Reduction of Overvoltages under Connection on a High-Voltage Cable Line Due to Optimal Controlled Switching

Lobodzinskiy V., Buryk N., Spinul L., Chibelis V., Illina O.
National technical university of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
Kyiv, Ukraine

Abstract. The purpose of the work is to develop a mathematical model of a cable transmission line, which allows modeling and choosing the optimal conditions for controlled switching to limit overvoltage at the development and design stage. The goal is achieved by solving the problem of determining the initial angle of each phase, so that each phase has an initial switching angle equal to zero with a time delay. A high-voltage cable line for a voltage of 330 kV, implemented using Matlab, has been chosen as the object of study. The most significant result is the method of numerical simulation of the cable line that allows you to analyze transients when each phase of a three-phase cable line is connected to a three-phase source with a time delay, the switching angle of all phases is zero. This, in turn, makes it possible to limit switching overvoltages. The significance of the results obtained lies in the possibility of the proposed technique to choose the optimal conditions for controlled switching, which makes it possible to use it in the design of switching nodes, as well as the use of controlled switching to eliminate unwanted electrical transients during planned switching. The simulation results showed that the greatest effect of using numerical simulation is when each phase of a three-phase cable line is connected to a three-phase source with a time delay of 1/150 second, then the switching angle of all phases is zero, which makes it possible to limit switching overvoltages.
***Keywords*:** three-phase cable line, switching overvoltage, transient processes, controlled switching, theory of multipoles, modeling of electrical engineering objects.
DOI: https://doi.org/10.52254/1857-0070.2023.3-59.03
UDC: 621.315

Reducerea supratensiunilor la pornirea unei linii de cablu de înaltă tensiune datorită comutării controlate optime

Lobodzinskii V., Burik N., Spânul L., Cibelis V., Illina O.
National technical university of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
Kiev, Ucraina
Rezumat. Scopul lucrării este elaborarea unui model matematic al unei linii de transmisie prin cablu, care să permită modelarea și alegerea condițiilor optime de comutare controlată pentru limitarea supratensiunii în stadiul de elaborare și proiectare. Scopul a fost atins prin rezolvarea următoarelor probleme: determinarea unghiului inițial al fiecărei faze, astfel încât fiecare fază să aibă un unghi inițial de comutare egal cu zero cu o întârziere de timp. Ca obiect de studiu a fost aleasă o linie de cablu de înaltă tensiune pentru o tensiune de 330 kV, implementată cu ajutorul Matlab. Cele mai semnificative rezultate sunt metoda de simulare numerică a liniei de cablu care permite analiza proceselor tranzitorii la modificarea unghiului inițial de comutare al fiecărei faze, pentru a lua măsuri de limitare a supratensiunilor de comutare. Semnificația rezultatelor obținute constă în posibilitatea utilizării metodologiei propuse pentru alegerea condițiilor optime de comutare controlată, ceea ce face permite utilizarea acesteia în proiectarea nodurilor de comutare, precum și utilizarea comutației controlate pentru a elimin tranzitorii electrici nedoriți în timpul comutării planificate. Rezultatele simulării au arătat că cel mai mare efect al utilizării simulării numerice este atunci când fiecare fază a unei linii de cablu trifazate este conectată la o sursă trifazată cu o întârziere de 1/150 secunde, atunci unghiul de comutare al tuturor fazelor este de 1/150 secunde, atunci unghiul de comutare al tuturor fazelor este zero, ceea ce face posibilă limitarea supratensiunilor de comutare.
Cuvinte-cheie: linie de cablu trifazat, supratensiuni de comutare, tranzitorii, comutare controlată, teoria multipolului, modelarea obiectelor electrice.

Снижение перенапряжений при включении высоковольтной кабельной линии за счет оптимальной управляемой коммутации

Лободзинский В.Ю., Бурик Н.П., Спинул Л.Ю., Чибелис В.И., Иллина О.А.
Национальный технический университет Украины "Киевский политехнический институт имени Игоря Сикорского", Киев, Украина
Аннотация. Целью работы является разработка математической модели кабельной линии электропередачи, позволяющая моделировать и выбирать оптимальные условия управляемой коммутации для ограничения перенапряжения на стадии разработки и проектирования. Поставленная

