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On a new approach for the simulation of transients in power systems[☆]

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Abstract

This paper presents a new simulation tool named EMTP-RV. EMTP-RV is a completely new program with a new graphical user interface and a new computational engine. The simulation uses a new matrix formulation for computing load-flow, steady state and time-domain solutions. Theoretical advantages are emphasized and demonstrated through practical examples. An open-architecture graphical user interface (GUI) is developed to maximize flexibility and allow creating and maintaining complex designs.

Keywords: Simulation tools; Numerical methods; EMTP

1. Introduction

Since its initial concept presented in 1969 [1] the basic EMTP type simulation approach remained unchanged. It is used in various commercial (DCG-EMTP Version 3, EMTP-V3 [2]) and non-commercial packages. The main system of symmetric equations used in [1] is given by

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

This is referred to in the literature as the standard nodal analysis formulation. It assumes that all network components can be given an admittance matrix model. Matrix $\mathbf{Y}$ is the admittance matrix, $\mathbf{v}$ the vector of unknown voltages and $\mathbf{i}$ is the vector of current sources combined with history current sources for the trapezoidal integration method. Since $\mathbf{v}$ also includes known voltage sources, Eq. (1) is actually implemented taking only a submatrix $\mathbf{Y}_n$ of $\mathbf{Y}$ for finding n unknown voltages. One of the important disadvantages of this formulation is the inability to incorporate ungrounded voltage sources. This has been corrected in [3] by using modified-nodal analysis, which incorporates an extra row for the voltage source equation and an extra column for the voltage source current which becomes listed in the vector of unknowns.

The assumption of admittance model existence for every component is a significant limitation. An ideal transformer model, for example, does not have admittance matrix formulation. This can be partially avoided by adding losses, but can then cause ill-conditioning problems. Other limitations are found in the representation of ideal switches. An ideal switch has pure zero resistance when closed and becomes infinity when opened. This is a fundamental principle in such a model to avoid superfluous natural frequencies and matrix conditioning problems. That is why system (1) is a variable rank system where closing a switch eliminates a matrix column and the corresponding row. The disadvantage of such manipulations is the computational effort, especially when the number of switches and switching frequency become high.

The EMTP-V3 code was written using the legacy Fortran-77 language and related methods. Such codes have significant limitations in automatic memory management, in code organization and interfacing with external programs. Modern computing languages and methods provide much more powerful and efficient

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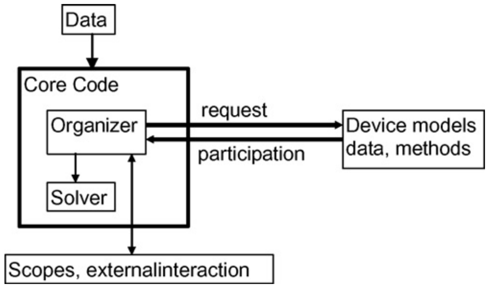

Fig. 1. EMTP-RV main architecture.

environments for software development while providing crucial advantages in code evolution and maintenance.

Another major aspect in the simulation of transients is the graphical user interface (GUI). It constitutes the first and the main facet directly apparent to the user. It also represents a technological barrier into the design and simulation of more complex cases. Although several GUI programming approaches are presented in the literature [4,5], the innovation path in this field is towards increased level of automation, open-architecture and advanced visualization.

This paper presents a new simulation tool named EMTP-RV with a new graphical user interface EMTPWorks. It supersedes EMTP-V3 and presents several improvements in computational engine, graphical user interface and software development aspects. Although there are commercial aspects in any industrial grade software development, this presentation is kept at the technical contribution level.

EMTP-RV has been written from scratch without any reverse-engineering or code recuperation from old EMTP-V3. It constitutes a historical moment in the complex evolution of EMTP type software.

2. New formulation

The development of EMTP-RV is based on the conception of a computational core for the solution of its system of equations. The main architecture is shown in Fig. 1. The core has a solution step controller (organizer) which is responsible for all data input and communication tasks. It schedules various task calls to the simulated network devices (models and options). These are request signals received by device codes organized into encapsulated modules with device objects holding data and methods. Devices may respond back by participating into various requests. Participation is optional since devices may have different equations and needs.

