Overhead Line Switching Surge Simulator

S. Sadovic, T. Sadovic

Abstract--This paper describes methodology for the electromagnetic transients computation, which is based on the system decomposition. A phase domain transmission line model is used. This approach is implemented in the software used for the overhead line switching surge studies. Overhead line is divided into short segments, enabling determination of the overvoltage distribution along the line.

Keywords: Electromagnetic transients computation, Transmission line modeling, System decomposition, Thevenin equivalents, Switching surge overvoltages, Risk of failure.

I. INTRODUCTION

IN the study of the overhead line switching surge insulation risk of failure it is important to take into account switching surge overvoltage distribution along the line. Risk of failure calculation based on the maximum overvoltages (usually at the line receiving end) leads to conservative results.

Recently developed phase domain line model for the electromagnetic transients simulation [1] enables accurate determination of switching overvoltages along the line. This line model, combined with the system decomposition, enables very efficient simulation engine for the switching surge overvoltage computation and risk of the insulation failure determination.

Computational algorithm presented in this paper is integrated into sigma slp software [2]. This software package, initially developed to study transmission and distribution line lightning performance, with a special reference to the application of line surge arresters, enables now the study of the following line switching surge transients studies:

- line closing
- line three pole re-closing
- line single pole re-closing
- single line to ground faults
- application of breaker closing resistor
- application of surge arresters

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II. LINE MODEL

A phase-domain transmission line model is used. Transmission line is subdivided into a number of segments. Line model is similar to that described in [3]. The difference is that each line segment consists of the two *ideal line* sections, while the block representing losses 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 modeling 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 [3]. In this paper [$\mathbf{Z}_{loss}$] is represented by only one R-L block corresponding to the line parameters determined at line natural frequency. Inductive element of R-L block is replaced by the resistive equivalent. In Figure 2, matrix [R_{RL}] represents resulting matrix for R-L block approximation, while [U_{L0}] is past history voltage vector related to the inductive branches.

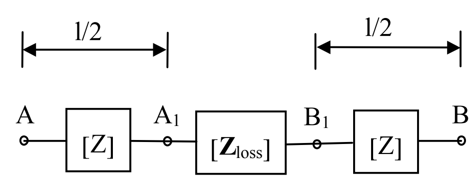

Fig. 1. Line segment

It should be noted that matrix [R_{RL}] is equal for all segments of the particular line.

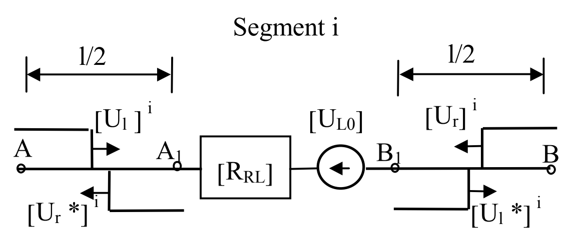

Fig. 2. Traveling waves on the line segment

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 traveling wave voltage vectors:

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

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

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

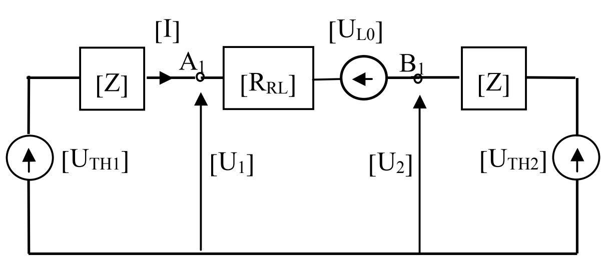

Fig. 3. Equivalent circuit for determination of the current vector

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 traveling 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 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.

III. 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 two subsystems (SS) and simulated line (L). Subsystem is a part of the network, which is composed of the lumped elements (coupled or uncoupled branches), switches, sources, surge arresters etc.. According to the definition of the line segments, line has at its end (sending and receiving) an ideal propagation section, which can be used for the separation of the line and subsystems (Figure 4).