цель достигается решением задачи определения начального угла каждой фазы, так чтобы каждая фаза имела начальный угол включения равный нулю с задержкой по времени. В качестве объекта исследования была выбрана высоковольтная кабельная линия на напряжение 330 кВ. Для решения практических задач при моделировании кабельной линии электропередачи в работе для исследования коммутационных переходных процессов используется схема замещения линии, состоящая из симметричного многополюсника, реализуемая с использованием Matlab. Наиболее существенным результатом является методика численного моделирования кабельной линии, что позволяет анализировать переходные процессы при изменении начального угла включения каждой фазы, для принятия мер ограничения коммутационных перенапряжений. Результаты моделирования показали, что при включении каждой фазы трехфазной кабельной линии в трехфазный источник с задержкой во времени, угол включения всех фаз равен нулю, это дает возможность ограничивать коммутационные перенапряжения. Синхронизация процессов коммутации осуществляется с напряжения фазы А и производится в последовательности A→B→C при коммутации трехфазной кабельной линии к генератору. Такие последовательности обусловлены стремлением к минимизации полного времени коммутации. Значимость полученных результатов состоит в возможностях с помощью предложенной методики выбирать оптимальные условия управляемой коммутации, что позволяет использовать её при проектировании коммутационных узлов, управляемых коммутаций для устранения нежелательных электрических переходных процессов при запланированных переключениях. Результаты моделирования показали, что наибольший эффект применения численного моделирования при включении каждой фазы трехфазной кабельной линии в трехфазный источник с задержкой во времени равном 1/150 секунды, то угол включения всех фаз равен нулю, что дает возможность ограничивать коммутационные перенапряжения.
Ключевые слова: трехфазная кабельная линия, коммутационные перенапряжения, переходные процессы, управляемая коммутация, теория многополюсников, моделирование электротехнических объектов.

INTRODUCTION

One of the modern methods of increasing the reliability and safety of high and ultra-high voltage power transmission cable lines is the use of cables with cross-linked polyethylene insulation, which is characterized by increased operational characteristics, especially in areas with dense construction and extensive communications.

When using ultra-high voltage cable lines, it is necessary to take into account the high-frequency transient processes of current and voltage, which arise as a result of commutative switches. It is extremely important to take into account the influence of this transitional process on the design requirements for the entire power transmission system [1-5].

Controlled switching, or synchronous switching, allows to reduce the load on the power line and switch during switching and minimize interference in the system. Thanks to this, the cable line lasts longer and wears out less. A smaller number of damages in the system (for example, repeated insulation breakdowns) increases the operational readiness of the power system. The switching operation (on and/or off, depending on the task to be performed) is carried out phase-selectively at predetermined switching angles [6–18].

It should be noted the great interest of the scientific community in the development and research of high-voltage cable power lines. Both simulation mathematical models and physical prototypes of ultra-high-voltage cable lines were developed [19–24]. In works [25, 26, 30] studies of electromagnetic processes in a powerful power transmission system, in which a cable line of ultra-high voltage is used, different modes of operation are analyzed. Models have been developed to estimate the transient process when ultra-high voltage cable lines are turned on [27–29]. However, the scientific community pays little attention to the study of transient processes when changing the initial phase of switching on a high-voltage cable line.

This work is distinguished by the fact that elements of the theory of multipoles and numerical methods of mathematical modeling, implemented in the Matlab program, were used in the development of the high-voltage cable line model. This significantly simplifies both conducting numerical calculation studies and obtaining generalizing results.

On the basis of modeling and analysis of transient voltages and currents in three-phase circuits of the type of long cable power transmission lines, which have distributed parameters and interphase mutual inductive and capacitive couplings, it is possible to determine the features of the appearance of inherent electromagnetic oscillations under complex boundary conditions and commutations.

The setting of such a scientific task is justified by the modern tendency in theoretical electrical engineering to consider multiphase electric circuits as a series-parallel connection of various n-poles, which ensures an increase in the efficiency of the calculation of transient electromagnetic processes.

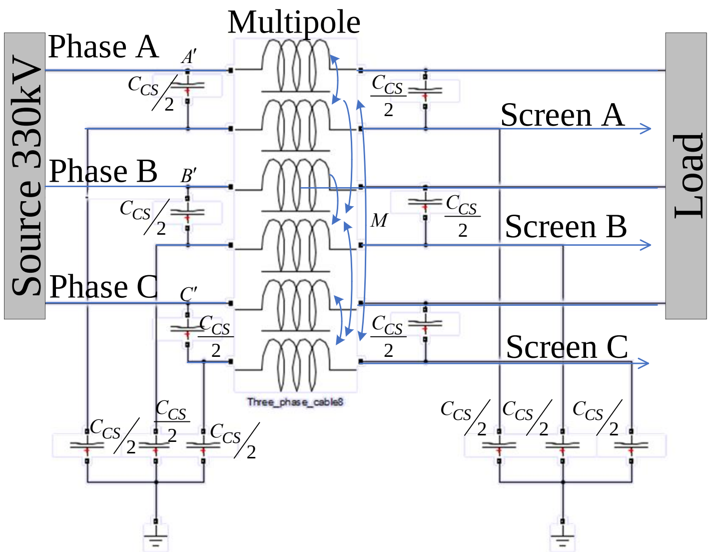

Fig. 1. The electrical equivalent circuit in the form of equivalent multiport network.