The key aspect in this architecture is the ability to easily accommodate device equations into the main system of network equations. A new system of modified-augmented-nodal analysis is proposed to eliminate various classical nodal or modified-nodal analysis limitations:

$$\begin{bmatrix} \mathbf{Y}_n & \mathbf{V}_c & \mathbf{D}_c & \mathbf{S}_c \\ \mathbf{V}_r & \mathbf{V}_\mathrm{d} & \mathbf{D}_\mathrm{VD} & \mathbf{S}_\mathrm{VS} \\ \mathbf{D}_r & \mathbf{D}_\mathrm{DV} & \mathbf{D}_\mathrm{d} & \mathbf{S}_\mathrm{DS} \\ \mathbf{S}_r & \mathbf{S}_\mathrm{SV} & \mathbf{S}_\mathrm{SD} & \mathbf{S}_\mathrm{d} \end{bmatrix} \begin{bmatrix} \mathbf{v}_n \\ \mathbf{i}_\mathrm{V} \\ \mathbf{i}_\mathrm{D} \\ \mathbf{i}_\mathrm{S} \end{bmatrix} = \begin{bmatrix} \mathbf{i}_n \\ \mathbf{v}_\mathrm{b} \\ \mathbf{d}_\mathrm{b} \\ \mathbf{s}_\mathrm{b} \end{bmatrix} \quad (2)$$

This is an augmented formulation which is keeping only the $\mathbf{Y}_n$ part from Eq. (1). Although submatrices are identified due to their typical contents and for symbolic explanations given below, Eq. (2) can be viewed as a generic $\mathbf{Ax}=\mathbf{b}$ system. Matrix $\mathbf{A}$ is not necessarily symmetric which provides another advantage over Eq. (1) for some device models.

For a voltage source connected between two nodes k and m, the source equation is given by: $v_k - v_m = v_{\mathrm{b}\,km}$. It is directly inserted into the main system by placing a 1 and a -1 in columns k and m, respectively, of $\mathbf{V}_r$. The source voltage is $v_{\mathrm{b}\,km}$. The source current condition is accounted by transposition in the submatrix $\mathbf{V}_c$. If the source is disconnected, then only its diagonal cell in $\mathbf{V}_\mathrm{d}$ is set to 1 and $v_{\mathrm{b}\,km} = 0$. A similar approach is used for entering other models. An ideal transformer with secondary nodes k–m, primary nodes i–j and a transformation ratio g is modeled with the equation: $v_k - v_m - gv_i + gv_j = 0$. This equation is again directly accommodated in the submatrix $\mathbf{D}_r$ with the equivalent row transposition appearing in $\mathbf{D}_c$. Ideal switches are included straightforwardly using submatrices $\mathbf{S}$. When a switch (between nodes k–m) is closed: $v_k - v_m = 0$. When the same switch is open, its current becomes 0 by setting the corresponding diagonal cell in $\mathbf{S}_\mathrm{d}$ to 1. The solved system is now of fixed rank and quickly reformulated at each switch status change. Adding a resistance and a fixed voltage drop (diode effect) to the switch, is achieved using $v_k - v_m - Ri_{km} = v_\mathrm{dc}$. This equation goes into $\mathbf{S}_r$, $\mathbf{S}_\mathrm{d}$ and $\mathbf{s}_\mathrm{b}$.

A system similar to (2) was initially proposed in [6]. The system above provides further generalization and introduces new non-zero submatrix possibilities.

2.1. Nonlinear functions

It can be proven that if nonlinear device equations are linearized at each solution time-point, matrix $\mathbf{A}$ becomes the Jacobian matrix of the Newton solution. This approach provides a true-nonlinear solution to all nonlinear devices. It eliminates the less precise pseudo-nonlinear devices and all topological restrictions (see [7]) encountered in the compensation method used in [2]. Machine models are also classified as nonlinear functions and solved through the same iterative solver for obtaining a simultaneous solution with all nonlinear devices and in any topological configuration. Further details on this approach will become available in a separate paper.