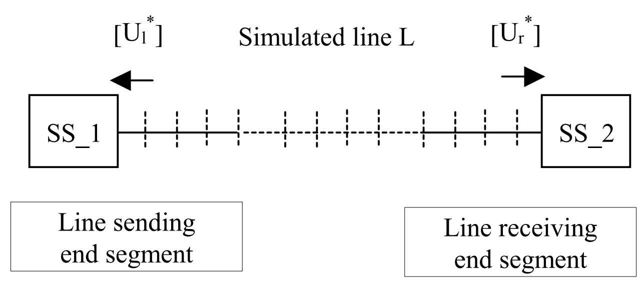

Fig. 4. Simulated line and two subsystems

For the subsystems, equivalent nodal conductance matrices $[G_1^*]$ and $[G_2^*]$ are created using numerical integration technique (resistive equivalents). Ideal propagation sections of line segments connected to the SS_1 and SS_2 are reduced to the corresponding Thevenin equivalents, defined by the segment's surge impedance $[Z_L]$ and the Thevenin voltage vectors. The Thevenin voltage vectors $[U_{THS}]$ and $[U_{THR}]$ are equal to (double of the arriving traveling wave voltage vectors):

$$[U_{THS}] = 2\ [U_l^*] \tag{10}$$

$$[U_{THR}] = 2\ [U_r^*] \tag{11}$$

The corresponding equivalent circuit is given in Figure 5. When line surge impedance matrices are included into $[G_1^*]$ and $[G_2^*]$ and Thevenin equivalents are converted into equivalent current source vectors, following nodal equations are obtained:

$$[G_1]\ [U_{SS1}] = [I_{SS1}] + [I_{LS}]$$

$$[G_2]\ [U_{SS2}] = [I_{SS2}] + [I_{LR}] \tag{12}$$

where:

$[G_1]$ & $[G_2]$ - SS_1 & SS_2 nodal conductance matrices, which include $[Z_L]$

$[U_{SS1}]$ & $[U_{SS2}]$ - SS_1 & SS_2 nodal voltage vectors

$[I_{SS1}]$ & $[I_{SS2}]$ - SS_1 & SS_2 nodal current vectors which take into account known voltages and past history terms

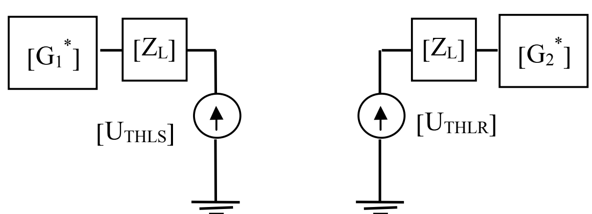

Fig. 5. Line segment ideal propagation sections connected to the SS_1 and SS_2 reduced to the Thevenin equivalents

Line equivalent current sources are given by the following equations:

$$[I_{LS}] = (\ [Z_L])^{-1}\ \ [U_{THS}]$$

$$[I_{LR}] = (\ [Z_L])^{-1}\ \ [U_{THR}] \tag{13}$$

Solving equation (12), the nodal voltage vectors $[U_{SS1}]$ and $[U_{SS2}]$ are obtained. Having now voltages of the nodes where lines are connected, reflected waves on the connecting segment propagation sections can be determined.

When reflected traveling waves are computed, transients on the simulated line are separately computed. It is important to note that all ideal propagation sections surge impedance matrices are the same. The same is for the middle segment equivalent matrices. Only these two matrices have to be saved.

Thanks to the complete system decomposition there is no need for the creation of the global system matrix. The corresponding matrices are created for each subsystem separately, while for each overhead line there is a need to create only two matrices ($[R_{RL}]$ and $[Z]$). This approach enables organization of a very efficient computational algorithm.

