Arnolda ROŽANSKIENĖ[1], Linas MARKEVIČIUS[2]
Kaunas University of Technology (1), JSC "Protronika" (2)

doi:10.15199/48.2018.02.18

Evaluation of electromagnetic processes in high voltage OHL by transient fast analysis models

***Abstract**. This paper presents fast transient analysis application for HV power systems with shunt reactors. It is proposed how to speed up analysis of transient processes by using digital filters method and modelling of power lines by wave equations. Proposed methodology enables to transform complicated power system by the abundance of elements to the simplified equivalent and adequate system. It is investigated auto-reclosing operation cases during the fault period, circuit breaker's phase asynchronous switching influence to overvoltages and overcurrents.*

***Streszczenie.** Przedstawiono aplikację do analizy szybkich stanów przejściowych w systemach elektroenergetycznych WN (wysokiego napięcia) z dławikami kompensacyjnymi. Pokazano jak przyspieszyć analizę za pomocą filtrów cyfrowych i modelowania linii elektroenergetycznych równaniami falowymi. Metodologia polega na zastąpieniu złożonego systemu elektroenergetycznego równoważnym układem uproszczonym. Analizowano operacje automatycznego ponownego zamykania po eliminacji zwarć oraz wpływ niejednoczesnego łączenia faz przez wyłącznik na przepięcia i przetężenia. (**Ocena procesów elektromagnetycznych w liniach napowietrznych WN za pomocą szybkiej analizy procesów przejściowych**).*

Keywords: electromagnetic transients, modelling, fault analysis, approximation.
Słowa kluczowe: elektromagnetyczne procesy przejsciowe, modelowanie, analiza zwarć, przybliżenie.

Introduction

Security and reliability of electrical power network means the ability of power network to continuously supply electricity to the customers. Among the power supply reliability and quality parameters, such as SAIDI, SAIFI, it is a parameter MAIFI, which indicates the number of momentary interruptions that a customer experience during a certain period.

In order to achieve necessary power supply cost-effectiveness it is important to maintain a balance between the power network security assurance, and costs that incurred in maintaining the power supply reliability and ensuring power supply reliability and quality parameters.

Short-term repetitive failures in power lines are a frequent reason for recurring switching of power lines. It is difficult to avoid the recurring switching of power lines, if protection and automation equipment responds only to the changes of measured current and voltage parameters. Such condition not only worsens the rate of MAIFI parameter, but also forces to increase the power network operating costs by installing various protections from overvoltage.

Fast identification and evaluation of fault circumstances would allow adequately respond to various emergency processes in power lines.

Based on analysis of recorded current and voltage fast transient parameters, would be possible to identify the overvoltage timely through assessments of non-simultaneity phases switching (asynchronous electrical switching) and other possible causality influences of overvoltage phenomena [1, 2].

Identification and analysis of fast transients shall be based on the algebraic methods, which allow creating a fast transient identification models.

Methodology

In various publications wave parameters most accurately are described by the formulas [3, 4]. They well enough reflect the electromagnetic processes in overhead lines, but for the transients fast analysis models they are not enough rational as require a large amount of arithmetic actions and time-consuming computer calculations.

It was therefore important to find approximate formulas, that enable the simplified calculation of line impedances, using basic functions, and without the prejudice of adequacy of the conditions and suitable for quick modelling of the fast transients processes.

Thus, the following expressions were used in this work:
- power line wires self-impedance:

$$Z_s = \frac{j\omega\mu_o}{2\pi} ln \frac{2h_i(1+l_i)}{r_i l_i} \quad (1)$$

where: h_i and r_i - wire's height from the ground and cross-sectional radius;

$$l_i = j2h_i k_g(0{,}563 - 0{,}00405 \cdot ln(\omega)) \quad (2)$$

- impedance of relationship between wires i and k:

$$Z_m = \frac{j\omega\mu_o}{2\pi} ln \frac{D_{ik}(1+l_{ik})}{d_{ik} l_{ik}} \quad (3)$$

where: $l_{ik} = jD_{ik} k_g(0{,}563 - 0{,}00405 \cdot ln(\omega))$.

