Recent Developments in Digital Real Time Simulation for Power Systems

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ABSTRACT

This paper introduces important new developments in digital real time simulation of electrical power systems and their complex components. Particular emphasis is placed on two recent developments, the voltage source converter (VSC) model and the phase domain frequency dependent transmission line model. Various issues such as background, algorithms, implementations, applications and validation have been described and included in the paper.

The paper also provides insight into the specific challenges faced when real time digital simulation is considered. Approaches commonly used in non real time simulation programs are not always possible when real time operation is required. For this reason accurate and efficient alternative methods must often be developed, implemented and validated.

Keywords: Voltage Source Converter, VSC, Phase Domain transmission line model, electromagnetic transient simulation, real time simulation

I. INTRODUCTION

In the past decade, the digital real time simulation of power systems has been recognized as an important emerging technology. Today it represents one of the most powerful tools for power system engineers involved in areas such as protection system design, closed-loop relay testing, control system design and testing, HVDC and FACTS research, and in more general system performance studies. To facilitate the wider and more detailed application of digital real time simulators, more accurate and more sophisticated models of power system circuits, which efficiently utilize today's more powerful processors must be considered.

This paper introduces important recent developments in digital real time simulation of power systems. In particular, two of the most recently developed models, the Voltage Source Converter (VSC) and the Phase Domain Transmission Line are described and demonstrated.

Modeling of voltage source converters (VSC) in real-time digital simulators has always been challenging. When considering VSC simulation, it is often necessary to include large networks containing many lines, machines and buses in the overall simulation circuit. To do this without using an excessively large amount of real-time simulator hardware, it is required that a timestep in the range of 50 μs be used for modeling the main network. However to properly simulate the operation of the VSC bridges, the turn-on/turn-off resolution of the valves must be in the order of a few microseconds.

In non-real-time electromagnetic transient (EMT) simulation programs, interpolation within the time-step is used to provide the firing resolution required by VSC models. Whenever switching occurs within a timestep, the EMT program decomposes the network matrix according to the new switching state and proceeds from the point of interpolation. If several valves switch at different points during a single timestep, it is then necessary to decompose the network matrix several times during that interval. The occurrence of multiple decompositions per timestep can be expected because the turn-on of a valve often leads to the turn-off of others. Off-line non-real time EMT programs can handle this without difficulty, but execution time is extended (i.e. slowed down).

In real time electromagnetic transient simulation, it is not a practical option to interpolate and decompose the main network matrix several times during a single timestep. The difficulty becomes clear when considering the effect of a switching point that occurs very late in time-step. There may not be enough time to complete the interpolation and decomposition before real time requires that the simulation move to the next timestep. Therefore, interpolation as a general method has limitations when applied to real time simulation.

This paper explores a new approach implemented for the RTDS® Simulator. The technique builds on past efforts, primarily by Hui and Christopoulos, to develop methods for fast time-domain simulation of switching networks [1]. The main advantage of the Hui and Christopoulos algorithm for real time simulation is that decomposition, or inversion, of the Dommel network conductance matrix is not required during a simulation. The same Dommel branch conductance represents the valve in the "ON" state and the "OFF" state. The difference in state is completely represented by the Dommel history current injection.

The RTDS Simulator implementation described in this paper was designed to operate in real time with a timestep of < 2 μs. The small timestep VSC bridges implemented with the Hui and Christopoulos algorithm are numerically interfaced to the main network solution running (typically) at 50 μs. The basic concept for the interface can be drawn from early work on interfacing digital simulators with analog equipment [2].

The second real time simulation development introduced in this paper is the Phase Domain Transmission Line. From early days of EMT simulation, transmission lines have been modeled using the modal analysis approach. The first models were classical Bergeron models where the capacitance and inductance of the line was calculated at the fundamental frequency only. However, the depth of penetration of current into the ground and conductors is known to change with frequency and resistivity. Consequently, the capacitances and inductances of a transmission line are dependant on frequency. This reality led to the development of frequency-dependant transmission line models for use in EMT type programs. The first generation of these frequency-dependant models arrived with the introduction of the famous J. Marti modal-domain frequency-dependant transmission line model. More recently, phase-domain frequency-dependant transmission line models have been introduced [3] [4] [5] [6].