IV. Comparison with EMTP Simulations

Computation of the three pole closing voltages for one 400 kV single circuit, horizontal configuration, two shield wires, 200 km long line, is performed using EMTP_RV program in order to compare simulation results. EMTP FD line model is used, while in our model line parameters are determined at line natural frequency. Results of the simulations are presented in Figure 6.

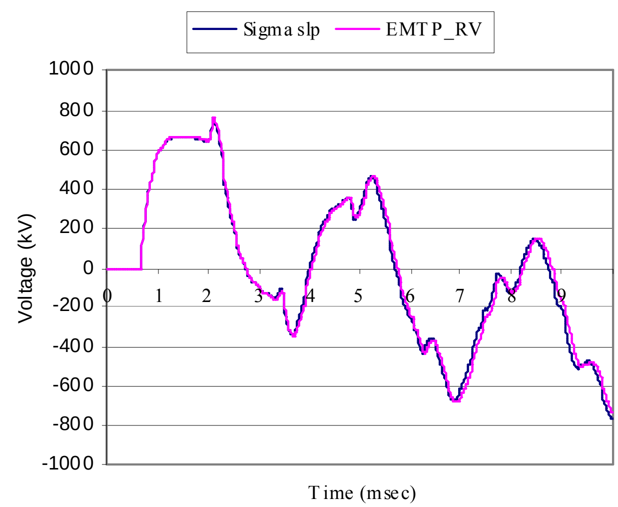

Fig. 6. Line receiving end closing overvoltages: EMTP_RV and sigma slp results

From the presented results we can see a very good agreement (especially for peak values we are interested in the risk of failure calculation).

Simulation time is similar to the EMTP-type software simulation time for the similar problem size. There are two possibilities for the problem initialization: steady state solution or direct initial condition specification.

V. Switching Surge Studies

The following line switching surge transients studies are possible:

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- single line to ground faults
- application of breaker closing resistor
- application of surge arresters

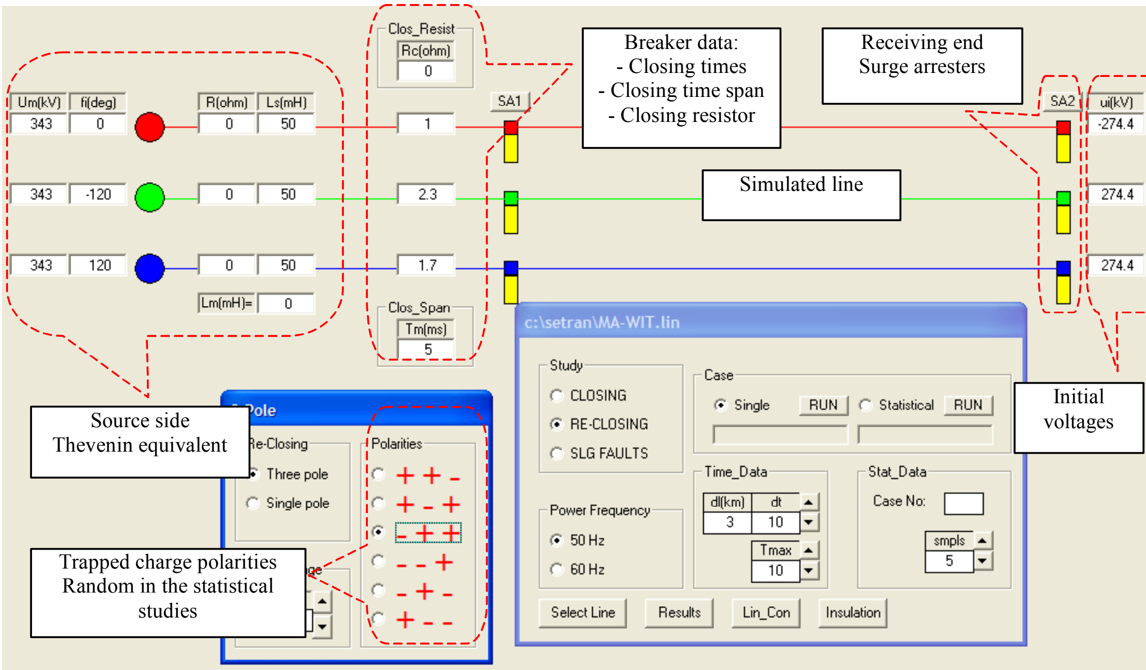

Fig. 7. Copy of the screen when running three pole re-closing study (Trapped charge voltage factor is 0,8)

