ELECTROMAGNETIC TRANSIENTS SIMULATIONS BASED ON COMPUTATION WITH COMPLETE SYSTEM DECOMPOSITION

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Abstract - This paper describes methodology for the electromagnetic transients computation which is based on complete system decomposition. System being analyzed is divided into two different types of the subsystems: the lumped element subsystems, which are treated by the numerical integration technique; the propagation element subsystems for which a lattice diagram method is used. A phase domain transmission line model is used.

Keywords: Electromagnetic transients computation, Transmission line modelling, System decomposition, Thevenin equivalents

1. INTRODUCTION

Recent development in the area of digital power simulators are concerned with increased accuracy as well improved efficiency of the transients simulations [1]. A number of approaches have been developed for an accurate transients simulation [2,3]. Likewise, attempts to improve the computational efficiency of the transients computation have been reported [4,5]. This paper introduces a new approach to the transients simulation where both accuracy and computational efficiency are enhanced [6].

The increased accuracy of the transients simulation has an important role in the simulator applications. Several test scenarios where high accuracy devices such as fault locators are evaluated, will benefit from this approach to the waveform generation. The ability of this approach to represent accurately voltage and current profiles along the lines may also be beneficial in the studies where this information is essential, such as the power quality and insulation co-ordination.

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The improved computational efficiency is of great interest when developing real-time simulators. It is feasible to use this approach in setting up a high speed transients computation on a multi-processor machine. The ability to decompose the computations, and yet to increase the accuracy, may create a unique improvement in the overall real-time digital simulator in the future

2. LINE MODEL

A phase-domain transmission line model is used. Transmission line (or cable) is subdivided into a number of segments. Line model is similar to that described in [2]. The difference is that each line segment consist of the two *ideal line* sections, while the block representing losses and internal flux is inserted in the middle of the segment (Figure 1).

In Figure 1, $[\mathbf{Z}_{loss}]$ represents the resistance and inductance inside the conductor and ground. This matrix is frequency dependent and in the time domain modelling must be synthesized in phase coordinates. The surge impedance matrix [Z] corresponds to the *ideal propagation*, which is defined by the capacitance matrix and inductance matrix related to the external magnetic field

The elements of matrix $[\mathbf{Z}_{loss}]$ are frequency dependent and can be approximated by series combination of parallel R-L blocks [2]. Representation by only one parallel R-L block corresponds to the line parameters determined at one particular frequency. Inductive elements of R-L parallel blocks (one or more) are replaced by the resistive equivalents. In Figure 2, matrix $[R_{RL}]$ represents resulting matrix for R-L block approximation, while $[U_{L0}]$ is past

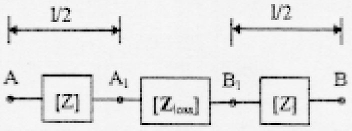

Figure 1 - Line segment

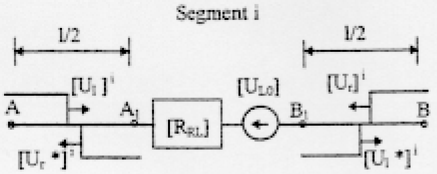

Figure 2 - Travelling waves on the line segment

history voltage vector related to the inductive branches. It should be noted that matrix $[R_{RL}]$ is equal for all segments of the particular line.

Transients on the *ideal propagation* sections are computed using the lattice diagram method, which is in the considered representation very easily implemented. According to Figure 2, we can define following travelling wave voltage vectors:

$[U_l]$ - left-hand side travelling wave voltage vector (from A to A_1)
$[U_r]$ - right-hand side travelling wave voltage vector (from B to B_1)
$[U_l^*]$ - modified left-hand side travelling wave voltage vector (from B_1 to B)
$[U_r^*]$ - modified right-hand side travelling wave voltage vector (from A_1 to A)

At the nodes connecting segment's ideal propagation sections (nodes A and B) there is no wave reflection because of the same surge impedance matrix. Voltage vectors at these nodes are simple addition of the modified left-hand and right-hand side voltage vectors arriving at these nodes, i.e.,

$$[U_A] = [U_l^*]^{(i-1)} + [U_r^*]^i \tag{1}$$

$$[U_B] = [U_l^*]^i + [U_r^*]^{(i+1)} \tag{2}$$

To determine current through the $[R_{RL}]$ matrix, and the modified travelling wave voltage vectors $[U_r^*]$ and $[U_l^*]$, circuit given in Figure 2 is reduced to the Thevenin equivalent circuit given in Figure 3. Left-hand and right-hand propagation sections are considered as open ended and reduced to the Thevenin equivalents, determined by the surge impedance matrix $[Z]$ and the Thevenin voltage vectors:

$$[U_{TH1}] = 2\,[U_l] \tag{3}$$

$$[U_{TH2}] = 2\,[U_r] \tag{4}$$

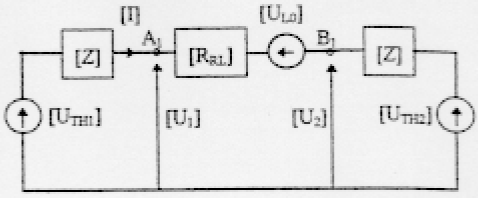

Figure 3 - Equivalent circuit for determination of the current vector

Vector of the currents which flow through the circuit given in Figure 3 is:

$$[I] = ([R_{RL}] + 2\,[Z])^{-1} ([U_{TH1}] - [U_{TH2}] - [U_{L0}]) \tag{5}$$

Voltage vectors for the middle of the segment are:

$$[U_1] = [U_{TH1}] - [Z]\,[I] \tag{6}$$

$$[U_2] = [U_{TH2}] + [Z]\,[I] \tag{7}$$

Finally, the modified voltage travelling wave vectors are given by:

$$[U_r^*] = [U_1] - [U_l] \tag{8}$$

$$[U_l^*] = [U_2] - [U_r] \tag{9}$$

Matrix ($[R_{RL}] + 2\,[Z]$) in equation (5) is the same for all segments of a given line and therefore has to be evaluated and inverted only once. Ideal propagation sections of each line segment separate segment's lumped-parameter part from the other segments, which enables treatment of the each segment separately. Equations (3) to (9) are applied for each segment separately. This separation (decomposition) provides very efficient computation scheme, which can be done in parallel. Solving equation (5), currents through each of the segments are also available.

3. MAIN SYSTEM DECOMPOSITION

Main system decomposition follows the approach applied for the line decomposition. To show this, consider the system shown in Figure 4, which consists of four subsystems (SS) and three lines (L). Subsystem is a part of the network which is composed of the lumped elements (coupled

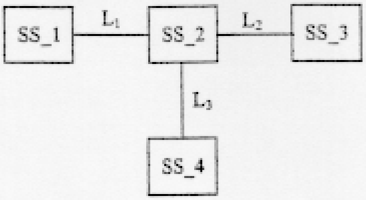

Figure 4 - Main system composed of four subsystems and three lines

or uncoupled branches), switches, sources, surge arresters etc. Lines (or cables) are N conductors propagation elements. According to the definition of line segments, each line has at its ends (sending and receiving) an ideal propagation section, which can be used for the separation of lines and subsystems. In order to illustrate methodology used for the separation of lines and subsystems, take subsystem SS_2 with the corresponding lines (Figure 5).

For subsystem SS_2, equivalent nodal conductance matrix $[G_2^*]$ is created using numerical integration technique (resistive equivalents). Ideal propagation sections of line segments connected to the SS_2 are reduced to the corresponding Thevenin equivalents, defined by the section's surge impedance $[Z_{Li}]$ and the Thevenin voltage vectors. The Thevenin voltage vectors $[U_{THL,i}]$ are equal to (double of the arriving travelling wave voltage vectors):

$$[U_{THL,i}] = 2\,[U_i^*] \quad (\,i = 1\,) \tag{10}$$

$$[U_{THL,i}] = 2\,[U_r^*] \quad (\,i = 2,3\,) \tag{11}$$

When line surge impedance matrices are included into $[G_2^*]$ and Thevenin equivalents are converted into equivalent current source vectors, following nodal equation is obtained:

$$[G_2]\ [U_{SS2}] = [I_{SS2}] + [I_{L1}] + [I_{L2}] + [I_{L3}] \tag{12}$$

where:

$[G_2]$ - SS_2 nodal conductance matrix which includes $[Z_{Li}]$

$[U_{SS2}]$ - SS_2 nodal voltage vector

$[I_{SS2}]$ - SS_2 nodal current vector which takes into account known voltages and past history terms

Line equivalent current sources are given by the following equation:

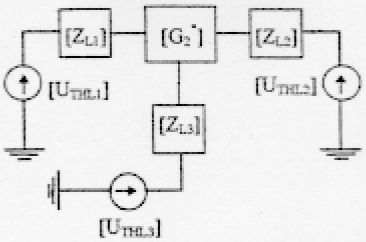

Figure 5 - Line segment ideal propagation sections connected to the SS_2 reduced to the Thevenin equivalents

$$[I_{Li}] = (\,[Z_{Li}]\,)^{-1}\ (\,[U_{THL,i}]\,) \tag{13}$$

Solving equation (12), the nodal voltage vector $[U_{SS2}]$ is obtained. Having now voltages of the nodes where lines are connected, reflected waves on the connecting segment propagation sections can be determined.

