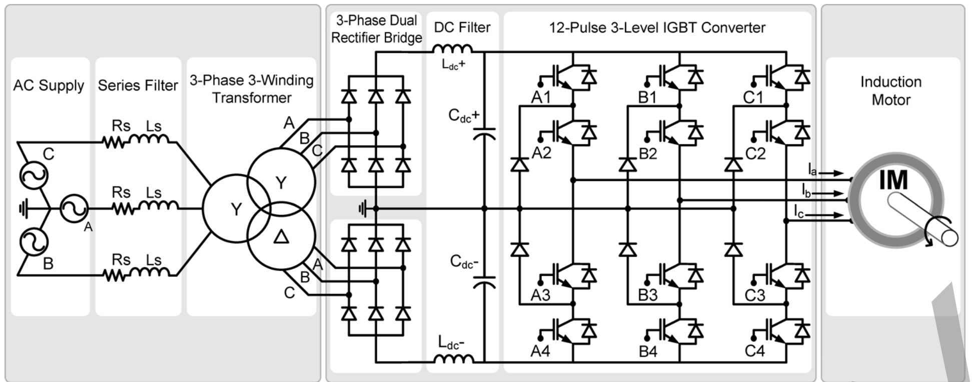

Fig. 10. Vector-controlled variable-speed ac drive.

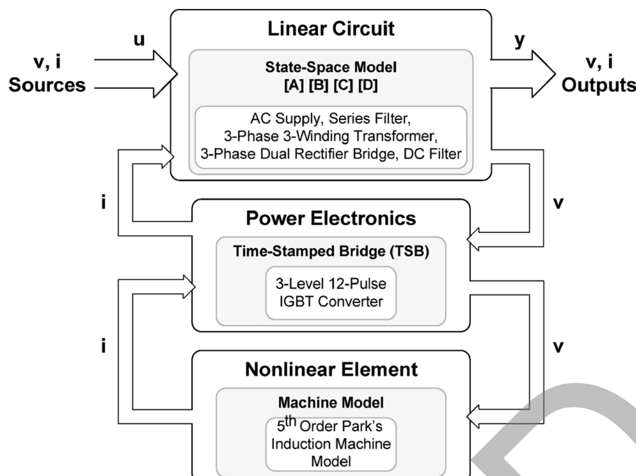

Fig. 11. System model separation for real-time simulation.

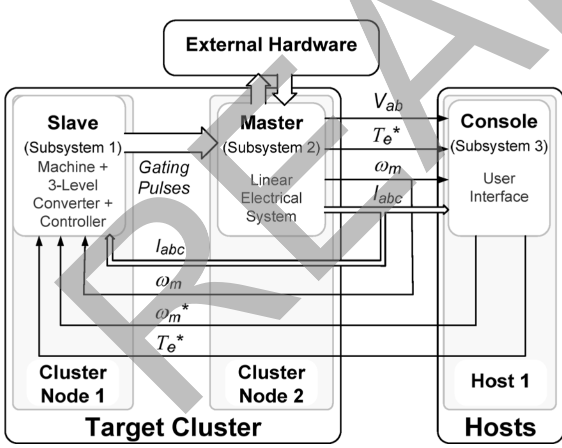

Fig. 12. Implementation subsystems for real-time simulation.

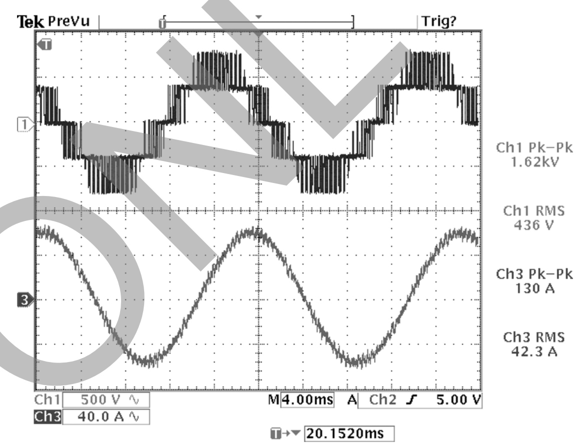

Fig. 13. Traces for steady-state line-to-line voltage and line current.