MATERIALS AND METHODS OF RESEARCH

In the work, a simulation model of a high-voltage cable power transmission line has been developed. This model consists of an equivalent circuit and is implemented in Matlab/Simulink. Such an implementation makes it possible simulate and analyze electromagnetic transients in normal and emergency modes of cable line operation. Depending on the desired result and the accuracy of solutions for simulation may be chosen rational method for solving partial differential equations, and the method of changing the simulation time (fixed or variable pitch). During the simulation, it is possible to follow the processes occurring in the electrical circuit.

When studying low-frequency transients in a three-phase cable power line, transient analysis is usually performed on the basis of a P- or T-shaped equivalent circuit with lumped parameters. The longitudinal and transverse parameters *R*, *L*, *C* of the line equivalent circuit are functions that depend on the frequency. At the same time, if one characteristic frequency can be distinguished for the investigated transient process, then the parameters at this frequency are used in the calculations. If the transient process is characterized by a wide range of frequencies, then for each of the parameters an additional equivalent circuit with lumped parameters is synthesized, which implements its frequency response. To calculate the transients in a long line, it is possible to use the calculated method of dividing this line into short sections of such a length that allows the use of an equivalent circuit with lumped parameters for each section.

The electric circuit of the equivalent section of the length L_{meters}, is implemented in the form of an equivalent multiport network on the Fig. 1, taking into account the mutual inductive connections existing between the inductances of the cores and screens.

In terms of analysis, the line is a six-wire system (three cores and three screens) with an additional seventh wire – ground.

The described model is simplified because it does not take into account the dynamic characteristics of energy sources and loads. However, using the user-friendly Simulink user interface, the open structure of the model allows you to quickly change its topology and block parameters depending on the specific task. In particular, the topology of the constructed model can be used in the future to study two-phase, three-phase and other complex short circuits in the cable transmission line. This model also allows for a comprehensive study of the readings of virtual instruments when including in the model of parallel nodes and loads with dynamically changing parameters, which allows calculations of various modes of operation of the power system of this type in the initial stages of design.

The investigated high-voltage power line has a power supply of 330 kV, the length of the line is 3000 m. The parameters of the line replacement scheme are calculated taking into account the geometric parameters of a single-phase cable (Fig. 2) r_1=17.4 *mm*, r_2=42.8 *mm*, r_3=46.5 мм, r_4=52.5 *mm*.

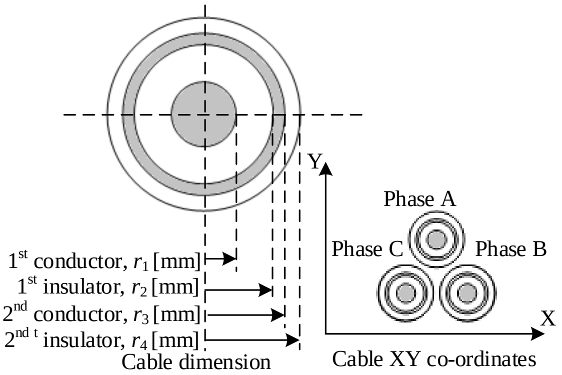

Fig. 2. Cable geometry.

The calculation expressions for the parameters of a single-phase cable are obtained from the known formulas for the linear active-inductive resistances of a multi-wire wire-ground system, which are presented in [31]. When calculating the capacitive parameters of the cable, it is assumed that the cable is laid underground (the depth in this case does not matter).

The matrix of cable parameters, voltage drops along the conductors U_c and screens U_s, related to the currents in them, is represented by the matrix equation:

$$\begin{bmatrix} U_{cA} \\ U_{sA} \\ U_{cB} \\ U_{sB} \\ U_{cC} \\ U_{sC} \end{bmatrix} = \begin{bmatrix} Z_c & Z_{cs} & 0 & 0 & 0 & 0 \\ Z_{cs} & Z_s & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_c & Z_{cs} & 0 & 0 \\ 0 & 0 & Z_{cs} & Z_s & 0 & 0 \\ 0 & 0 & 0 & 0 & Z_c & Z_{cs} \\ 0 & 0 & 0 & 0 & Z_{cs} & Z_s \end{bmatrix} = \begin{bmatrix} I_{cA} \\ I_{sA} \\ I_{cB} \\ I_{sB} \\ I_{cC} \\ I_{sC} \end{bmatrix} \quad (1)$$

where I_A, I_B, I_C – are the currents of the cable cores; I_{sA}, I_{sB}, I_{sC} – cable shield currents; Z_c, Z_s – linear internal resistances of the core and screen; Z_{cs} – is the linear mutual resistance between the core and the screen of the same cable. The calculation of the parameters was carried out using the geometric mean distance between the axes of the phases of the cables *A*, *B*, *C*.