2.2. Control system equations

Improvements in the solution of control system equations are presented in a separate paper [8]. Numerical delays that existed in [2] between control blocks due to nonlinear feedback loops, are eliminated using a Jacobian matrix formulation.

2.3. Steady-state solution

The main purpose of a steady-state solution in EMTP is to initialize the network state variables for minimizing the natural response at startup in time-domain. The formulation method is the same as in Eq. (2), only now all variables become complex and devices must provide steady-state equivalents for each frequency in the generic harmonic steady-state solution.

2.4. Load-flow solution

The steady-state solution can provide acceptable operating conditions (power-flow) when initialized from a load-flow solution. The augmented matrix concept is expanded to include load-flow constraint equations and the solved nonlinear function becomes:

$$\begin{bmatrix} \mathbf{A} & \mathbf{A}_{\mathrm{I}} \\ \mathbf{L}_{\mathrm{LA}} & \mathbf{L}_{\mathrm{d}} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{x} \\ \Delta\mathbf{x}_{\mathrm{LF}} \end{bmatrix} = \mathbf{F} = \mathbf{0} \tag{3}$$

The matrix $\mathbf{A}$ is the linear network matrix (left-hand side matrix in Eq. (2)), $\mathbf{A}_{\mathrm{I}}$ is a connectivity matrix for accounting for load-flow devices, $\mathbf{L}_{\mathrm{LA}}$ and $\mathbf{L}_{\mathrm{d}}$ provide load-flow device constraint equations. The unknowns are the standard network variables $\Delta\mathbf{x} = [\,\Delta\mathbf{v}_n \quad \Delta\mathbf{i}_{\mathrm{V}} \quad \Delta\mathbf{i}_{\mathrm{D}} \quad \Delta\mathbf{i}_{\mathrm{S}}\,]^{\mathrm{T}}$ and the load-flow device currents $\mathbf{I}$ and internal voltages $\mathbf{E}$:

$$\Delta\mathbf{x}_{\mathrm{LF}} = [\,\Delta\mathbf{I}_{\mathrm{L}} \quad \Delta\mathbf{I}_{\mathrm{PQ}} \quad \Delta\mathbf{I}_{\mathrm{PV}} \quad \Delta\mathbf{I}_{\mathrm{SL}} \quad \Delta\mathbf{E}_{\mathrm{PQ}} \quad \Delta\mathbf{E}_{\mathrm{PV}} \quad \Delta\mathbf{E}_{\mathrm{SL}}\,]^{\mathrm{T}}$$

Above subscripts are: L for loads, PQ for PQ control sources, PV for PV control and SL for slack bus.

Eq. (3) presents a new approach for multiphase load-flow solution. It is different from earlier presentations [9] by means of a concatenation of load-flow equations with the readily available network equations. It can inherently accommodate all EMTP device models and provide the most precise initialization. Non-classical load-flow devices, such as frequency-dependent transmission lines, become automatically included. There is no need to perform separate and cumbersome Jacobian derivations [9] for network models, but only for load-flow device constraint equations.

3. Implementation

The EMTP-RV design is object-oriented. Such a design has several benefits in program development and maintenance. Modern programming concepts, such as data hiding and encapsulation, eliminate data corruption problems caused by device models and allow establishing a clear programming approach by gathering all model data and methods through a single object and module. Model code legibility is dramatically increased in comparison with old Fortran-77 coding used in EMTP-V3 while improving computational speed. Although the core of the code is programmed using Fortran-95 (new object oriented language, see [10]) for achieving best computational speed, mixed language programming is allowed specially for establishing connections with external functions and the graphical user interface. Another major benefit over EMTP-V3 is case-tailored and automatic memory allocation. It is a key issue in the software's ability to solve extremely large cases and/or usage of very small time-steps with transmission line models.

Modern programming methods and tools can significantly alleviate the software development process and contribute to the implementation of more complex algorithms.

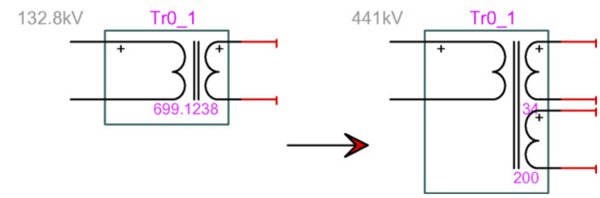

Fig. 2. Automatic redrawing.