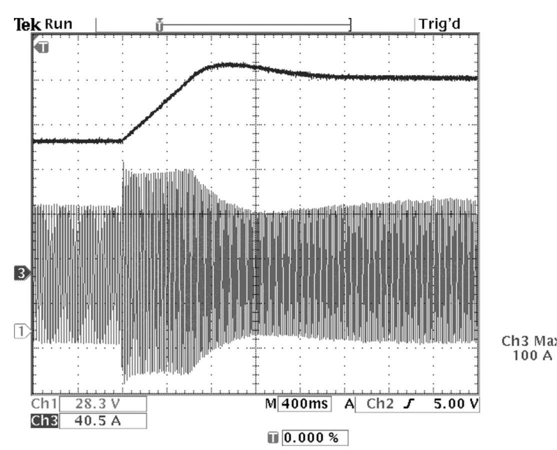

Fig. 14. Traces of the transient response: machine speed and line current.

and the *Slave* are allowed to run in real-time using two *target* nodes in the PC-Cluster. The *Console*, runs on the host computer and communicates with the targets for controlling the inputs and outputs. The real-time simulation is fully interactive and all variables can be either through the console or through external devices such as an oscilloscope connected to the FPGA-based I/Os. The real-time simulation utilizes multi-node multirate sampling.

A time-step of 10 μs was assigned for the real-time simulation, and a carrier frequency of 2.5 kHz was used for the PWM. The simulation results have been recorded for the two operating conditions: steady-state and transient situations. Fig. 13 shows the real-time scopes of the steady-state waveforms (up to 40 ms). These results were corroborated using off-line simulations.

For the transient shown in Fig. 14 the reference torque is maintained at 140 Nm, while the reference speed is changed from 120 rad/s to 160 rad/s at 10 s.

The model has been sufficiently optimized so that the model step-size of real-time simulation can be brought down as small as possible. A time-step dissection revealed that using a single target node, real-time simulation has been achieved with a step-size of 10 μs, without causing any overruns, of which the maximum computation time is only 5.35 μs. A detailed breakdown of the execution time also revealed a processor idle time of 2.49 μs which indicated the possibility of further reduction in the step-size. The experience gained during this case study indicates that practical ac drive controllers can be simulated and tested with great accuracy and efficiency.

VIII. Conclusions

Computer programs using the off-line approach and specifically the EMTP-type algorithms are today the most widely used simulation tools for power system transients. They are also the most precise and provide the largest library of models specific to power system transients.

The advantage of general purpose modeling tools such as MATLAB/Simulink lies in a fairly wide user base and a set of comprehensive toolboxes for modeling general purpose control and mathematical functions. The speed of execution remains an important drawback for studying larger or more complex systems. However, these tools offer a great advantage in prototyping new component models or control strategies.

Tools originating from the simulation of electronic circuits provide advanced models for semiconductor devices and are useful for designing electronic equipment with increased precision for the actual switching devices. Some of these tools are capable of bridging simulations in various engineering fields. Other advantages are in the establishment of common modeling languages and large libraries of manufacturer component models. However, these tools do not provide specialized models for high-voltage power apparatus such as machines and transmission lines and thus do not currently offer the capabilities of EMTP-type programs.

Real-time digital simulators embody several of the advantages of conventional TNAs except that the models are digitally computed instead of being physically constructed, which offers much more flexibility and precision in some cases. Special purpose digital hardware ensures that the simulation is in step with the real-time during hardware-in-the-loop simulations. Their advantages include a relatively lower cost, easy setup and reproducibility of results.

This paper also identified several trends and research fields in the computation of power system transients. It is apparent that there are significant improvements in the real-time simulation approach. The off-line tools are also offering many new advantages including convergence of environments from load-flow to time-domain and increased speed for simulating over an even wider range of frequencies.

The speed of computers will contribute to further convergence in power system simulation environments.

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Jean Mahseredjian (SM'82) graduated from École Polytechnique de Montréal, Montréal, QC, Canada, and received the M.A.Sc. and Ph.D. degrees in 1985 and 1991, respectively.

From 1987 to 2004, he was with IREQ (Hydro-Québec), working on research and development activities related to the simulation and analysis of electromagnetic transients. In December 2004, he joined the Faculty of Electrical Engineering at École Polytechnique de Montréal.

Venkata Dinavahi (M'00) received the Ph.D. degree in electrical and computer engineering from the University of Toronto, Toronto, ON, Canada, in 2000.

Presently, he is an Associate Professor at the University of Alberta, Edmonton, AB, Canada. His research interests include electromagnetic transients, power electronics, and real-time digital simulation and control.

Juan A. Martinez (M'83) was born in Barcelona, Spain.

He is a Professor Titular at the Departament d'Enginyeria Elèctrica, Universitat Politècnica de Catalunya, Catalunya, Spain. His teaching and research interests include transmission and distribution, power system analysis, and EMTP applications.