Using these approximating expressions overhead line impedances in frequency range between 50 Hz and 10 MHz are calculated with an error that does not exceed 0.1%.

Transients models for power lines

Transients models for power line is advisable to construct on the basis of d'Alembert's wave equations, using spreading and reflecting waves concepts. Conducting research of fast transients and overvoltage in power network, values of surge impedances are set as constant values, when values of traveling waves in power line are set according to the frequency dispersion laws.

However, the above mentioned assumption is not very acceptable in electromagnetic transients' recognition tasks, for example, in the task to locate insulation damage place in power line. At the most appropriate for recognition transient initial moment, due to inadequate correlation between current and voltage, calculation errors can reach up to 10 percent. Performing research of overvoltage, due to electrical asynchronous connections in phases, such inadequacy is also undesirable. Initial transients, especially is short line length, are essential in overvoltage formation processes.

Voltage wave reflected from the end of the power line, due to specific parameters change in time, change its shape in every multi wire line mode, depending on frequency functions of specific parameters:

$$U_1^+(t)=(u_2(t-\frac{l}{v})-U_2^+(t-\frac{l}{v}))*h(t-\frac{l}{v}) \qquad (4)$$

where: U_1^+ and U_2^+ – voltage waves reached the lines begin (1) and the lines end (2); u_2 – voltage at the lines end; h – waves transient characteristic in time domain.

Operational image function $\bar{h}(p)$ and waves transient characteristic are bind by integral operation:

$$h(t)=\frac{2}{\pi}\int_0^{\infty}\lim_{p\to j\omega} real(\bar{h}(p))\frac{\sin\omega t}{\omega}d\omega \qquad (5)$$

* - a sign that symbolizes convolution of two functions, for example:

$$u(t)*h(t)= =\int_0^t h(x-t)\frac{d}{dx}u(x)dx \Leftarrow \bar{u}(p)\bar{h}(p) \qquad (6)$$

Variables with $(t-\frac{l}{v})$ arguments – delay function, which has zero values, when $(t<\frac{l}{v})$;

l and v – power line length and electromagnetic surface wave propagation in the line speed.

Frequency function $\bar{h}(j\omega)$ is found from surge impedance and conductivity, when conversion to time domain transient characteristic - $\bar{h}(t)$, and convolution of functions are found by digital modeling.

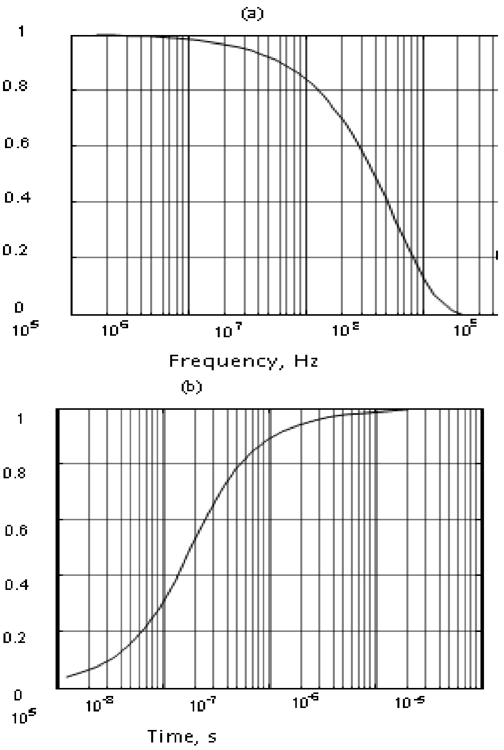

Fig.1. Electromagnetic wave suppression's real frequency function (a) and in time function (b)

In the figure 1, as illustration are shown wave's channel (mode) „ground – wire" electromagnetic wave suppression real frequency function (a) and time function (b) for the 10 km length line, and 100 Ωm specific ground resistivity. Line is equipped with wires of 75 mm^2 cross section. Average wire's hanging height over the ground surface – 7 meters.