4. New graphical user interface

The innovations in this field are in the development of an open architecture and generic circuit oriented interface with extended single-line-diagram handling capability. Signals (not nodes), devices and connectivity pins are the constitutive elements. EMTPWorks is designed for manipulating extremely large networks.

Almost all aspects of the GUI named EMTPWorks are scriptable and modifiable by the user. The scripting language is JavaScript with EMTPWorks extensions. Connectivity with other languages and ActiveX usage is readily available. Data input is based on web pages. Each device has a local web address. This approach also allows data exchange and device addressing through the Internet. It also provides quasi-unlimited capabilities in the development of data forms through dynamic HTML programming. The fact that device data and symbol methods are not hard-coded provides users with maximum flexibility for creating customized devices.

EMTPWorks is an object-oriented program written in C/C++ and based on Microsoft Foundation Class library. Each network device is an object with attributes. Attributes are available to the user and used for entering data and methods. Device attributes are the customization entry point. Other objects, such as device pins and signals are given attribute specification menus. This is an open-architecture approach.

Scripting is extended to drawing using EMTPWorks methods (extensions) added to JavaScript. Drawings can be automatically updated through scripts for reflecting data changes. This is demonstrated in Fig. 2 for the ideal transformer unit when updating the number of secondary windings and winding data.

In addition to scriptable drawing, a Symbol Editor is available for complete customization. The example of Fig. 3 [11] makes the substation drawing appear as the actual substation using the Symbol Editor and subcircuits. An assembly of devices can be placed into a subcircuit with programmable masking. Subcircuits can contain subcircuits. This is a hierarchical approach with unlimited number of levels. In EMTPWorks subcircuits are created automatically from user selections on the screen and pin interfaces.

Hierarchical designs allow visualizing study cases at a higher level. In the wind park study of Fig. 4, the details of the wind generator control circuits, the wind generator model, the wind effect representation, the static compensator (Statcom) and the load are hidden in subcircuits to provide a high level visualization to the actual simulation. These are multilevel subcircuits with masks for allowing the user to specify internal parameters. Masking allows entering extensive script codes or calls to

