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MODELLING OF ELECTROMAGNETIC WAVE PROCESSES TAKING INTO ACCOUNT REACTORS WITH UNGROUNDED NEUTRALS AND OVLS IN DOUBLE-CIRCUIT LONG-DISTANCE ETL

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Abstract- This paper studies the effects of switching overvoltages considering reactors with ungrounded neutrals and non-linear overvoltage limiters (OVL) in double-circuit long-distance power transmission lines (ETL). In long-distance extra high voltage double-circuit electric transmission, one of the causes of surges occurs during line switching. Traditionally, shunting reactors (SR) are used at both ends of lines in order to ensure protection against switching overvoltages. However, in long distance AC ETL it becomes difficult to limit overvoltages by SR only, and the operation of the system is not stable enough. The combined shunt compensation method helps limit the switching overvoltages in long distance double circuit lines. A combined shunt compensation of overhead extra high voltage power lines which contains, apart from traditional SR connected to the power line through reactor circuit breakers, reactors permanently connected to the line according to the star with ungrounded neutral configuration. Using the proposed method, calculations were made on the switching overvoltages occurring with OVLs connected in parallel between SR and ungrounded reactors (UR) at the sending ends and receiving ends of double-circuit ETL. Mathematical models of reactors with ungrounded neutrals, OVLs and sources are developed based on the calculation methods as part of the conducted studies. Using the bivariate cubic spline interpolation method for switching overvoltages, line voltage (u) and current (i) values are calculated, and voltage change curves at the sending ends of the line are observed.

Keywords: Overhead Power Lines, Power Transmission Lines, Ungrounded Reactor, Overvoltage, Mathematical Model, Spline-Interpolation, Simulation.

I. INTRODUCTION

At present, several countries in the world have carried out research on the overvoltage control of the extra-high voltage and ultra-high voltage system and promoted practical application of their respective research results. High voltage ETL form the basis of modern power systems.

One of the main challenges is long-distance transmission of 500-1150 kV electric power. Protection against switching overvoltages in long distance overhead high voltage ETL, is one of the major problems. Elimination of overvoltage is very difficult and high cost. The single serious problem encountered with extra high voltage levels is the overvoltages during switching operations, commonly called switching-surge overvoltages [1], [2]. Investigation of switching overvoltages has assumed very great importance as transmission voltages are on the increase and line lengths and capacity of generating stations are also increased [3].

Due to the double circuit long-distance power transmission line, the charging power for the extra high voltage and ultra-high voltage power transmission lines is very huge. To give an example the reactive power consumption of the 500 kV headline exceeds 100 MVar/100 km [4], [5].

With respect to the longest power transmission line, accordingly installation of high and ultra-high voltage shunt reactors and URs with high compensation degree at the middle part of the line is beneficial to the limitation of the overvoltage [6].

One of the main problems arising from the transmission of high power over remote distances in modern times is the possible voltage increasing to unexpected levels in substation busbars under switching overvoltages [7]. In this regard, various measures are implemented in order to reduce allowable excessive voltages, including through combined transverse compensation reactors and parallel reactors with ungrounded neutrals at the sending ends and receiving ends of the double circuit power transmission lines. A combined shunt compensation of overhead extra high voltage power lines which contains, apart from traditional SR connected to the power line through reactor circuit breakers, reactors permanently connected to the line according to the star with ungrounded neutral configuration [8]. In modern practice, a number of units are used in order to limit switching overvoltages. Combined SR and URs also play a significant role in elimination of switching surges [9].

When these reactors are installed at the sending ends and receiving ends of the power transmission line, they suppress the surges occurring during the power transmission line switching.

Single phase and three-phase auto reclosing also plays a significant role in surges and emergency breaks that occur when switching high voltage ETL [10]. The use of combined compensation makes it possible to exclude the occurrence of resonance overvoltages under incomplete-phase short-circuit faults in the double circuit of single-phase reclosing [11], [12]. For above the high voltage transmission lines 90-95 % of the faults result from the single phase short double circuits.