The modal-domain frequency-dependant transmission line models use constant phase-to-mode and mode-to-phase transformation matrices for all frequencies. The frequency-dependence of the modal-domain models is provided only in the representation of the characteristic impedance and the attenuation of the separate modes. This was a very good development. However, in reality it can be shown that the transformation matrices should also be frequency-dependant. Unfortunately, when frequency dependant transformations were included in EMT simulations, the simulations were numerically unstable in some cases. This led to the development of phase-domain frequency-dependant transmission line models. Implementation of phase domain line models for the RTDS real time simulator will be described.

II. REAL TIME VSC REPRESENTATION

Various approaches have been applied in an effort to make interpolation work adequately for real time simulation. One approach has been to isolate the VSC bridges into sub-networks which are interfaced into the main network. With this approach, interpolation and decomposition become operations that are isolated in the sub-network. However, unless the number of valves in the VSC sub-network is small, multiple interpolations within a time-step of the sub-network can defeat real-time operation. Decomposition can be avoided in a VSC sub-network by pre-inverting and storing a matrix for each combination of switch states for the N switches. However, the need to store 2^N pre-inverted matrices also places a fairly low limit on the number of switches, N. The limitations of the interpolation algorithm have made it necessary to seek alternative algorithms for VSC sub-network solution.

Fortunately, there have been efforts in the past, primarily by Hui and Christopoulos, to develop methods for fast time-domain simulation of networks with switches [1]. The advantage of these methods is that decomposition or inversion of the Dommel network conductance matrix during a simulation is not required because the same Dommel branch conductance represents the valve in the "ON" state and the "OFF" state. In the "OFF" state, the valve is represented as a series RC branch with Dommel resistance of $R_b = R_{RC} = R + \Delta T/2C$ Ohms. In the "ON" state, the valve is represented as an inductor with $R_b = R_L = 2L/\Delta T$. Figure 1 illustrates the branch configurations for the ON and OFF states respectively.

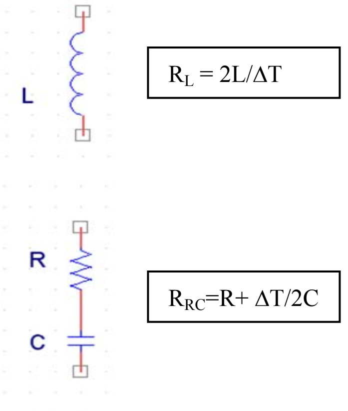


Fig. 1. Valve Representation

In order to avoid the need for matrix decomposition, the algorithm requires that $R_L = R_{RC}$ (i.e. $R + \Delta T/2C = 2L/\Delta T$). In order to get a high-impedance RC branch and a low-impedance L branch from the same branch resistance Rb, it is necessary that the time-step ΔT must be quite short. In fact, the time-step must be less than about two microseconds to obtain an impedance ratio in excess of 1.0e6 between the "ON" and "OFF" states. The difference between an "ON" valve and an "OFF" valve is completely represented in the small time step solution algorithm by the Dommel history current injection parallel to the Dommel conductance

The desirability of a damping resistance, R, in series with the capacitance representation is mentioned by Pejovic and Maksimovic [7]. However, little guidance is provided as to selection of the R, L and C values illustrated in Figure 1. Of course, it is required that the selected values ensure $R_L = R_{RC}$. Recent work [8] reveals that appropriate values for L, C and R can be found using Equations (1), (2) and (3) below:

$$L = \sqrt{2}(\Delta T \cdot F) v / i \tag{1}$$

$$C = {(\Delta T \cdot F)^2} \big/ L \tag{2}$$

$$R = \frac{2L}{\Delta T} - \frac{\Delta T}{2C} \tag{3}$$

where $$F = \frac{1}{2\left(\sqrt{\delta^2 + 1} - \delta\right)}$$

v = switched voltage
i = switched current
δ = damping factor

The approach described above does not remove the need to create an interface between the main network solution, which runs at approximately 50 µsec and the VSC sub-network which runs at approximately 2 µsec. Fortunately, the basic concept can be drawn from early work on interfacing digital simulators with analog equipment [2] as illustrated in the top of Figure 2. Interfacing to a short time-step VSC sub-network is very much like interfacing to an analog model. The similarity can be seen clearly by comparing the top of Figure 2 with the bottom. However, the digital-to-digital interface eliminates the D/As, amplifiers, current transducers and A/Ds normally needed in the digital-to-analog interface. Eliminating these components reduces the closed-loop interface delay and makes the digital-to-digital interface more accurate and stable.