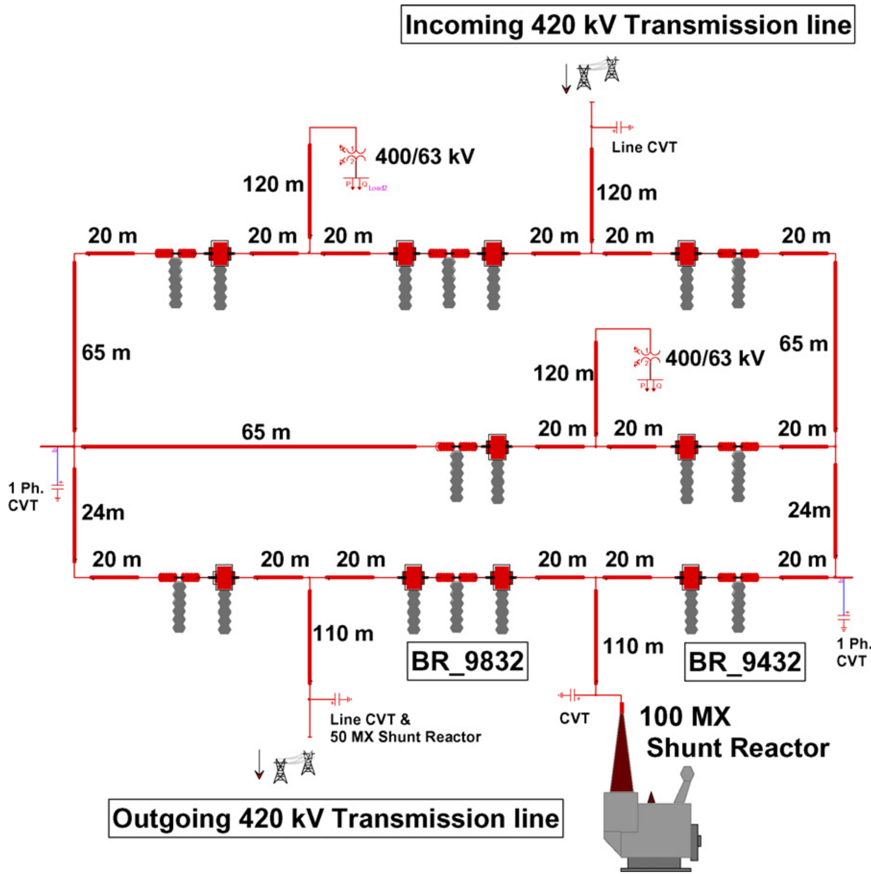

Fig. 3. Example of complete redrawing with Symbol Editor.

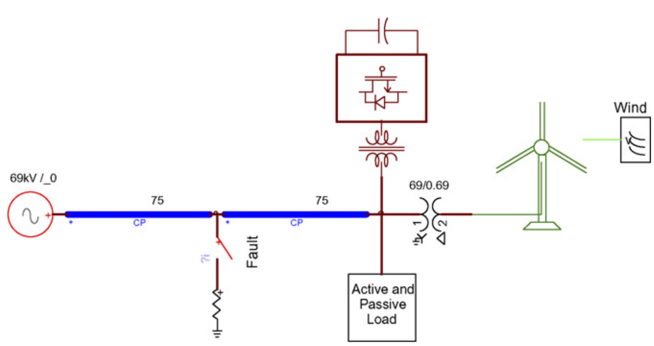

Fig. 4. Wind park test case with wind behavioral model.

external functions for calculating primitive device data at any subcircuit level.

5. Demonstration examples

5.1. Case 1

The diagram of this test case is shown in Fig. 3. The simulation results can be found in [11]. It is a demonstration of numerical stability and precision in solving extremely nonlinear arc model problems. Handling of specific computer requirements, such as memory for the frequency dependent models with very small time-step usage, are also confirmed.

5.2. Case 2

The design view for this test case is twice the size of the network shown in Fig. 4. The test case is explained in details in [12]. The Statcom is a three-level Statcom with PWM control. Its IGBT model is based on a nonlinear diode function for increased precision. All nonlinear functions, including the asynchronous machines are solved simultaneously with network equations. The simulation time-step is 50 μs. The mean number of iterations per time-point is below 3.

5.3. Case 3

In this example (Fig. 5) five asynchronous machines are initially in steady state when a motor is started. A fault on the connected network bus is initiated at 9 s and islanding occurs near 9.15 s. Local power is delivered by the synchronous machine SM2. Fig. 6 presents connected asynchronous machine slips. Machine data is taken from [13]. Machines are automatically initialized using their slip specification. The synchronous machines and the corresponding controls are also automatically initialized.

All nonlinear devices are solved simultaneously with network equations. Transformers are modeled with a nonlinear magnetization branch. In EMTP-RV machines are also classified as nonlinear devices and solved through the iterative process. All nonlinear devices are true-nonlinear and can coexist in the same