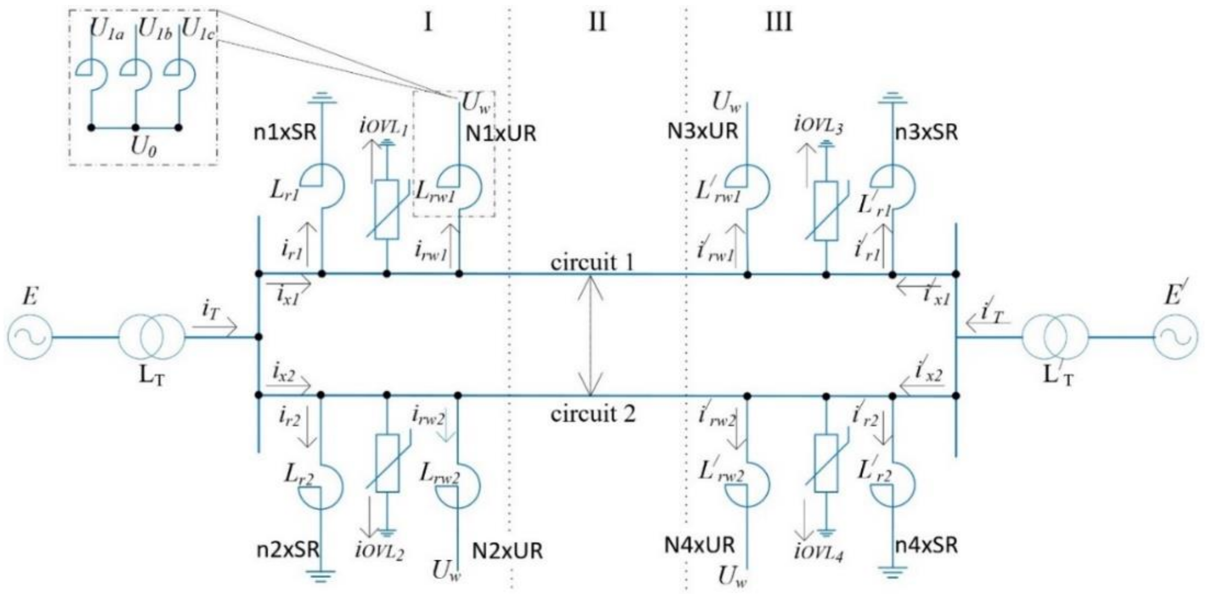

Figure 1. Reactors with combined transverse compensation in long-distance double circuit overhead power transmission lines with parallel connected OVLs at the beginning and end of line

When a fault is cleared on a single lines to ground fault by opening circuit breakers, due to mutual induction from the healthy phases, a current of 25-35Amperes keeps flowing in the arc at the fault on the grounded lines. The time delay, or the time interval between opening of the faulted line and its reclosure must be established. However, combined SR and URs are not sufficiently effective in ensuring stable operation during switching in double-circuit long-distance electric transmission. A question of present interest is minimizing the requirements related to insulation and protection devices of double-circuit ETL.

The problem of limitation of switching overvoltages in double circuit long distance electric transmission can be significantly alleviated. It is proposed that non-linear overvoltage limiters should be connected in parallel between SR and URs at the sending ends and receiving ends of long distance ETL, which will significantly reduce the requirements for insulation and protection facilities in long distance electric transmission. OVL is one of the main elements of the surge protection system, which protects electric equipment of the switchgear of substation and lines from switching surges [13].

To check the switching overvoltages of the high voltage power transmission lines, a bank of OVLs needs to be connected at the sending ends and receiving ends of the double circuit lines.

Parallel connection of non-linear overvoltage limiters between SR and UR at the sending ends and receiving ends of double circuit long distance ETL, reduction and minimization of line switching overvoltages are analysed using specific analytical methods. For the simulation, an OVL is modelled to investigate the sending-end receiving-end switching overvoltage.

II. CALCULATION METHOD

The proposed double-circuit long distance electric transmission system is shown in Figure 1. Multiconductor power transmission line equations that account for skin effect in earth and conductors and corona effect shall be written in a matrix form as follows:

$$\begin{aligned} -\frac{\partial u}{\partial x} &= L_0 \frac{\partial i}{\partial t} + f\left(\frac{\partial i}{\partial t}, i\right) \\ -\frac{\partial i}{\partial x} &= C_0 \frac{\partial u}{\partial t} + \phi\left(\frac{\partial u}{\partial t}, u\right) \end{aligned} \tag{1}$$

where, u and i are the column matrices of the voltage and currents, L_0 and C_0 are matrices of internal / mutual geometric inductances and capacitances of a power transmission line, u, i are column matrices of voltages and currents, $f\left(\frac{\partial i}{\partial t}, i\right)$ is function accounting for skin effect in earth and conductors and $\phi\left(\frac{\partial u}{\partial t}, u\right)$ is column matrice accounting for the impact of the surface effect in the ground and power transmission line conductors, and corona effect of the line conductors, respectively.