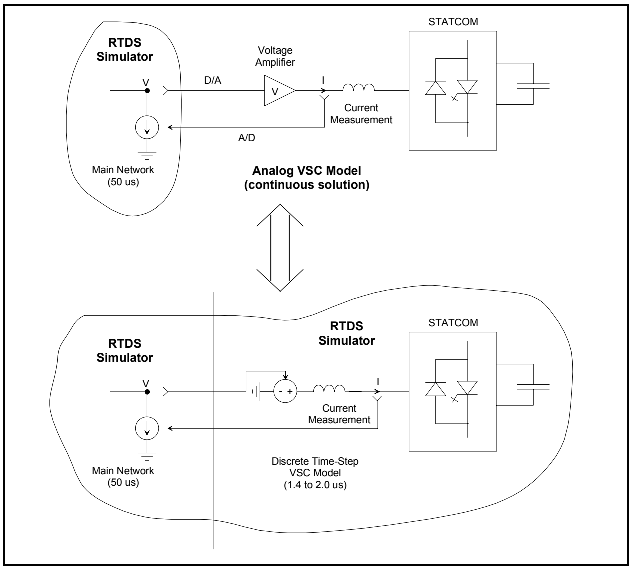


Fig. 2. VSC Interface to Main Network Solution

III. REAL TIME HARDWARE IMPLEMENTATION

An advanced processing card has recently been developed and introduced by RTDS Technologies for simulation of very complex devices including VSC bridges. The so-called Giga-Processing Card (GPC) contains two (2) IBM 750GX double-precision RISC processors each operating at 1.0 GHz. These processors are preferred because of low latencies (3 or 4 clock cycles) in the floating point pipeline and low power usage. Figure 3 includes a picture of the GPC card.

Fig. 3. GPC Card and Real Time Waveform

Either one or both of the processors on the GPC can be used for a VSC simulation depending on the size and configuration of the circuit. When two processors are used, each processor will solve approximately half of the individual components and create nodal injections for each. The nodal injections for computing voltages that are created on one processor and required on the other processor are sent through an on-board FPGA. The FPGA also signals the beginning of each small time-step in order to maintain the synchronism of the small time-steps in the two GPC processors.

Figure 3 shows a real time oscilloscope recording of node voltage VLOADA from the simulation of the 3-level bridge illustrated in Figure 4.

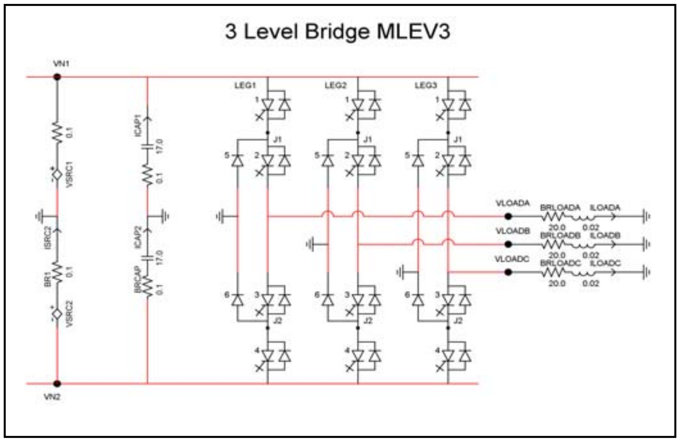


Fig. 4. Three-Level Bridge Circuit

In practical applications it may be necessary to interconnect the simulated VSC bridge(s) to external control systems. In order facilitate the interconnection of physical controls the GPC card has been designed to work together with several specialized I/O components.