Procedure given before is applied separately for the other subsystems. When waves reflected from the nodes where line are connected are determined, the procedure for the computation of line segments voltage vectors starts. Each line is also treated separately.

4. CHANGES DURING SIMULATION

Thanks to the complete system decomposition it is possible to make computations with very efficient change of the system configuration, time step, and parameters of line and other elements during simulation. Each subsystem can have it's own time step being multiple of the shortest time step. Subsystem's time step can be changed also during simulations. Line segmentation (number of segments into which line is divided) can be also changed. It is possible to start simulation with very 'fine' segmentation, when frequency is higher and later reduce the number of segments when coming closer to the steady state.

To illustrate this possibility one example in which the line parameters are changed during simulation is selected. Considered is 400 kV, 100 km long line which is closed from the source having inductance of 50 mH. Circuit breaker pole A is closed at $t = 0$. Results of the simulations are given in Figure 6. Voltage waveform No 1 corresponds to the simulation with the transmission line parameters determined at natural frequency of the line, while waveform No 2 is for the simulation with the line parameters changed from 0.5 kHz to 50 Hz in the period of 25 msec. Both simulations are performed using one R-L block representation. In the second simulation R-L block data are changed in several time-frequency steps. Waveform number 2 is almost identical to the waveform obtained by the frequency dependent simulations (with a four R-L block in the middle of the segment).

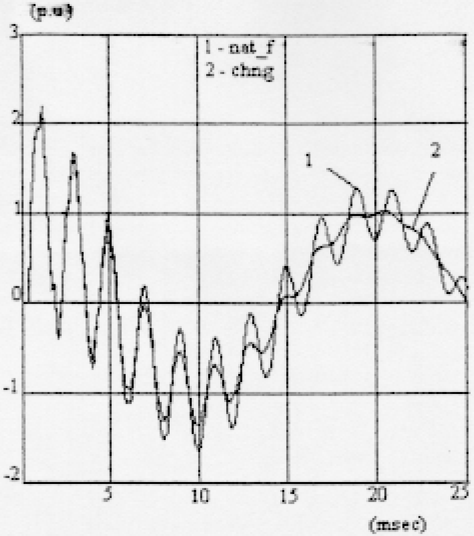

Figure 6 - Comparison of the voltage waveform for the simulation with constant line parameters and line parameters change during simulation

5. GRAPHICAL POSTPROCESSOR

Subdivision of lines (and cables) into short segments and their treatment by the combination of the numerical integration techniques and the lattice diagram method gives the possibility for the visualization of the voltage and current travelling waves in time. A separate graphical processor presents a travelling waves spatial distribution in time. Figure 7 illustrates overvoltage distribution on the phase conductors for the single line to ground fault which happens at one quarter of the line length (measured from the line receiving end). Line in question is 150 km long, while fault happens at the instant when phase to ground voltage of the conductor A is at it's maximum. Source side is represented as a subsystem number 1 (inductive equivalent with a damping matrix), while the line open end is treated as a subsystem No 2. The line is divided into a hundred short segments. C_1 , C_2 are C_3 are phase conductors A, B and C respectively. Presentation given in Figure 7 corresponds to the instant of 1.1 msec after fault application. Distribution of the currents in time along the simulated line can also be presented.