$$u=\begin{vmatrix}u_1\\u_2\\u_3\end{vmatrix},\ i=\begin{vmatrix}i_1\\i_2\\i_3\end{vmatrix},\ f\left(\frac{\partial i}{\partial t},i\right)=\begin{vmatrix}f_1\\f_2\\f_3\end{vmatrix}$$

$$i_{x1}=i-i_{r1}-i_{r2}-i_{w1}-i_{w2}-i_{x2}$$
$$\left(Z+Z_n\right)\left(i-i_{r1}-i_{r2}-i_{w1}-i_{w2}-i_{x2}\right)=v_{q1}-v_{q2}$$
$$\left(Z+Z_n\right)\left(i-i_{r1}-i_{r2}-i_{w1}-i_{w2}-i_{x2}\right)-2\left(Z+Z_n\right)i_{x2}=$$
$$=v_{q1}-v_{q2} \tag{2}$$
$$i_{x2}=0.5\left(Z+Z_n\right)^{-1}\begin{bmatrix}v_{q1}-v_{q2}-\left(Z+Z_n\right)\\ \left(\begin{matrix}i-i_{r1}-i_{r2}-i_{w1}-\\-i_{w2}-i_{x2}\end{matrix}\right)\end{bmatrix}$$
$$2u_1+\left(Z+Z_n\right)\left(i_{x1}+i_{x2}\right)=v_{q1}-v_{q2}$$
$$u_1=0.5\left[\left(Z+Z_n\right)\left(i_{x1}+i_{x2}\right)-v_{q1}-v_{q2}\right]$$

For the 1st node of the equation, disregarding the magnetization current of transformer, we have the following for the generator-transformer group:

$$\frac{di_s}{dt}=L_s^{-1}\left(u_s-u_n-r_s i_s\right) \tag{3}$$

where, L_s, r_s are matrices of 3×3 equivalent inductances and active resistances of the generator-transformer group, u_s, i_s are the source voltage and current of the node.

The source voltage is:

$$E_{\max}=\begin{bmatrix}\sin\left(\omega t+\phi\right)\\ \sin\left(\omega t+\frac{2\pi}{3}+\phi\right)\\ \sin\left(\omega t+\frac{4\pi}{3}3+\phi\right)\end{bmatrix} \tag{4}$$

where, ϕ is the angle of the source supply voltage when the switch is on, $E_{\max}$ is the maximum generated voltage of the source supply. For the reactors at the beginning of the first and second circuits:

$$\frac{di_{r1}}{dt}=L_{r1}^{-1}\left(u_n-r_{r1}i_{r1}\right)$$
$$\frac{di_{r2}}{dt}=L_{r2}^{-1}\left(u_n-r_{r2}i_{r2}\right) \tag{5}$$

where, i_{r1}, i_{r2} are the reactor currents; $L_{r1}, r_{r1}, L_{r2}, r_{r2}$ are matrices of 3×3 inductances and active resistances of the reactors (types depend on the reactor schemes). The equivalent capacity of the node is not considered, since it does not have a significant impact on the process under study. For the UR at the beginning of the first and second circuits:

$$\frac{di_{rw1}}{dt}=L_{rw1}^{-1}\left(u_n-r_{rw1}i_{rw1}\right)$$
$$\frac{di_{rw2}}{dt}=L_{rw2}^{-1}\left(u_n-r_{rw2}i_{rw2}\right) \tag{6}$$

where, i_{rw1}, i_{rw2} are the reactor currents; $L_{rw1}, r_{rw1}, L_{rw2}, r_{rw2}$ are matrices of 3×3 inductances and active resistances of the UR (types depend on the UR schemes).