The GTDI board is a 64-bit digital input board. It samples firing pulses from external controllers every 320 nanoseconds and sends the firing pulses through a 2 GHz fiber-optic link to the FPGA on the GPC board as shown in Figure 5. The FPGA makes all 64 bits available for reading by either of the two processors in each small time-step. Therefore, the latency between a firing pulse occurring and application of that firing pulse in a simulation is less than 2 µsec.

The small time-step simulation can also update twenty four 12-bit D/A output ports on the front of each GPC card once in each small time-step. A twelve channel, 16-bit optically-isolated D/A board is currently under development which will also be updated once in each small time-step. Therefore, the total latency is about 4 microseconds from a new firing pulse being created by an external firing controller to the point where resulting D/A output waves are updated.

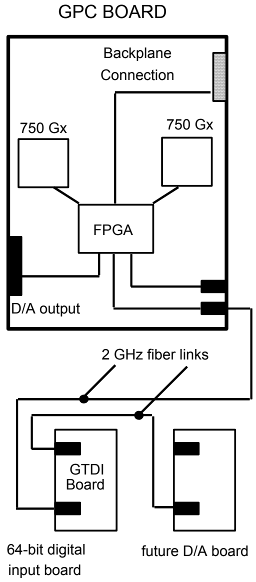


Fig. 5. Hardware Interface

IV. REAL TIME TRANSMISSION LINE REPRESENTATION

Transmission lines have been modeled in EMT type programs using the modal analysis approach since almost the beginning of electromagnetic transients simulation of power systems. The first models were classical Bergeron models where the capacitance and inductance of the line was calculated at the fundamental frequency only. However, the depth of penetration of current into the ground and conductors is known to change with frequency and resistivity. Consequently, the capacitances and inductances of a transmission line are dependant on frequency. This reality led to the development of frequency-dependant transmission line models for use in EMT type programs. The first generation of these frequency-dependant models arrived with the introduction of the famous J. Marti modal-domain frequency-dependant transmission line model. More recently, phase-domain frequency-dependant transmission line models have been introduced.

The modal-domain frequency-dependant transmission line models use constant phase-to-mode and mode-to-phase transformation matrices for all frequencies. The frequency-dependence of the modal-domain models is provided only in the representation of the characteristic impedance and the attenuation of the separate modes. This was a very good development. However, in reality it can be shown that the transformation matrices should also be frequency-dependant. Unfortunately, when frequency dependant transformations were included in EMT simulations, the simulations were numerically unstable in some cases. This led to the development of phase-domain frequency-dependant transmission line models. The phase-domain frequency-dependant transmission line models completely avoid using phase-to-mode and mode-to-phase transformations so as to avoid the problems with the frequency-dependance of the transformations. There are a number of good references that can be consulted concerning the benefits of frequency-dependant phase-domain transmission line models [3][4][5][6].

The basic idea of the phase domain model is to fit the characteristic admittance matrix $Y_c(\omega)$ and propagation function $H(\omega)$ directly in the phase domain. Then the two frequency domain functions $Y_c(\omega)$ and $H(\omega)$ are transformed into the time domain. Finally the time simulation is conducted through the convolution integration similar to the method used in modal domain models.

V. TRANSMISSION LINE MODEL FORMULATION

The voltage and current at the ends of a transmission line are given by

$$Y_c(\omega)V_s(\omega) - I_s(\omega) = 2H(\omega)I_r \tag{4}$$

where V_s and I_s are the voltage and current of the sending end; I_r is the reflection current wave form the receiving end. The matrices for characteristic admittance $Y_c(\omega)$ and propagation function $H(\omega)$ can be expressed as

$$Y_c(\omega) = \sqrt{\frac{Y(\omega)}{Z(\omega)}} \tag{5}$$

$$H(\omega) = \exp(\sqrt{Y(\omega)Z(\omega)}l) \tag{6}$$

in which Z and Y are the series impedance and shunt admittance matrix of per unit length, and l is the length of the transmission line.