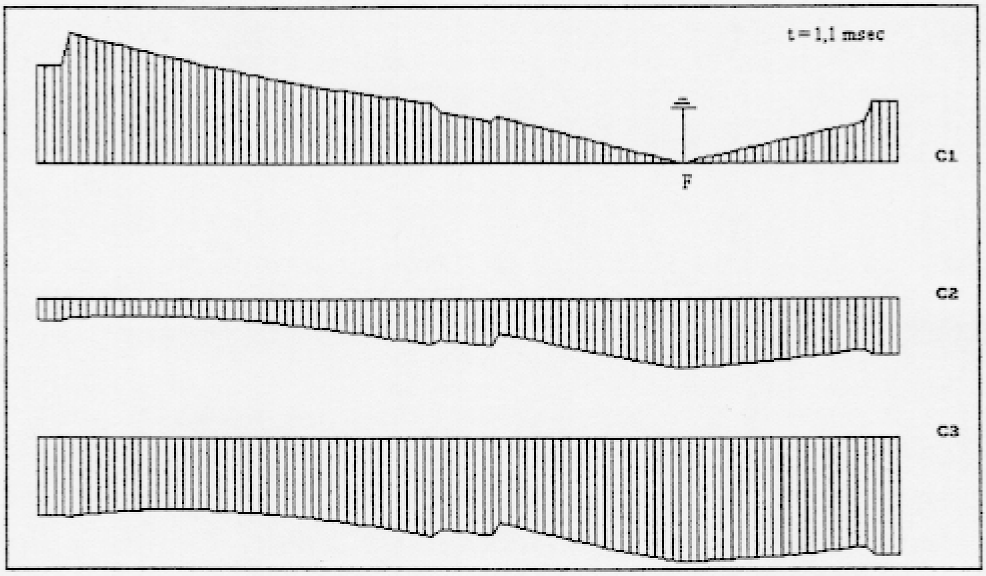

Figure 7 - Overvoltage profile along the phase conductors for the single line to ground fault (t = 1.1 msec after fault)

6. CONCLUSIONS

- Representation of the transmission lines or cables by several short segments enables organization of very effective computation of electromagnetic transients. Separation of line losses from the corresponding series impedance matrix and segment representation by the ideal propagation sections with loss impedance matrix in the middle, gives the possibility for very accurate time-domain formulation of frequency dependent lines. Problem is formulated directly in phase coordinates.

- Ideal propagation sections of the line segments, which are treated by the lattice diagram method, provides separation between line segments. This enables separate treatment of the lumped-parameter segment loss matrix. This frequency dependent matrix is represented by several parallel R-L blocks, which are treated by the numerical integration techniques.

- Separation of the line segments enables that the corresponding computations can be done in parallel. Each segment and each line can be considered separately

- Ideal propagation sections at the line ends separate lines from the subsystems. This enables that each subsystem can be treated separately.

- The accurate time domain representation of the transients can be used to determine the voltage and current profiles. This information may be very useful in the simulator studies aimed at testing high accuracy fault location and power quality devices.

- The computational decomposition of the simulation leads to an efficient utilization of the parallel architectures in the real-time digital simulator design. This approach is promising for very demanding real-time applications involving a large number of circuit elements.

7. REFERENCES

[1] Proceedings of the International Conference on Digital Power System Simulators ICDS: First, College Station, April 1995; Second, Montreal, May 1997.

[2] F. Castellanos, J.R. Marti, "Full Frequency-Dependent Phase-Domain Transmission Line Model", 1996 IEEE/PES Summer Meeting, July 28 - August 1, 1996, in Denver Colorado, Paper 96 SM 569-4 PWRS

[3] J.R. Marti, L.R. Linares, "Real-Time EMTP-Based Transients Simulation", IEEE Trans. on Power Systems, Vol. 9, No 3, August 1994 , pp. 1309 - 1317

[4] D. Falcao, E. Kaszkurewitz, H. Almeida, 'Application of Parallel Processing Techniques to the Simulation of Power System Electromagnetic Transients', IEEE Trans. on Power Systems, Vol. 8, No 1, February 1993, pp. 90 - 96

[5] K. Werlen, H. Glavitch, 'Computation of Transients by Parallel Processing', IEEE Trans. on PWD, Vol. 8, No 3, July 1993, pp. 1579 - 1585

[6] S. Sadovic, R. Joulie, S. Tartier, "Transmission Lines Lightning Performance Improvement by the Installation of Line Surge Arresters", Ninth International Symposium on High Voltage Engineering, Graz, Austria, September 1995, Paper 6731

8. BIOGRAPHIES

S.Sadovic was born in Trebinje, Bosnia -Herzegovina in 1947. He received the Diploma engineering degree from the University of Sarajevo (B&H) and Master and Doctor of Science degrees from the University of Zagreb (Croatia) in 1973 , 1977 and 1981 respectively. Since 1973 Dr Sadovic has been with the University of Sarajevo, where he is Professor of Electric Power Engineering. He was Dean and Vice Dean of Electrical Engineering Department of the same University. In 1993 and 1994 he was with Electricite de France - Research and Development Department. Currently he is a consultant. His research interests include overvoltages and insulation co-ordination, power systems analysis, numerical field computations and computer applications in power engineering.

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