III. MATHEMATICAL MODEL OF THE OVL IN THE POWER TRANSMISSION LINES

If, according the calculation scheme (Figure 1), the overvoltage limiters for the first and second circuits at the sending ends and receiving ends of the double circuit power transmission line are written as a matrix, then the condition of the overvoltage limiter may be described as follows:

$$i_{OVL}=\phi\left(u_{OVL}\right)$$
$$\frac{di_{OVL1}}{dt}=L_{OVL_1}^{-1}\left(u_1-u_{OVL1}\right)$$
$$\frac{di_{OVL2}}{dt}=L_{OVL_2}^{-1}\left(u_2-u_{OVL2}\right) \tag{7}$$
$$i_{OVL_1}=\begin{vmatrix}i_{OVL_{1a}}\\i_{OVL_{1b}}\\i_{OVL_{1c}}\end{vmatrix},\ i_{OVL_2}=\begin{vmatrix}i_{OVL_{2a}}\\i_{OVL_{2b}}\\i_{OVL_{2c}}\end{vmatrix}$$
$$i_{OVL_3}=\begin{vmatrix}i_{OVL_{3a}}\\i_{OVL_{3b}}\\i_{OVL_{3c}}\end{vmatrix},\ i_{OVL_4}=\begin{vmatrix}i_{OVL_{4a}}\\i_{OVL_{4b}}\\i_{OVL_{4c}}\end{vmatrix}$$

where, i_{OVL} is the current passing through the overvoltage limiter, u_{OVL} is the voltage on the overvoltage limiter, $\phi\left(u_{OVL}\right)$ can be approximated to spline interpolation.

IV. SPLINE-INTERPOLATION AND METHODS

Reference [14] is widely based on the cubic spline-interpolation method. Reference [15] used spline interpolation method for modelling of the OVLs for single circuit power transmission lines.

In the considered mathematical model of the double circuit power transmission line, the traveling spline-interpolation shall improve the model's performance which is modelled in the finite-difference approach to the analysis of switching overvoltages.

In order to compare groups of calculation formulas that allow calculations with variable calculation steps while taking into account the surface effect of the overvoltage limiter, on the one hand, and with constant calculation steps, on the other hand, we are going to find the approximation fault of the ETL equations with these calculation formulas.

The approximation, using the finite-difference method is presented in Figure 2 [16].

According to Figure 2, in order to compare groups of calculation formulas that allow calculations with variable calculation steps while taking into account the surface effect of the overvoltage limiter, on the one hand, and with constant calculation steps, on the other hand, we are going to find the approximation error of the ETL equations with these calculation formulas.

Voltage across magnetic shunts:

$$u_\mu=\frac{d\psi}{dt}$$

where, ψ is magnetic flux.

Matrix coefficients and variables are as follows:

$$\psi = \begin{vmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{vmatrix}, u_\mu = \begin{vmatrix} u_{\mu 1} \\ u_{\mu 2} \\ u_{\mu 3} \end{vmatrix}, i_\mu = \begin{vmatrix} i_{\mu 1} \\ i_{\mu 2} \\ i_{\mu 3} \end{vmatrix}$$

Let us consider the same under switching overvoltage in double circuit ETL. Let us divide the line into n sections. Each section is $2h$ long.

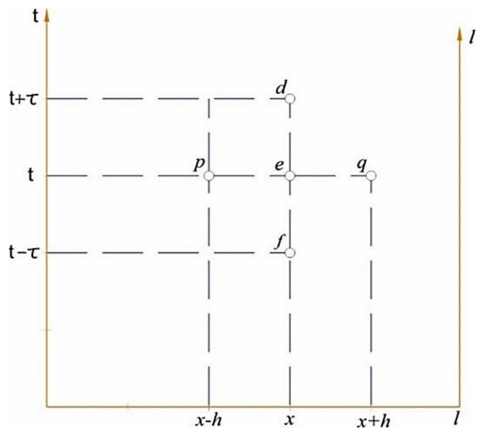

Figure 2. Difference scheme for approximation of power transmission line equation

Then we can find the time step from the following formula:

$$h = \left(L_0 L_0\right)^{-0.5} \tau = \vartheta \cdot \tau \tag{8}$$

where, ϑ is electromagnetic wave propagation speed, h, τ are calculation steps across x and t.