D'Alembert's equation for power line's start parameters, with evaluation of surge impedance variability, can be formed as follows:

$$u_1(t)+wi_1(t)= =2U_1^+(t)-w\cdot[k(t-dt)*i_1(t-dt)] \qquad (7)$$

where: dt - digital integration step; w – surge impedance of wave channel of power lines with no losses;

$$w=\lim_{w\to\infty} real(w(jw)) \qquad (8)$$

And $k(t)$ - lines surge impedance change in time factor that can be found by converting frequency function to time domain:

$$K(\omega)=\frac{w(j\omega)}{w}-1\Rightarrow k(t) \qquad (9)$$

In the figure 2, are shown surge impedance's real frequency function (a) and change in time factor (b) in wave channel (mode') „ground – wire". Line is equipped with wires of 75 mm^2 cross section. Average wire's hanging height over the ground surface – 7 meters.

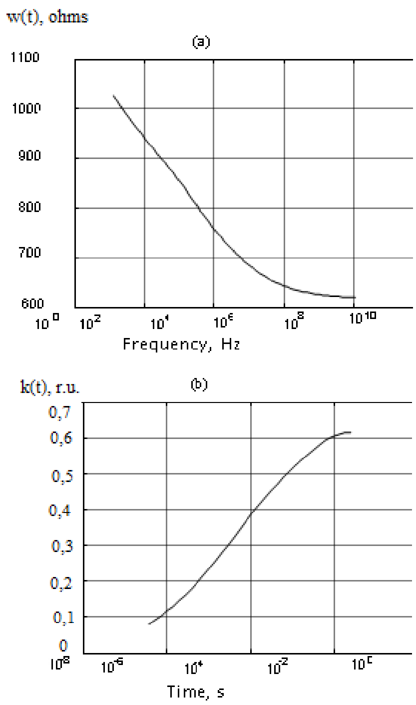

Fig.2. Surge impedance's real frequency function (a) and change in time factor (b)

For modeling of fast transients caused by various switching procedures, algebraic equations system reaches the twelfth position; therefore work with it in every digital modeling stage would be completely irrational. Transients modeling speed would be slowed down. To speed up calculation procedures is possible by pre-forming in advance special non recursive digital filters.

Voltages and currents of connecting contacts of *m* and *n* nodes in single line diagram determine restrictive conditions:

$$\begin{cases} u_{m,r=s}-u_{nr=s}=0\,, \\ i_{m,r=s}+i_{n,r=s}=0\,, \\ i_{m,r\neq s}=i_{n,r\neq s}=0\,; \end{cases} \qquad (10)$$

where: *s* – phase coupled pair of contacts from possible pairs: $r \in \{aa, bb, cc\}$.

Residual wave currents, phases' currents and voltages values with values of model currents and voltages bind up the general nature equations system:

$$\begin{bmatrix} \boldsymbol{I}_m^+ \\ \boldsymbol{I}_n^+ \\ (i_{m,r} + i_{n,r}) \\ (u_{m,r} - u_{n,r}) \\ (i_{m,r}) \\ (i_{n,r}) \end{bmatrix} = \boldsymbol{K}_{18x12} \cdot \begin{bmatrix} \boldsymbol{U}_m \\ \boldsymbol{U}_n \\ (i_{mv}) \\ (i_{nv}) \end{bmatrix} \tag{11}$$

where: $(i_{m,r} + i_{n,r})$, $(i_{m,r})$, $(i_{n,r})$ and $(u_{m,r} + u_{n,r})$ – blocks of voltage and currents, $\boldsymbol{I}_m^+$, $\boldsymbol{I}_n^+$, $\boldsymbol{U}_m, \boldsymbol{U}_n$, (i_{mv}) and i_{nv} – vectors of reached current waves, vectors of voltages and currents of model nodes in *v* coordinates system.

