An Overview of Simulation Tools for Electromagnetic Transients in Power Systems

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Abstract— **This paper presents an overview on available tools for the simulation of electromagnetic transients in power systems. Simulation tools range from specialized computer programs operating in real-time or non-real-time modes, to customized general purpose modeling environments. The various categories of tools are presented with highlights on applicability ranges and available modeling capabilities.**

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

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 protection systems and for analyzing power systems in general.

The simulation tools or methods for electromagnetic transients fall into the category of EMT-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. As for control systems, they are usually represented using block-diagrams. There are no inherent limitations in studying harmonics, nonlinear effects and balanced or unbalanced networks.

EMT-type simulation tools may be 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 using a programmed mathematical solution. Although an off-line tool must be designed to be highly efficient using state of the art 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 mathematics.

Real-time simulation tools are capable of generating results in synchronism with a real-time clock. Such tools are 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. These tools can be based on physical analogs such as in transient network analyzers (TNA) or can be digitally implemented using special computer architectures or assemblies. The digital real-time tools are sometimes called DTNA (digital TNA) or referenced in this paper as real-time digital simulators. These tools are mostly used for testing manufacturer control and protection systems or equipment for which an off-line model cannot be synthesized or imitated with sufficient confidence.

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. The presentation is on the applications and usage. A separate paper will be written on solution methods.

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II. APPLICATIONS

EMT-type tools are used in several important power system study fields such as:

- overvoltage calculations
- insulation coordination studies
- saturation and surge arrester influences
- harmonic propagation
- power quality
- interaction between compensation and control components
- wind generation
- distributed generation
- precise analysis of short-circuit currents
- detailed behavior of synchronous machines and related controls, auto-excitation
- subsynchronous resonance
- power oscillations
- protection systems
- multiterminal HVDC systems
- FACTS and Custom Power devices
- other power electronics applications.

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. Some studies can be conducted only in off-line programs. Real-time methods are most useful for studying actual (real) manufacturer equipment and embedded algorithms. When both approaches can be used for a given study case, then the only advantage of a real-time program is its capability to perform a very large number of repetitive simulations for statistical or sensitivity analysis. The off-line tools are usually more precise for the network solution part. There is also an issue of availability which will usually favor off-line tools.

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.

III. Off-line simulation tools

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

Modern off-line tools are designed for increased flexibility and user-friendliness. The most common features are: data input method, time-domain solver and solution visualization features. It is almost a common practice to provide graphical user interfaces for entering data and visualizing results. The time-domain solver is capable of providing solutions at discrete time-points. Since component models may have differential equations, it is needed to select and apply a numerical integration technique for their solution. A network simulation may start from 0-state conditions meaning that all devices are initially de-energized or from automatic initialization. In the 0-state case there is a significant disadvantage for conducting the studies since the user must wait till all natural response transients have completely decayed before starting the study. When an automatic initialization method is not available, some programs offer a snap-shot feature which allows preserving the steady-state solution conditions for successive studies. This option does not offer a complete solution since in many cases it may be necessary to apply changes before restarting a study.

The ultimate initialization method must be able to start from a load-flow solution since in a power system the generator phasors are set from the solution for load-flow constraints. Combined load-flow, steady-state and time-domain solutions are available in some packages. It is also feasible to initialize with different steady-state frequencies and through iterative methods capable of determining transformer tap settings or asynchronous machine slip calculations. In the case of a synchronous machine its field voltage can be propagated backwards through the control blocks of the exciter. The main difficulty remains the initialization process in the presence of nonlinear components. This includes power electronics based systems in which the steady-state firing pattern is difficult to predict and convey into the actual initialization of surrounding circuit state-variables. The time required to compute initial conditions should be noticeable smaller than the natural decaying of transients.

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 control strategies of HVDC links. It was then extensively used in synchronous machine exciter systems. 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. Nodal analysis type tools: power systems

The first nodal analysis tool used for power systems was named EMTP (Electromagnetic Transients Program) [1]. 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 $\mathbf{Y}$:

$$\mathbf{Y}\,\mathbf{v} = \mathbf{i} \tag{1}$$

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 equation (1) is real means that it contains only resistances in the symmetrical admittance matrix $\mathbf{Y}$. This is achieved by applying a numerical integration technique 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 $\mathbf{Y}$.