Simulated line data is taken directly from the line database (the same database as for the lightning overvoltages simulations). When line is selected, the software computes all line related matrices.

SS_1 is predefined and may consist of:

- three phase sources
- thevenin equivalent of the source side
- breaker (single case and statistical)
- closing resistor
- surge arrester

SS_2 may consist of surge arrester, load impedance or no element (receiving end opened).

The statistical study is performed for the previous study case. The main study data is:

- 300 re-closings (samples)
- breaker closing time span 5 msec
- trapped voltage factor 0,8
- surge arresters: Rated voltages 336 kV, IEC Class III
- line insulation phase to ground CFO = 1050 kV
- line insulation σ = 6 %
- line segment length was 4,5 km

The main characteristics of the statistical study are:

- breaker closing times were randomly generated according to the normal distribution
- source voltage phase angles are generated according to the uniform distribution (0 - 360 deg)
- trapped voltage polarity combinations were changed according to the uniform distribution
- direct risk of failure computation method is implemented. For each statistical case, insulation characteristics are computed according to the normal distribution

Overvoltage distribution (peak values) along phase conductor A is given in Figure 8. Total switching surge phase to ground insulation risk of failure was 0,0141 (1,41 flashovers per 100 breaker operations).

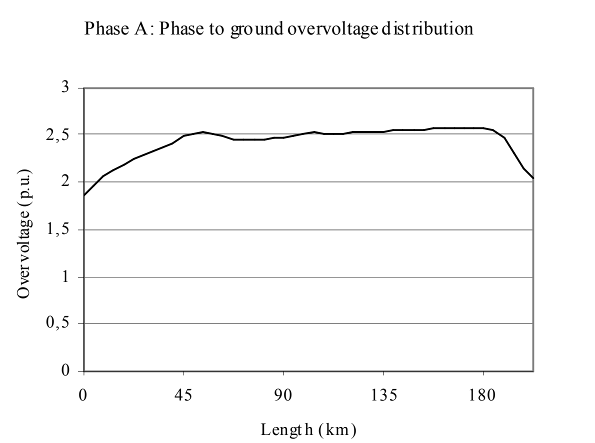

Fig. 8. Phase conductor A phase to ground overvoltage distribution along the line