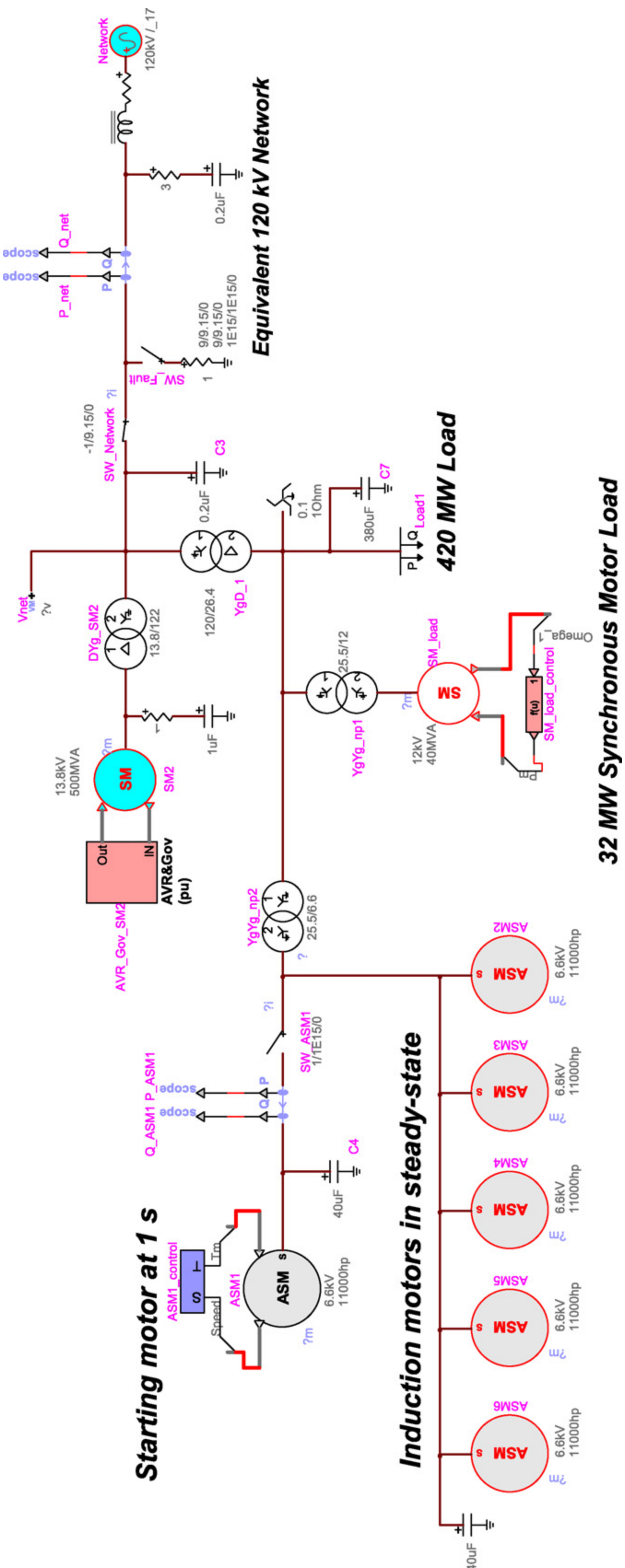

Fig. 5. Fault and system islanding test case with machines.

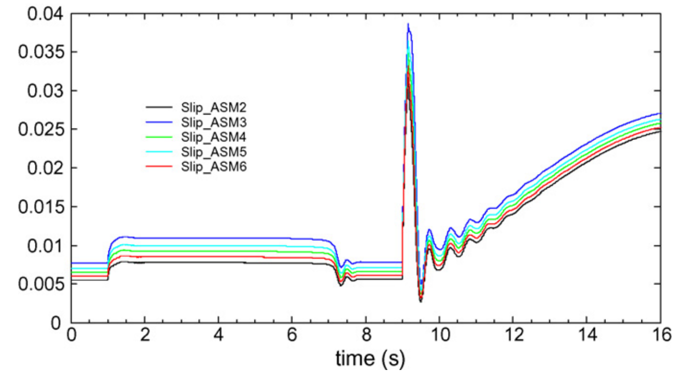

Fig. 6. Connected asynchronous machine slips.

network without artificial insertions, such as stub lines used in EMTP-V3. The test case assembled in Fig. 5 could not be simulated in EMTP-V3.

Despite the strongly connected network of several machines, the mean number of iterations per time-point is 3. Only 55 s (!) of CPU time are required to simulate an interval of 50 s with a time-step of 200 μs (2 GHz computer).

5.4. Case 4

The 230 kV network case shown in Fig. 7 starts from a load-flow solution and automatically initializes network state variables and machine controls for almost immediate establishment of steady-state operating conditions in the time-domain simulation. The network has unbalanced transmission lines and unbalanced loading at BUS13. Multiphase load-flow constraint data is entered through load-flow (LF) devices and is layered over the network simulated in time-domain. Any network can be augmented with load-flow devices without any other manipulations. All machine voltage amplitudes and angles are initially arbitrarily set to positive sequence data with phase-a at zero degrees. The load-flow algorithm is started first. It converges within six iterations and generates load-flow solution data which automatically initializes the steady-state solution of the actual network with synchronous machines. All synchronous machines and corresponding control circuits (AVR and Governor) are automatically initialized at the time-domain simulation startup. This is demonstrated by the waveforms for speed and power shown in Figs. 8 and 9. The initialization of synchronous machine models is particularly more difficult under unbalanced operating conditions and requires special treatments in the steady-state solution process.