A rational function based vector fitting method is used to approximate the matrix of $H(\omega)$ and $Y_c(\omega)$. With the poles and time delays known, each component of the propagation function can be fitted as

$$H_{ij}(j\omega) = \sum_{k=1}^{n}\sum_{m=1}^{N_k} \frac{c_{mk,ij}}{j\omega - p_{mk}} e^{-j\omega\tau_k} \tag{7}$$

in which N_k is the number of poles for mode k. Writing (7) for some frequencies then the coefficient matrix C can be obtained by solving a least square optimization problem.

The elements of $Y_c(\omega)$ are smooth functions of frequency which can be fitted. In fact, $Y_c(\omega)$ has no time delays, so a suitable set of poles can be obtained by fitting the sum of all modes. Furthermore, for a square matrix A with eigenvalues λ, there is the relation:

$$\sum_{i=1}^{N} \lambda_i = \sum_{i=1}^{N} A_{ii} \tag{8}$$

Thus, instead of fitting the sum of modes we can fit the sum of the diagonal elements of $Y_c(\omega)$. The sum is fitted with an approximation form

$$f(j\omega) = d + \sum_{m=1}^{N} \frac{c_m}{jw - a_m} \tag{9}$$

Finally, the elements of $Y_c(\omega)$ are fitted in the phase domain using the known poles.

By converting the (4) and the associated fitted functions back to the time domain, a standard Norton equivalent is obtained as in Figure 6.

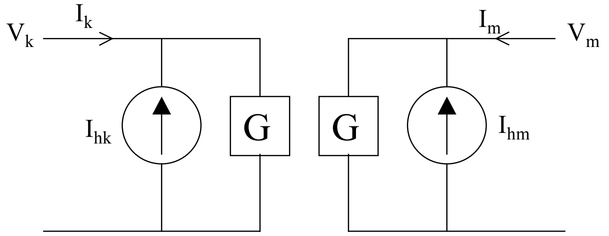


Fig. 6 Norton equivalent of transmission line model

The algorithm to update the history term is as follows;

$$I_k(t-\Delta t) = GV_k(t-\Delta t) - I_h(t-\Delta t) \tag{10}$$

$$I_{kr}(t-\Delta t) = I_k(t-\Delta t) + I_{ki}(t-\Delta t) \tag{11}$$

$$I_{ki}(t) = H(t) \otimes I_{mr}(t-\tau) \tag{12}$$

$$I_{hk}(t) = -Y_c(t) \otimes V_k(t-\Delta t) + 2I_{ki}(t) \tag{13}$$

In Equations 10-13, the subscript i and r denote incident and reflect waves respectively, and k and m refer to the sending end and receiving end.

VI. SAMPLE SIMULATION TEST CASES

Simulation cases were prepared for validation and testing of the new models (and features) described in this paper. Sample test cases for both the VSC and the Phase Domain transmission line models are presented in this section.

The VSC simulation test was performed using the circuit given in Figure 7.

This circuit includes a Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation [9]. The VSC circuit (running with a small time step) is interfaced to the main network (running with a large time-step) through an interface transformer. A high-pass filter, rated at 0.1 P.U. MVA and tuned to the 21 pulse PWM rate, is also included in the simulated apparatus.

The rotor q-axis current order, irq*, controls the electrical torque which the induction machine will produce. Positive irq* corresponds with positive electrical torque which corresponds to generation of power into the electrical system. In Figure 7, the irq* order is shown as originating in the optimal power controller. However, the irq* order could also be provided