V. DESCRIPTION OF THE PROPOSED METHOD

Considering the circumstances, third-degree spline polynomials can be used to perform the numerical calculation of voltages and currents at additional internal points of the line; such approach will enable to retain stability and a higher convergence rate compared to the calculation of voltages and currents in the initial section of the line. Here, for each $(x,t)-(x+2h,t)$ we can write a cubic polynomial as follows [17]:

$$\vartheta(x,y) = \vartheta_{k,l}(x,y) = = \sum_{i,j=0}^{3} a_{i,j}^{k,l} \left(x_k - x\right)^i \left(y_l - y\right)^j \tag{9}$$

$k = 1,2,3...$ are number of reference points with coordinates $(0,t),(2h,t),(4h,t),...,(2nh,t)$ or,

$$\vartheta(x_{i-1}, y) = H_{i-1,j-1}\frac{(y_i - y)^3}{6\tau_i} + H_{i-1,j}\frac{(y - y_{i-1})^3}{6\tau_i} + \left(f_{i-1,j-1} - \frac{H_{i-1,j-1}\tau_j^2}{6}\right)\frac{y_i - y}{\tau_i} + \left(f_{i-1,j} - \frac{H_{i-1,j}\tau_j^2}{6}\right)\frac{y - y_{j-1}}{\tau_i} \tag{10}$$

$$\vartheta(x_i, y) = H_{i,j-1}\frac{(y_i - y)^3}{6\tau_i} + H_{i,j}\frac{(y - y_{i-1})^3}{6\tau_i} + \left(f_{i,j-1} - \frac{H_{i,j-1}\tau_j^2}{6}\right)\frac{y_i - y}{\tau_i} + \left(f_{i,j} - \frac{H_{i,j}\tau_j^2}{6}\right)\frac{y - y_{j-1}}{\tau_i} \tag{11}$$

where, $H_{ij} = \vartheta_{yy}\left(x_i, y_i\right), h_i = x_i - x_{i-1}$, $M_{ij} = \vartheta_{xx}\left(x_i, y_i\right)$, $\tau_i = y_i - h_{j-1}$. In our case $(2h,t)-(0,t),(4h,t)$ $-(2h,t)...(2nh,t)-(nh,t)$, f_i are defined voltage or current values at the nodal points of the calculation grid.

The following equations are proposed to determine m_i:

$$\frac{H_i}{6}m_{i-1} + \frac{H_i - H_{i+1}}{3}m_i + \frac{H_i}{6}m_{i+1} = = \frac{f_{i+1} - f_i}{H_{i+1}} - \frac{f_i - f_{i-1}}{H_i}$$

Considering that the voltages and currents in the nodes of the line are at the same distance from each other, at one time calculation step, i.e. $H_1 = H_2 = H_3 = ...H_n$, $\vartheta_{xx}\left(x_{i-1}, y\right)$ and $\vartheta_{xx}\left(x_i, y\right)$ in accordance with Equation (9) then we can write the values of $\vartheta_x\left(x, y\right)$ as follows:

$$\vartheta_{xx}\left(x_{i-1}, y\right) = K_{i-1,j-1}\frac{(y_i - y)^3}{6\tau_i} + K_{i-1,j}\frac{(y - y_{i-1})^3}{6\tau_i} + \left(M_{i-1,j-1} - \frac{K_{i-1,j-1}\tau_j^2}{6}\right)\frac{y_i - y}{\tau_i} + \left(M_{i-1,j} - \frac{K_{i-1,j}\tau_j^2}{6}\right)\frac{y - y_{j-1}}{\tau_i} \tag{12}$$

where, $K_{ij} = \vartheta_{xxyy}\left(x_i, y_i\right), \vartheta_{xx}\left(x_i, y\right)$, $\vartheta_{xx}\left(x_i, y\right)$ and ϑ_{xx} are coordinates are calculated with the following equations:

$$\vartheta_{xx}\left(x_i, y\right) = K_{i,j-1}\frac{(y_i - y)^3}{6\tau_i} + K_{i,j}\frac{(y - y_{i-1})^3}{6\tau_i} + \left(M_{i,j-1} - \frac{K_{i,j-1}\tau_j^2}{6}\right)\frac{y_i - y}{\tau_i} + \left(M_{i,j} - \frac{K_{i,j}\tau_j^2}{6}\right)\frac{y - y_{j-1}}{\tau_i} \tag{13}$$

$$\vartheta(x, y) = \vartheta_{xx}\left(x_{i-1}, y\right)\frac{(x_i - x)^3}{6\tau_i} + \vartheta_{xx}\left(x_i, y\right)\frac{(x - x_{j-1})^3}{6\tau_i} + \left(\vartheta\left(x_{i-1}, y\right) - \frac{\vartheta_{xx}(x_{i-1}, y)h_j^2}{6}\right)\frac{x_i - x}{h_i} + \left(\vartheta\left(x_i, y\right) - \frac{\vartheta_{xx}(x_i, y)h_j^2}{6}\right)\frac{x - x_{i-1}}{h_i} \tag{14}$$