$\boldsymbol{K}$ extended matrix consists of square blocks that simulate contacts position. It composed from the third row square matrixes.

$$\boldsymbol{K} = \begin{pmatrix} \boldsymbol{Y}_m & \boldsymbol{O} & \boldsymbol{V} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{Y}_n & \boldsymbol{O} & \boldsymbol{V} \\ \boldsymbol{O} & \boldsymbol{O} & \boldsymbol{T}^{-1} & \boldsymbol{T}^{-1} \\ \boldsymbol{T}^{-1} & \boldsymbol{T}^{-1} & \boldsymbol{O} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{O} & \boldsymbol{T}^{-1} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{O} & \boldsymbol{O} & \boldsymbol{T}^{-1} \end{pmatrix}_{18x12} \tag{12}$$

where: $\boldsymbol{Y}_m$ and $\boldsymbol{Y}_n$ – matrixes of surge conductivities of *m* and *n* nodes; $\boldsymbol{O}$ and $\boldsymbol{V}$ - matrix of zero and matrix of one; $\boldsymbol{T}^{-1}$ - reverse modal matrix.

Depends on circuit breaker contacts position in $\boldsymbol{K}$ matrix are eliminated unnecessary 12 rows and 6 columns. For example, when circuit breaker is in disconnected position, last 12 rows and last 6 columns are eliminated. Then instant voltage values of vectors $\boldsymbol{U}_m$ and $\boldsymbol{U}_n$ for *m* and *n* nodes are found by digital filter:

$$\begin{pmatrix} \boldsymbol{U}_m \\ \boldsymbol{U}_n \end{pmatrix} = \boldsymbol{K}_{6x6}^{-1} \cdot \begin{pmatrix} \boldsymbol{I}_m \\ \boldsymbol{I}_n \end{pmatrix} \tag{13}$$

For example, when contacts of phase are paired, in matrix $\boldsymbol{K}$ are eliminated rows 16, 13, 12, 11, 9, 8. Remaining $\boldsymbol{K}_{12x12}$ part is converted, afterwards in matrix are eliminated lowers 6 rows and last 6 columns. Such filter matrix preparation is performed only after change of circuit breaker contact position; therefore such recalculation throughout the whole modeling procedure does not extend the entire length of calculations.

Fast transient analysis

When in power network are connected or disconnected shunt reactors, working conditions changed throughout the system. Then, to perform switching operations as usual is no longer possible, as it can lead to switching overvoltage [5].

Tests were performed in 330 kV power network. Line was connected to the voltage by air-blast circuit breaker and line's single phase was shortly circuited.

After the fault voltage and current transient's processes we recoded in phases A, B and C. Single phase short circuit fault was disconnected from both sides of power the line, and after 2.74 seconds auto-reclosing operation (AR) was performed.

The test showed that the phase-switching time difference between the first and latest phases is about one period, and is close to 20 milliseconds. During circuit breaker opening process pressed air affects all three drive mechanisms, and phase switching sequence takes place randomly, scattered in time.

Single phase short circuit fault disappear, however insulator may have been damaged by the arc in short circuit location, and it was the reason for disconnection of the line. Further sequentially performed auto-reclosing operation can be successful only if switching overvoltage is not too high.

Due to the fact that the phases of the line are connected not at the same time, voltage in the line can increase. For this reason, a study was carried out what kind of impact for overvoltage has factor, that circuit breaker phases contacts merge not at the same time. Power network single line diagram is used (see Fig. 3).

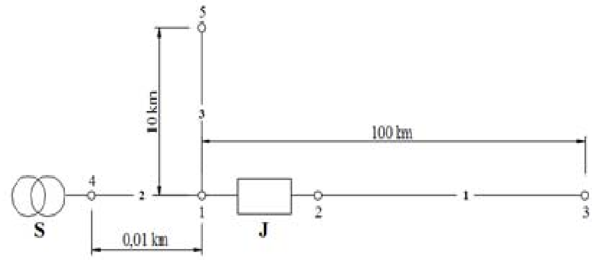

Fig.3. Diagram of power network computational structure

In the diagram distance of the line between first and third nodes is 100 km. Line is powered from transformer. In reality, the electrical power network has more transmission lines; therefore the computational diagram of 10 km line is necessary in order to create conditions close to reality.

In Fig. 4 are shown voltage and current variations in the first node. Up to 41 milliseconds is reached stationary regime which is leading to a commutation. Circuit breaker connects the line and all three phases are simultaneously activated. After 0.8 milliseconds, voltage reaches value - 143 kV, and the current of the 1st line - 0.34 kA.