5.5. Case 5

An exceedingly complex software engineering matter with the graphical user interface design and the computational engine is the capability to show and simulate very large networks within acceptable clock time. EMTP-RV has been tested on very large networks. The largest network assembled so far is taken from the Hydro-Québec system. The summary printout on primitive devices indicates: 25 synchronous machines, 63 ideal sources

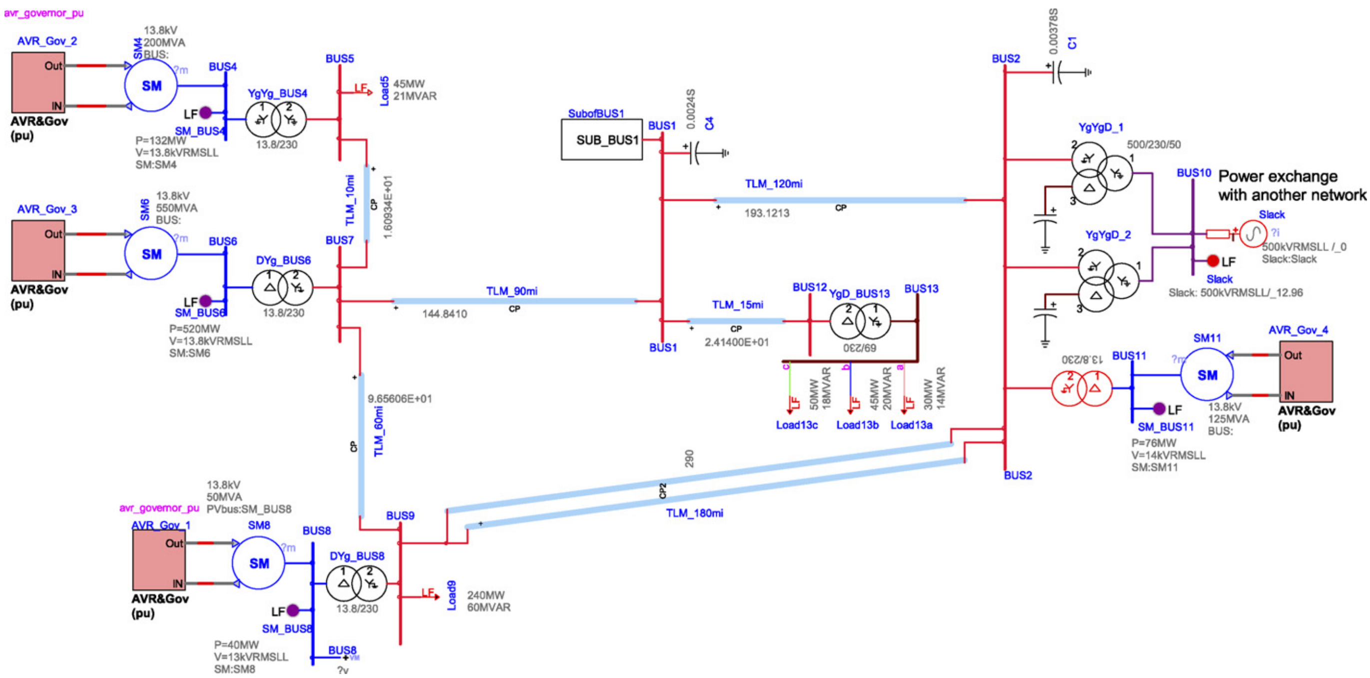

Fig. 7. Load-flow demonstration test case.