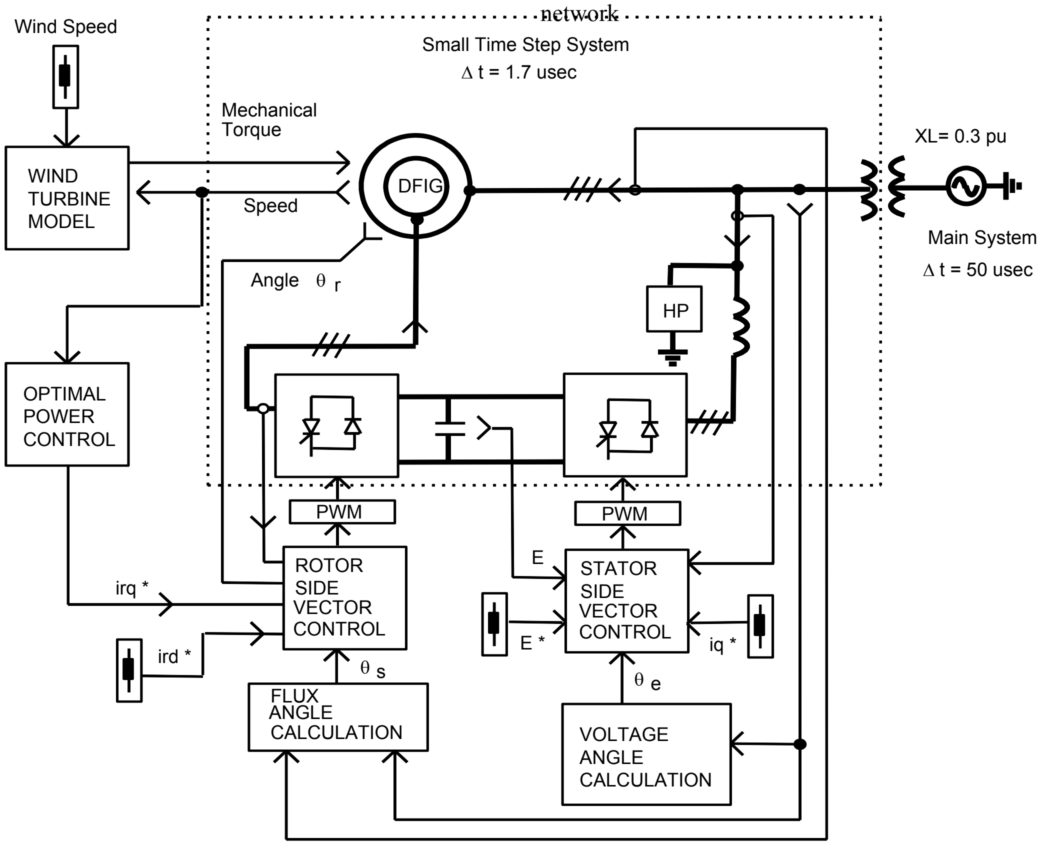


Fig. 7 Schematic of Simulation Test Case

through a slider in the RTDS *RunTime* environment.

Figure 8 shows the response of electrical torque to a step change in irq* order from 0.0 p.u. to 1.414 p.u. which essentially provides a change in electrical torque order from 0.0 to 1.0 per unit. Figure 9 illustrates corresponding plots of the rotor currents. Prior to the change in irq* order, the ird* order was 1.0 p.u. which corresponds to 0.707 p.u. reactive excitation provided from the rotor side. The machine speed at the time was 1.2 per unit.

For validation purposes, an EMTDC simulation (version 1.41.1) of the circuit was also run with a 50 microsecond time-step and interpolation enabled. The same torque order change, described above for the RTDS simulation, was applied in the EMTDC simulation. The rotor currents and torque from the EMTDC simulation were shown to match closely with those obtained from real time simulation.

Execution time in the small time-step VSC code is kept to a minimum by linking pre-created modules of machine code during the circuit compiling process. It is useful to know the execution times of various modules in order to judge what can be done in real-time simulation. Therefore, at this point, the execution times of various modules are presented. The simulated circuit contains a double-fed induction machine (DFIG) in the small time-step area. This model includes saturation and requires approximately 0.40 µsec of execution time per time-step. Each of the six-valve two-level bridges requires approximately 0.22 µsec of execution time. The three-phase high-pass filter bank requires approximately 0.09 µsec. The three-phase RL branch requires about 0.05 µsec. The capacitor branch requires about 0.025 µsec. The three-phase interface transformer requires about 0.11 µsec. The solution requires approximately 0.2 µsec on each processor. The overall VSC circuit including the machine is simulated in real-time with a small time-step of 1.67 µsec. These execution times should make it possible, in the absence of machine models, to simulate 36 switched devices in one lumped connected circuit in real-time. However, we do not yet have controls arranged for a back-to-back three-level DC link and therefore verification of the 36 valve capability is left for future work.