All the resulting calculation formulas can set out as follows:

$$\begin{aligned} u_d + Zi_d &= u_p + Zi_p - h\vartheta_p \\ -u_d + Zi_d &= -u_p + Zi_p - h\vartheta_q \end{aligned} \tag{15}$$

where, ϑ_p and ϑ_q are designate energy losses of an electromagnetic wave as it moves along the ETL.

$$\begin{aligned} u_d &= 0.5(1+\sigma)^{-1} \cdot \begin{bmatrix} u_p + u_q + Z\left(i_p + i_q\right) - \\ -2\sigma\left(\pm u_3\right) \end{bmatrix} + 2\theta_2 \\ i_d &= 0.5(Z+Z_n)^{-1} \cdot \begin{bmatrix} u_p - u_q + Z\left(i_p - i_q\right) + \\ +2\sigma\left(\pm u_3\right) \end{bmatrix} + 2\theta_1 \end{aligned} \tag{16}$$

where, u_p, u_q, u_d, i_p, i_q and i_d are the voltage and current in the points of the investigated domain of the Equations (15) and (16) with coordinates $p(x-h, t-\tau)$ and $q(x+h, t-\tau)$, respectively. Then, using u_d and i_d values, ϑ_p and ϑ_q are determined for time $(t+\tau)$.

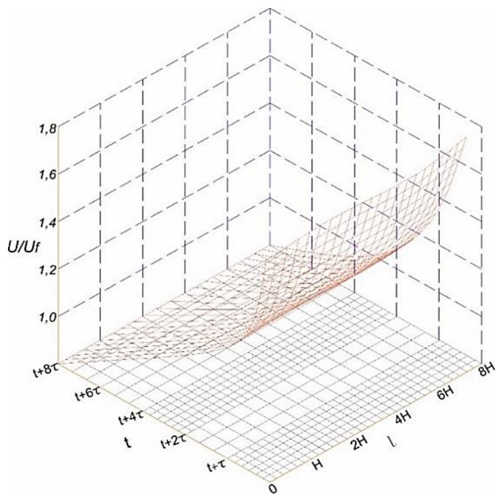

Figure 3. Three-dimensional calculation grid

Three-dimensional calculation of the grid point is shown in Figure 3 and $2h, 4h, 6h, ...$ are calculated as follows:

$$\begin{aligned} \vartheta_p &= u\left(x_1 + y_1 + 2h, t+\tau\right) + \\ &+ Zi\left(x_1 + y_1 + 2h, t+\tau\right) - \\ &Z_0\left[\left(i_{02} - i_{01}\right)\left(x_1 + y_1 + 4h, t - 2\tau\right)\right] + \\ &+ Z_3 \sum_{k=1}^{3} \chi_k i\left(x_1 + y_1 + 4h, t - 2\tau\right) + \theta_{1\gamma} \\ \vartheta_q &= -u\left(x_2 + y_2 + 2h, t+\tau\right) + \\ &+ Zi\left(x_2 + y_2 + 2h, t+\tau\right) + \\ &Z_0\left[\left(i_{02} - i_{01}\right)\left(x_2 + y_2 + 4h, t - 2\tau\right)\right] + \\ &+ Z_3 \sum_{k=1}^{3} \chi_k i\left(x_2 + y_2 + 4h, t - 2\tau\right) - \theta_{2\gamma} \end{aligned} \tag{17}$$

or by another form, u_d and i_d are the voltage and current in the points of the considered domain solution of Equation (16) with coordinates (x,t), $(x+2h,t)$ respectively.

$$u_d = 0.5(1+\sigma)^{-1} \cdot \begin{bmatrix} u\left(x_1 + y_1 + 2h, t+\tau\right) + \\ +u\left(x_2 + y_2 + 2h, t+\tau\right) + \\ +Zi\left(x_1 + y_1 + 2h, t+\tau\right) - \\ -i\left(x_2 + y_2 + 4h, t+\tau\right) - \\ -2\sigma\left(\pm u_3\right) \end{bmatrix} + 2\theta_2$$