The modelling [6-8] was performed by fixing the voltage increases when the circuit breaker is connected and all three phases are simultaneously activated (see Fig. 5), and all three phases are not simultaneously activated (see Fig. 6).

The diagram (see Fig. 5) shows that in the third node after switching the current change in the line is negligible, and at the end of the line voltage reaches even 39%.

In oscillogram (see Fig. 6.) difference between the A and C phase asynchronous electrical switching time is 12.7 msec. Voltage increase in comparison with situation when and all phases are simultaneously activated is 6%, and for currents there is no big influence.

During the single phase fault voltages increase in the remaining phases, because in the symmetrical components system the resistance of zero sequence is often greater than in direct or reverse sequences. Voltage increases during auto-reclosing operation due to asynchronous electrical activation in phases, and there is a risk that line connection to the network might be unsuccessful. Before switching the line, it is appropriate to determine, that there is a fault in the line, and auto-reclosing must be avoided.

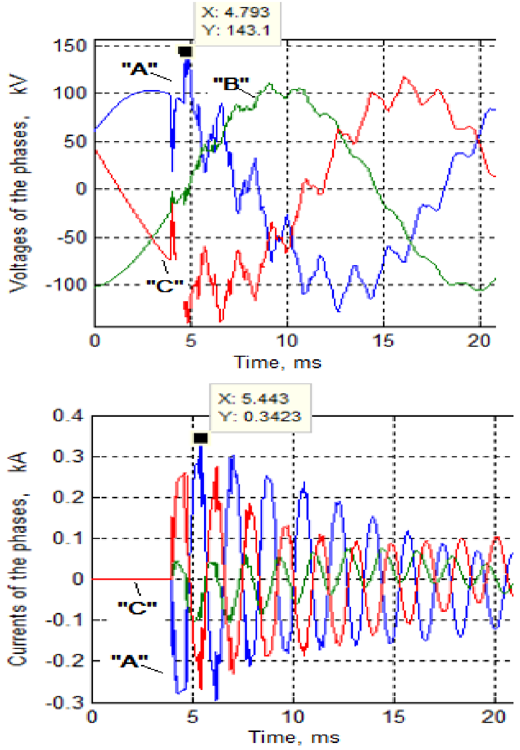

Fig.4. Voltage (U_{1MAX}) value in the first node, and current (I_{1MAX}) value in the first line. Circuit breaker operation from the stationary regime, and all phases are simultaneously activated

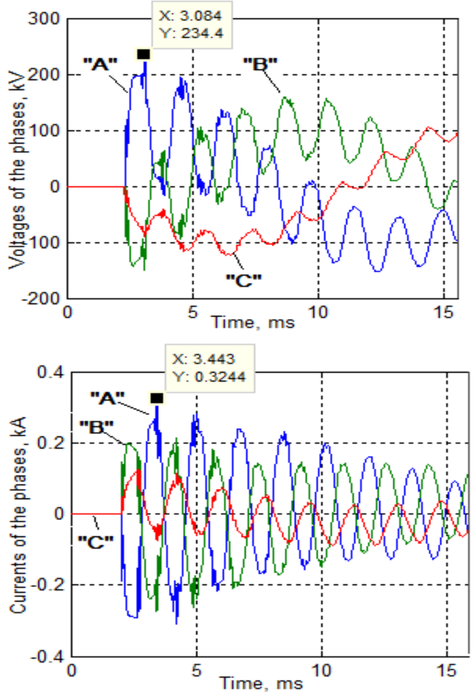

Fig.5. Voltage (U_{3MAX}) value in the third node, and current (I_{1MAX}) value in the first line. Circuit breaker operation from the stationary regime, and all phases are simultaneously activated

Fig. 5 shows that the presence of single phase fault with the substantial zero-sequence reactance, voltage increases in remaining healthy phases. If there is an unsuccessful line connection, it can be expected that the voltages will be higher compare to the case when line is connected successfully. The investigation was performed when the single phase fault occurs via resistance of 10 Ω.