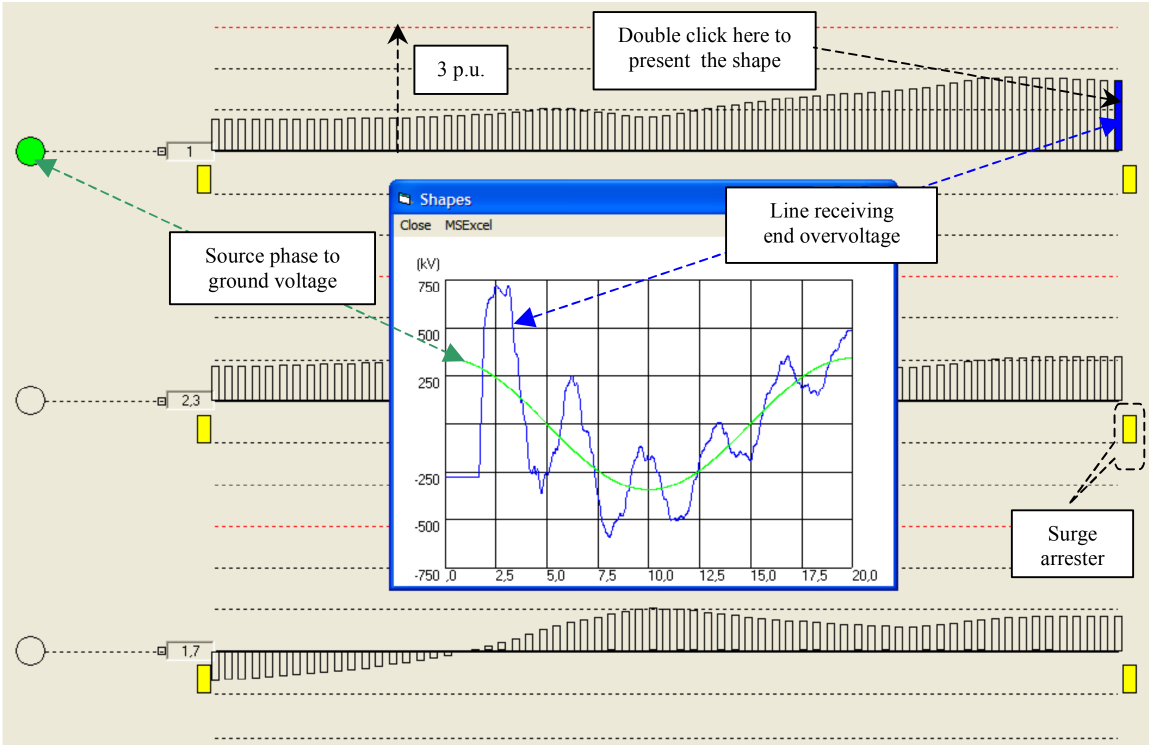

Fig. 9. Overvoltage profile along the phase conductors (t = 2,0 msec)

Cumulative distributions of the receiving end surge arrester currents (Ia - peak values) and energies (W) is given in Table 1. Presented values correspond to the middle phase arrester (most stressed arrester - phase conductors are in the horizontal configuration).

TABLE I
CUMULATIVE FREQUENCY DISTRIBUTIONS OF THE ARRESTER CURRENTS AND ENERGIES - RECEIVING END ARRESTER - MIDDLE PHASE

p (%)	I_a (kA)	W (kJ)
Max	1,661	826,82
1 %	1,285	746,51
2 %	1,189	731,82
5 %	1,058	666,00
10 %	0,942	591,81
15 %	0,839	530,95
20 %	0,743	462,63

VI. GRAPHICAL POSTPROCESSOR

Subdivision of line into short segments and their treatment by the combination of the numerical integration techniques and the lattice diagram method give the possibility for the visualization of the voltage and current traveling waves in time. A separate graphical processor presents traveling waves spatial distribution in time. Figure 9 illustrates overvoltage distribution on the phase conductors for the previous studied re-closing overvoltage case. This presentation corresponds to the time of 2 milliseconds.

VII. CONCLUSIONS

Representation of the transmission lines 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, provide separation between line segments. This enables separate treatment of the lumped-parameter segment loss matrix.

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

A separate software package for the computation of overhead line switching transients is included into sigma slp simulation software.

Overhead line switching surge software computes real distribution of the ovevoltages along line. This enables accurate insulation risk of failure computation.

Line insulation risk of failure is computed automatically, by so-called ‘direct method’. Line insulation characteristics are randomly generated (normal distribution).

If surge arresters are used for the switching surge control, arrester currents and energies are also statistically presented.

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IX. 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.

T. Sadovic was born in Sarajevo, Bosnia-Herzegovina in 1981. He received the Master degree from the Institut Supérieur d'Electronique de Paris in 2005. His research interests are remote monitoring and control, power quality, measurement. Presently he is working at Sadovic Consultant and following doctoral studies at the Graz University of Technology, Institute of High Voltage Engineering and System Management.