$$i_d = 0.5\left(Z + Z_n\right)^{-1} \cdot \begin{bmatrix} u\left(x_1 + y_1 + 2h, t+\tau\right) - \\ u\left(x_2 + y_2 + 2h, t+\tau\right) + \\ +Zi\left(x_1 + y_1 + 2h, t+\tau\right) - \\ -i\left(x_2 + y_2 + 4h, t+\tau\right) + \\ +2\sigma\left(\pm u_3\right) \end{bmatrix} + 2\theta_1$$

where, $u_p, u_{q,} i_p$ and i_q represent *k*-three dimensional column matrices of accepted voltages and currents, p and k of a power transmission line with coordinates $p(x-h)(t-\tau), q(x+h), (t-\tau)$ are *k*-three dimensional column matrix is:

$$\theta_1 = \begin{bmatrix} \theta_{11} \\ \theta_{12} \\ \theta_{13} \end{bmatrix}, \ \theta_1 = Z = \sum_{k=1}^{3} \chi_{ki_k}$$

where, Z_1 and χ_k represent matrix coefficients and current. The column *k*-three dimensional matrix as follow:

$$\theta_2 = hZ \sum_{k=1}^{3} G_k u_{f_{ck}}$$

where $u_{f_{ck}}$ is accepted voltage in point f, h-is distance calculation step, Z is the square matrix of line characteristic impedance, G_k is the coefficients, addicted [16-18].

The Runge principle [19] is used here below to estimate the inaccuracy and the convergence of the solution using calculation formulas for solving the ETL equations with an account for losses in the general case:

$$\varepsilon(x,t) = \frac{U_h(x,t) - U_{2h}(x,t)}{2^{n-1}}$$

where, $\varepsilon(x,t)$ is fault of solution at the point (x,t) of the integration domain; $U_h(x,t), U_{2h}(x,t)$ - solution of the problem with an increment of h and $2h$, respectively; n is order of fault of the solution $n = 2$, and:

$$\varepsilon_u = \frac{u(x,t) - u_{2h}(x,t)}{2}, \ \varepsilon_i = \frac{i_h(x,t) - i_{2h}(x,t)}{2}$$

The fault of approximation for power line equations can also be found for other calculation formulas in which losses are accounted for through voltages and currents at points *p* and *q* or *d* that belong to the solution domain. The stated differential method and the decomposition of *u*, *i* is into a Taylor series about points *p* and *q* or *d* is applied to this end.

VI. SIMULATION RESULTS AND DISCUSSION

The simulation results of the 500 kV double circuit ETL were compared. The simulation results for the switching overvoltage phenomenon are shown for both circuits at the sending end of the double circuit power transmission lines, and these results are analysed. Figure 4 shows a switching voltage curve at the sending end of the power transmission line for the first circuit. Figure 5 shows a switching voltage curve at the sending end of the power transmission line for the second circuit. Once the first circuit is connected, the voltage fault in the ABC phase is up to 0.3 sec. The voltage surge was stopped after the UR and OVL was connected to the first circuit. It is observed that the voltage value is normal after 0.04 sec once an ungrounded reactor and OVL are connected. Peak voltage curve in phase A is observed at the time of the line connection (Figure 4). The second line was also analysed. For the second circuit, the phase A at the sending end of the power transmission line when switching is observed to be lower than the first circuit phase A (Figure 5). The voltage curve is normalized after 0.04 sec once UR reactor is connected.

SR neutral voltage curves for the sending ends for both circuits are shown in Figures 6 and 7. The simulation results (maximum values) are also provided in Table 1.

Table 1. Voltage change curves

Sending end, circuit 1			Sending end, circuit 2			Reactor neutral
U_1	U_2	U_3	U_1	U_2	U_3	$U_{N/n}$
1.41	1.18	1.19	1.69	1.28	1.29	0

The simulation results are provided for the sending ends of 500 kV double circuit ETL. EMTP simulations and comparisons for shunt reactors switching transients when connecting SR in long distance ETL are reviewed in [18], [20]. The obtained results suggest that operation of UR and overvoltage limiters is of utmost importance for limiting the extreme voltage phenomenon when switching long distance lines in interconnection electric transmission. Comparison of UR and controlled shunt reactors at overvoltages was also performed [21, 22].