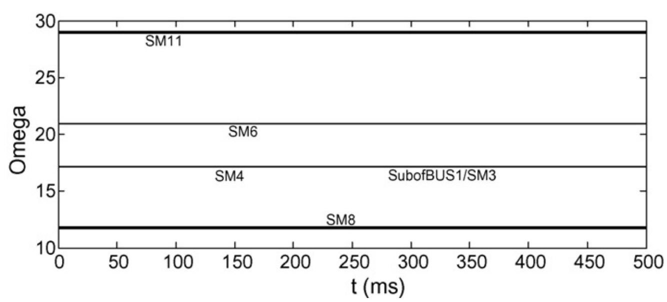

Fig. 8. Machine angular velocity (rad/s).

with impedance, 1248 transformer units, 3704 RLC branches, 610 coupled branch sections, 365 transmission lines, 1600 load models, 1500 switches, 378 nonlinear devices (arresters, nonlinear inductances,. . .) and 6838 control system devices. In several cases primitive devices are used for building specialized devices

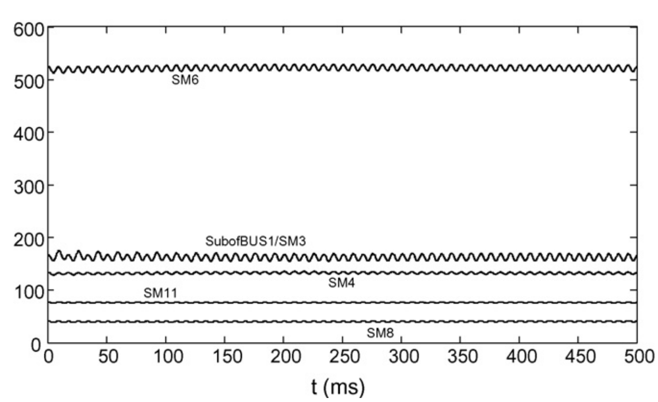

Fig. 9. Machine power (MW).

such as SVCs. The total number of devices is above 16,000 for approximately 7500 nodes. The entire design can be shown in EMTPWorks using six pages and has a load time (from open command to the complete appearance) of less than 14 s on a 2 GHz computer. It requires slightly less than 40 min per actual real-time second of simulation with an integration time-step of 50 μs.

There are several advantages in the ease of maintaining such a network: unique location of network data, exclude/include functions for partial simulations and capability to perform tests on the actual network and/or in several locations. EMTPWorks provides scripting methods and table-browser editing functions for manipulating data without clicking on devices one-by-one.

6. Conclusions

This paper presents an overview on a new simulation tool named EMTP-RV. It is the new generation of the DCG-EMTP software. It constitutes a new contribution in the history of industrial grade EMTP tools. EMTP-RV has several original solution methods that contribute to the elimination of topological restrictions, to improving the solution of nonlinearities, to the flawless simulation of control systems and to the automatic steady-state initialization methods. EMTP-RV is also based on a new graphical user interface with innovations in its open-architecture approach and scripting methods.

The recoding from scratch of major scientific software such as EMTP, constituted an enormous challenge. The stressed points were research and development on improved solution methods and software engineering approaches. Modern programming methods and tools can significantly alleviate the software development process and result into more powerful and user-friendly programs even within a highly scientific context.

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L. Dubé (M'77) obtained the B.A. (1967) and B.E. (1972) from Sherbrooke University and M.E. (1973) from École Polytechnique de Montréal. He developed the TACS program of EMTP and the MODELS simulation language and solver. He recently worked with IREQ (Hydro-Québec) on the development of user-defined modeling for EMTP-RV. His consulting activities are in the field of user-defined modeling methods and languages.

B. Khodabakhchian holds B.S. and M.S. (École Polytechnique de Montréal) degrees in electrical engineering. He has over 23 years of experiences in power system studies at Hydro-Québec. He is currently in charge of the marketing and sales of EMTP-RV, the new Restructured Version of the DCG-EMTP.

L. Gérin-Lajoie received his B.Sc.A in electrical engineering from École Polytechnique de Montréal in 1982. From 1982 to 1985, he worked for Hydro-Québec in System Planning. In 1985 he joined the Control and Protection team in the Systems Studies Department. His responsibilities include protection specification, modal analysis, optimization and control coordination, as well as electromagnetic phenomena and analytic studies related to the performance of SVC and synchronous machines on the bulk transmission system. He also contributed for Hydro-Québec, the validation of the new EMTP-RV software.