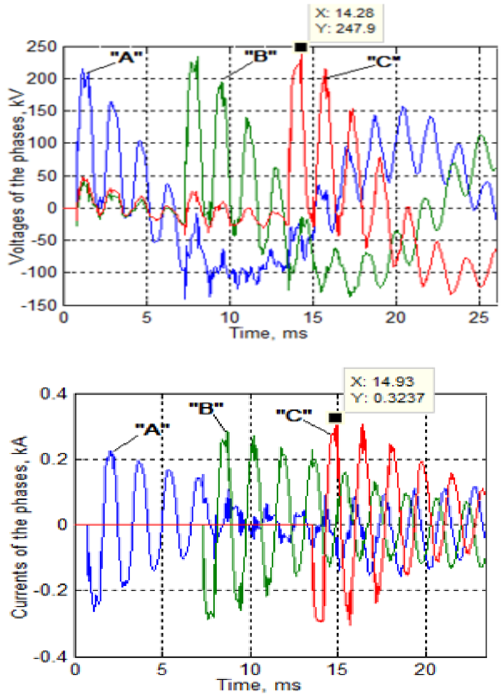

Fig.6. Voltage (U_{3MAX}) value in the third node, and current (I_{1MAX}) value in the first line. Circuit breaker operation from the stationary regime, and all phases are not simultaneously activated

In oscillogram (see Fig.7) in phase C, voltage reaches a maximum of 272 kV ratios when phase asynchronous electrical connection time is 13.8 milliseconds. Are visible two factors which determine the voltage and current increase – unsuccessful switching, and phase asynchronous electrical connection in. Table 1 illustrates that for insulation is more dangerous phase asynchronous electrical switching.

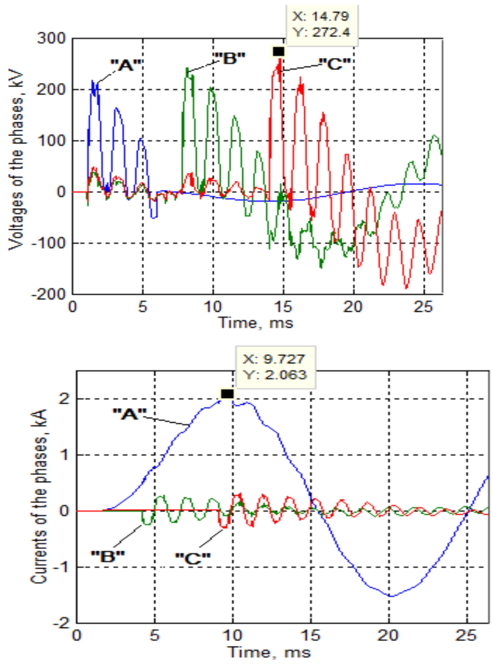

Fig.7. Voltage (U_{3MAX}) value in the third node, and current (I_{1MAX}) value in the first line during single phase fault. All phases are not simultaneously activated

During auto-reclosing operation circuit breaker's asynchronous phase switching determines increase of voltage (9%), and in particular increase of current (84%).

The obtained research results show that it is appropriate to perform calculations and determine the circuit breaker's asynchronous phase switching limits.

In practice, the circuit breakers need to be adjusted so that the asynchronous phase switching would be not greater than half of period.

Tab.1. Voltage and current changes due to the circuit breaker asynchronous phase electrical switching

Phase switching / Voltage & current changes	Synchronous phase switching from stationary regime	Asynchronous phase electrical switching	Asynchronous phase electrical switching during single phase fault	Voltage and current changes asynchronous electrical switching), %
Voltage at 3rd node, U_{3MAX}, kV	234	248	272	9
Current in 1st line, I_{1MAX}, kA	0,32	0,32	2,06	84
Time difference between phase „A“ and „C“ switching, msec	0	12,7	13,8	8

Fault identification task may require information about power line wires interposition to understand whether it makes any impact on voltages and currents. Therefore, measurements were made, taking into account the different types of overhead line poles: a tower and portal type.

To find the distance to the fault – single phase fault - is quite complicated identification task.

During the fault, current flows not only through fault affected phase or earth, but also through wires of other phases. It is important to correctly perform measurements of voltages, and to evaluate current alteration in the power line.

The modelling was carried out taking into the account the changes of wiring layout geometry in the power line poles, line wiring lengths and soil resistivity [9, 10].