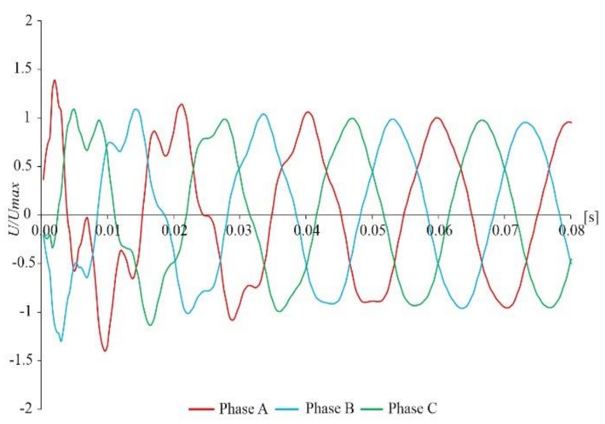

Figure 4. Circuit 1 voltage curves A, B, C (sending end)

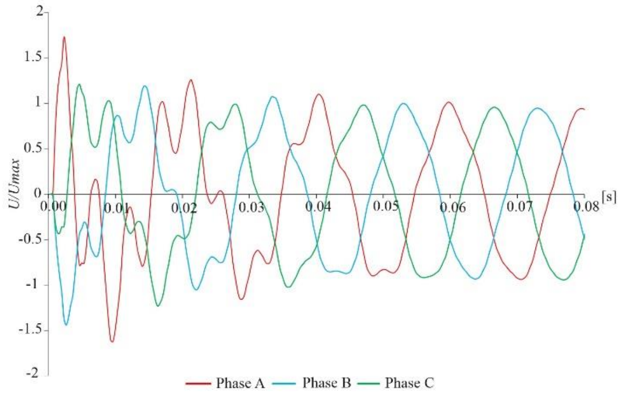

Figure 5. Circuit 2 voltage curves A, B, C (sending end)

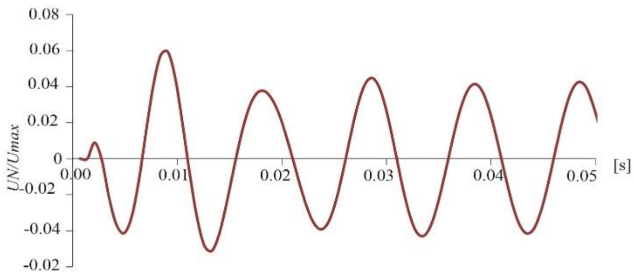

Figure 6. Circuit 1 SR neutral voltage curve (sending)

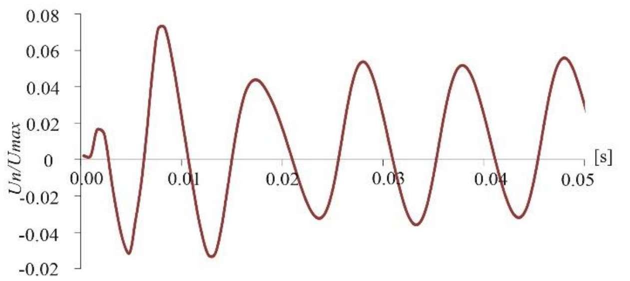

Figure 7. Circuit 2 SR neutral voltage curve (sending)

It has been found that the operation of controlled shunt reactors at overvoltages in double-circuit lines is more reliable and dynamic for short-distance power lines, but not for the long-distance lines. The observations of overvoltages in double-circuit long-distance power transmission lines considering UR and OVLs suggest that the operation of UR with OVLs during long-distance electromagnetic wave processes is more efficient and more dynamic. The disadvantage is that it is not sufficiently stable and reliable for the line lengths less than 380 km.

The electromagnetic wave process modelling is suitable for long-distance lines. This method can be used to protect against and limit the high and ultra high voltages in double circuit long distance lines.

VII. CONCLUSIONS AND FUTURE WORK

The proposed mathematical models are intended for modelling electromagnetic wave processes, taking into account URs and OVLs in double circuit long distance ETL. The operation of combined SR and UR in high voltage ETL is more flexible and optimized in comparison with the operation of other variable reactors.

In this article, switching overvoltage cases on long distance double circuit ETL were modelled using OVL and UR. The OVL and UR traveling spline-interpolation is applied to improve the model's performance in the finite-difference approach to the analysis of switching overvoltage. The voltage and current values at nodes were calculated by applying this method. As for future work, it is intended that transient processes for receiving ends of double circuit long distance ETL will be analysed and studied, as well as UR and OVL switching electromagnetic wave processes will be examined and simulated. It is also envisaged that analyses will be conducted for the receiving ends of double circuit long distance ETL.

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