Equation (1) is linear. The nonlinear functions are linearized at each operating point and solved through an iterative method with the repetitive solution of the entire system (1) or a reduced equivalent. The best methods have fast convergence and are capable of solving arbitrary systems without user intervention. The methods based on network equivalents are usually less general and can encounter various numerical problems or require the insertion of dummy devices.

Equation (1) is solved using sparse matrices which provides the capability to solve very large systems efficiently.

Since the introduction of the original EMTP [1] method a significant effort has been dedicated to the development of models for various power system components. Due to the wideband aspects, model development is not simple and may require a substantial research effort in some cases. On the programming aspects much effort has been also devoted to the improvement of graphical user interfaces for simplifying the data input and visualization tasks. The development of the first tools was mainly motivated by the calculation of lightning and switching overvoltages. The increased presence of power electronics in power systems has triggered the development of related models. Due to increased computer speeds and memory it is now feasible to apply EMT-type software for stability-type simulations for larger systems.

The most widely used and available packages in power system applications are: ATP, EMTDC [2] and EMTP-RV [3]. These tools are all based on the fixed time-step trapezoidal integration method using equation (1). EMTP-RV has introduced the non-symmetric and modified-augmented version of (1). The trapezoidal integration method is chosen for its stability properties, performance and precision for a given time-step when compared to other integration techniques. The main reason for using a fixed time-step is due to the fact that power systems have many transmission lines in which the maintenance of history buffers with a variable time-step becomes computationally inefficient. Other numerical problems can occur when dealing with machine models. The fixed time-step selection does not constitute a particular problem since typical values can be used and precision can be tested against reduced time-step trials when doubts exist.

In the above nodal analysis packages the control system block-diagrams are usually solved separately and sequentially with the power network equations. Some options may be available for finding a simultaneous solution through network equivalents or iterations. The simultaneous solution with control system equations is particularly important when building and connecting user-defined models. In some applications there are specific functions for building user-defined models. In ATP, a proprietary language named (MODELS) is used for entering and solving model equations. In other software, a widely available scripting language or capability to call external DLLs (Dynamic Link Library) allows users to create elaborate device models and even interface with external applications. The DLLs are based on compiled programming languages which allow better performance and unlimited programming sophistication.

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 model 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, such as wind parks. 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 [4]. SPICE is using the modified version of equation (1), 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. Some versions may provide extra integration techniques, but the trapezoidal method remains the most popular choice.

The main difference with the power system applications described in the previous paragraph is the support for elaborate electronic switching device models. Such models are designed to account much more precisely for the stresses and losses in semiconductor devices. In EMTP-type solution methods devices such as thyristors or transistors are 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.

SPICE allows using 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. SPICE allows using non-monotonically increasing characteristics. Some electronic circuit simulators may also allow searching 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.

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 [5], [6]. 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 [6].

Simulink is a block-diagram based package available in MATLAB. It is a general purpose application, but can be directly 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:

$$\dot{\mathbf{x}} = \mathbf{A}\,\mathbf{x} + \mathbf{B}\,\mathbf{u} \quad (2)$$

$$\mathbf{y} = \mathbf{C}\,\mathbf{x} + \mathbf{D}\,\mathbf{u} \quad (3)$$

where $\mathbf{x}$ is the vector of states and $\mathbf{u}$ is the vector of inputs. This is the main concept behind the development of a specialized tool named SimPowerSystems for the simulation of power systems transients [7]. This tool offers unsurpassed flexibility for customization and definition of user-defined models. It is also capable of interacting with the standard environment of MATLAB.

Such tools are ideal for designing and testing control systems. The solution of network equations allows accounting for network reactions in the control system simulations. The drawbacks are in the usage of the state-space formulation for network equations. The computer time required for the formulation of equation (2) can become unaffordable for larger systems. In some cases the formulation time can become longer than the entire simulation. 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 (2) and that is why they must be modeled externally through feedback loops which can create numerical problems.

There are other applications based on the utilization of Simulink for simulating electrical circuits [8].

D. *Other methods*

In addition to the above, there are many different types of tools which are not necessarily of industrial grade or capable of solving generic circuits with controls and nonlinearities, but can offer various advantages in solving complex problems.