The obtained results showed that due to different parameters of the line poles, the different wiring layout has an impact to the voltages and currents.

Comparing the minimum and maximum values of voltage increase, the overvoltage can reach 10%, and accordingly the overcurrent - 8%. The current shape and amplitude depends on different power line length. Then it turns out, that the current increases significantly - up to 37%. Modeling with different specific oil resistances, the obtained results showed that here it may be possible significant current increase – up to 10%.

Applied fast transient processes modelling technology, when power lines are described by wave equations, allows shortening the calculation time.

Calculation time shortening is achieved also for circuit breaker and for connected external power system by applying for modeling the digital filters. Voltage and current calculations values with 2.9 GHz personal computer were found in 0.2 s.

Conclusions

1. The circuit breaker asynchronous phase switching, during the auto-reclosing can lead to voltage increase (up to 9%), and particular to current increase (up to 84%).
2. Solving the electromagnetic transient processes identification tasks, changes of current and voltage parameters can be limited by adequate description of power lines geometry:
   - Different parameters of the line poles with different wiring layout has an impact to the voltage alteration (up to 10 %), and to the current alteration (up to 8 %).
   - Different power line length has less impact to the voltage alteration (up to 7%), than impact to the current alteration (up to 37%).
   - Impact of variety of specific soil resistance to the alteration of voltage maximum values are small (about 2%), when to the current alteration is more notable (about 10%).
3. Founded approximate formula accelerates modeling processes. Fast transient process modeling error does not exceed 0.1%.

Acknowledgments

We would like to show our gratitude to prof. dr. Andronis Linas Markevičius for assistance with fast transients analysis methodology, and for sharing his wisdom with us during this research.

***Authors**: Arnolda Rožanskienė, Department of Electric Power Systems, Kaunas University of Technology,Studentu str. 48, 51367 Kaunas, Lithuania,e-mail: arnoldarozanskiene@gmail.com; Linas Markevičius, JSC „Protronika“, Saulėtekio av. 15-513 B, Vilnius, Lithuania; e-mail: info@protronika.com*

REFERENCES

[1] A. W. Skomudek, „Analysis and Assessment of Overvoltage Effects in Medium and High Voltage Power Networks” (Analiza i ocena skutków przepięć w elektroenergetycznych sieciach średniego i wysokiego napięcia), Politechnika Opolska, Studia i monografie, z. 225, Opole 2008

[2] Y. Varetsky, R Pavlyshyn, M. Gajdzica, “Harmonic current impact on transient overvoltages during filter switching-off”, *Przegląd Elektrotechniczny*, ISSN 0033-2097, R. 89 NR 4/2013

[3] L. M. Wedepohl, D. J. Wilcox. Transient analysis of underground power transmission systems*. Proceedings IEE*, 1973, 20(2), pp. 253–260

[4] A. Semlien, Ground Return Parameters of Transmission Lines an Asymptotic Analysis for very High frequencies*. IEEE Trans. on Power Apparatus and Systems*, 1981, 100(3), pp. 1031-1038

[5] Q. SU. Chales, Electromagnetic transients in transformer and rotating machine windings*. IGI Global*, 2012-07-31, ISBN 1466619228

[6] D. Bleecker,, G. Csordas. Basic Partial Differential Equations. *Taylor & Friends*, 1992

[7] A. O. Soysal,, A. Semlyen. Reduced order transmission line modeling for improved efficiency in the calculation of electromagnetic transient. *IEEE Transactions on Power Systems*. 1994, vol. 9(3), pp. 1494-1498

[8] J. A. Martinez-Velasco Power system transients: parameter determination. *CRC Press*, p. 644, 2009

[9] J. Mahserdjian, F. Alvorado. Creating an electromagnetic transients program in MATLAB: MatEMTP. *IEEE Transactions on Power Delivery*, Jan. 1997, vol. 12(1), pp. 380-388

[10] H. W. Dommel,Digital computer solution of electromagnetic transients in single-and multiphase networks. *IEEE Trans Power Apparatus and Systems*, April 1969, vol. PAS-88(4), pp. 388-399