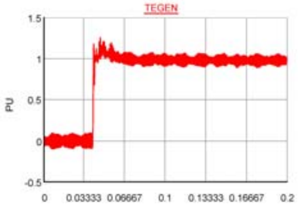


Fig. 8 Machine Electrical Torque vs Time

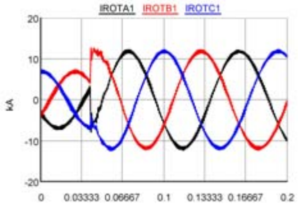


Fig. 9 Machine Rotor Currents vs Time

For the phase domain transmission line model the circuit of Figure 10 was used as part of the validation tests. Although

Bergeron line models are widely used in the electromagnetic transient simulation of transmission lines, they do not always accurately represent mutual coupling between adjacent circuits. For example, if one considers the situation where an AC and an HVDC transmission line share the same right of way, the coupling between the circuits must be properly modeled to obtain meaningful results.

Figure 10 shows a very simple circuit including a 100km 230kV AC line and a parallel mono-polar DC line separated by 50 meters on a right-of-way.

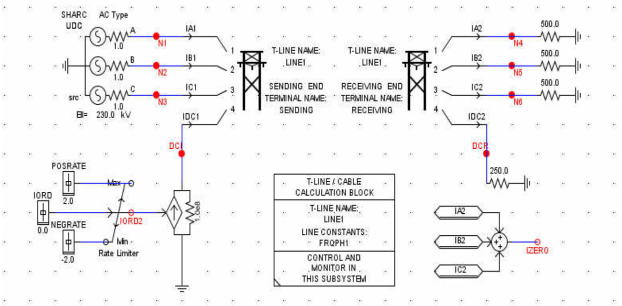


Fig. 10 Transmission Line Model Test Circuit

For comparison purposes the parallel lines were first modeled as Bergeron type and then as phase-domain frequency-dependant. The results were compared and analyzed. The DC current in the HVDC line was ramped from 0.0 kA to 1.0 kA over a period of 0.1 seconds as shown in Figure 11. The zero-sequence current in the adjacent AC line is shown in Figure 12. Results for both the Bergeron line and phase domain line models are included. Clearly, the low frequency (in this case DC) coupling provided by the Bergeron line model representation is not accurate. In reality, when ramping of DC current is completed and the di/dt of the DC line is 0, then the zero-sequence current in the parallel AC line should also go back to 0. The zero-sequence current in the parallel AC line should be temporary. Figure 12 therefore shows a more accurate and realistic result produced by the frequency-dependant phase-domain transmission line model for the zero-sequence current

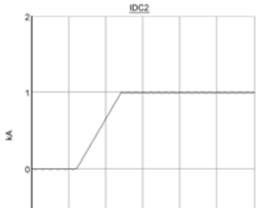
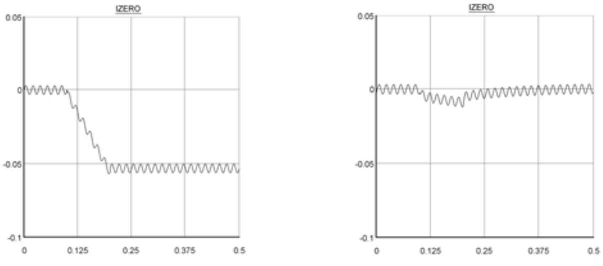


Fig. 11 DC Current Ramp



(Bergeron) (Phase Domain)

Fig. 12. Line Model Response - Zero Sequence Current

VII. CONCLUSIONS

This paper summarizes two significant recent advances in digital real time simulation of power systems. New methods for representation of VSC bridges and transmission lines have been reported. Because of the unique challenges inherent in real time simulation, novel approaches that do not utilize iterative methods are needed. The multi-time-step solution approach introduced in this paper is a practical way to improve the simulation accuracy when high speed switching devices, like those typical in VSC bridges are considered.

The increased processing power and flexibility offered in today's real time digital simulators allows use of very complex mathematical algorithms together with specialized methods not normally needed in non-real time simulation programs. The recent introduction of the GPC processing card for the RTDS simulator has provided an opportunity to improve representation of various power system components. This paper has described two such improvements that are expected to have significant impact on the accuracy with which real time power system simulation can be achieved.

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