An important family of tools is based on frequency domain analysis through Fourier transform theory. Instead of applying a numerical integration technique the steady-state responses of a network to a number of harmonically related frequencies are obtained first and then the superposition principle is applied for synthesizing the transient responses.

Another family of methods can be classified as being hybrid. Employing frequency domain and time-domain methods for initialization purposes, for example, constitutes a hybrid approach. Combining nodal analysis and state-space formulation also constitutes a hybrid approach.

IV. 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 (TNA)*

A TNA is an assemblage of scaled down models of physical equipment. The topological layout of a TNA is similar to a physical power system. In this sense 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 to build and maintain which is why they are owned and operated by large utilities. TNAs require excessive time to prepare test setups. 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 $50\,\mu s$ in the actual system, the real-time simulator should be able to perform the necessary computations for the transient and output the results within $50\,\mu s$. 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. These simulators can easily accommodate tests that are normally not performed on an actual power system during commissioning due to the engineering and economic risks involved.

There are several commercially available real-time digital simulators such as RTDS [9], HYPERSIM [10], and RT-LAB [11]. 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: (1) Closed-loop testing of digital controllers for power electronic based FACTS and HVDC systems. (2) Closed-loop testing of protective relays. (3) Electromagnetic transient simulations specifically for analyzing a large number of operating scenarios and fault conditions. Other applications such as the real-time harmonics modeling and simulation for power quality evaluation are also cropping up [12], [13].

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 [14]. 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 [15], [16]. The fixing of interpolated signals within fixed time-step simulations is an ongoing research topic (see also references in [17]).

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 [13], [18]. 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. 1.

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

- dual 3.0GHz 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 30Gigabit-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.

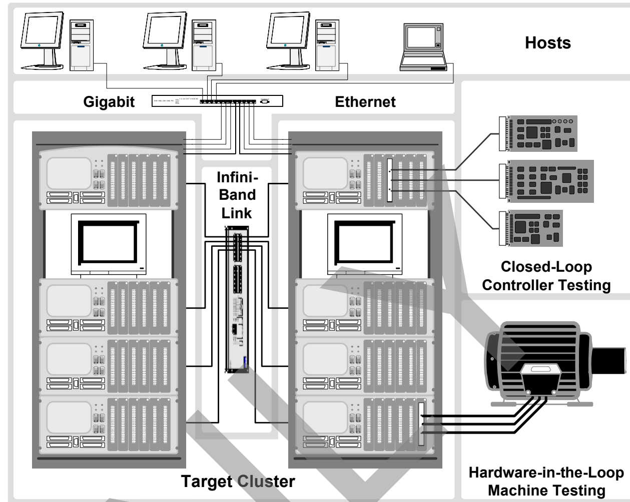

Fig. 1. A PC-Cluster Based Real-Time Digital Simulator [13].

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.

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. Since it is not possible to predict the device's response *a priori* the transient data being played back could not have incorporated the device's response during the off-line simulation. Hence a playback simulator can test the device under open-loop conditions only. The device's response cannot be feedback to the simulator and therefore cannot be expected to have an influence on the simulation. 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. Real-time playback systems are capable of reproducing complex waveforms that are generated from complex operations on the power systems, without the constraints of accuracy or bandwidth.

V. 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 and Simulink lies in a fairly wide user base and a set of comprehensive toolboxes for modeling general purpose control and mathematical functions. More recent developments include a special blockset for power systems, e.g. SimPowerSystems. 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.

Simulation tools based on SPICE algorithms have a very powerful set of models for semiconductor devices and are useful for designing converter equipment with increased precision for the actual switching devices. However, the inherent solution methods have a slower performance for the simulation of large networks. Detailed models for high voltage power apparatus such as machines and transmission lines are not in the application targets and will not offer the capabilities of EMTP-type programs.

The advantage of TNAs lies in the fact that the simulated network is physically constructed in the form of a scaled model and provides a powerful platform for testing actual controllers and protection equipment. The disadvantages lie mainly on considerably long setup times, high costs and limitations in models.

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 hardware ensures that the simulation is in step with the real time. Their advantages include a relatively lower cost, easy setup and reproducibility of results.

A real-time playback system is a hybrid of the off-line simulation and real-time rendering. This approach allows carrying out protection and control studies, without limitations in the simulated network. The main disadvantage is that there is no feedback to the simulation from the controller or relay.

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VII. Biographies

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