To accurately calculate the electrical parameters of cables *Z*, taking into account the mutual influence of phases and circuits on each other, as well as taking into account the frequency dependences of these parameters, the following assumptions were made:

- the cable line consists of metal conductors, the axes of which are mutually parallel and parallel to the ground surface;
- the line is homogeneous along its axis;
- for the lines under consideration, we neglect the propagation of the electric field in the radial direction in the earth.

Calculation formulas for the parameters of the cable line, taking into account their dependence on frequency and actual geometric location in the ground:

$$Z_c = Z_1 + Z_2 + Z_3 + Z_5 + Z_6 + Z_7 - 2Z_4$$
$$Z_s = Z_3 + Z_6 + Z_7$$
$$Z_{cs} = Z_5 + Z_6 + Z_7 - Z_4$$

Linear longitudinal parameters are represented by resistances $Z_1 \ldots Z_7$, the formulas for calculating which in the range of relatively low frequencies are presented in [31].

RESULTS AND DISCUSSION

The oscillograms of the transient process of voltage and current in the shields of single-phase cables when the cable line is connected to the source in the idle mode are shown in fig. 3 and 4. From the given oscillograms in fig. 3 shows that the overvoltage on the cable shields at the moment of switching will be 4 kV.

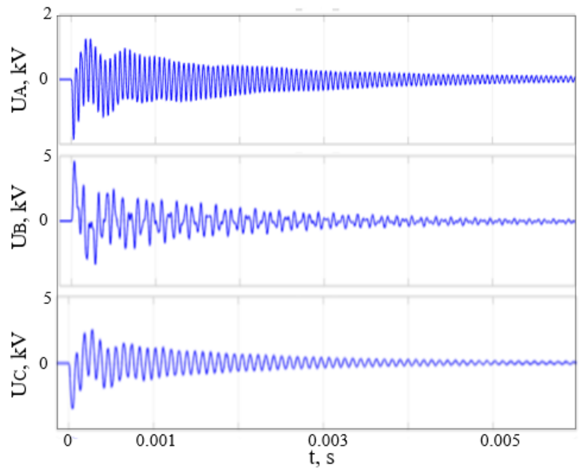

Fig. 3. Oscillograms of the transient process of voltage in screens of single-phase cables.

This is explained by superimposing the form of oscillations of different frequencies, caused by the effect of the mutual induction of the cores of all phases of the cable on the screen. Rapid attenuation of transient phenomena in screens of a three-phase cable line of single-phase execution is observed due to the presence of active components of all elements.

The appearance of currents is caused by the grounding of the screens at the end and at the beginning of the cable line. Since at the moment of switching, due to the magnetic connection between the core and the screen, the EMF of the mutual induction increases, which contributes to the flow of currents in the screens of about 280 A.

After the attenuation of the main components of the switching transient process in the cores of the cable, induced in the circuit due to mutual inductance, the emf of each core decreases, which leads to the attenuation of the voltage and current curves in the cable shield to minimum values.

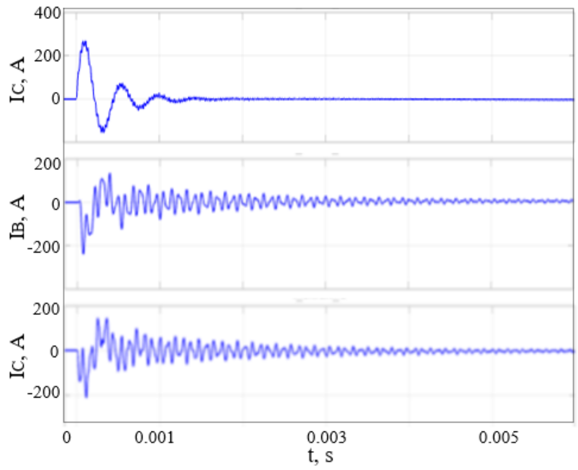

Fig. 4. Oscillograms of the transient process of the current in the shields of single-phase cables.

To limit the switching voltage, the principle of selecting favorable initial conditions of the transition process, in which the amplitudes of free oscillations have minimum values, is used, for example, control of the switching moment by changing the initial angle of each phase.

Let us consider the oscillograms of the transient processes of currents and voltages in the shields of a three-phase cable line of single-phase execution when the cable line is turned on to a three-phase voltage source when the initial angle changes.

The switching of each phase took place at different moments of time, so that each phase had an initial switching angle equal to zero. At the angle of inclusion $\varphi=0^{O}$, the phase amplitude has a nominal value, which can be seen on the oscillograms of Fig. 5.

Analyzing the oscillograms of Fig. 5, we can conclude that if each phase of a three-phase cable line is connected to a three-phase source with a frequency of f=50 Hz with a time delay equal to 1/150 sec, then the angle of inclusion of all phases will be zero, which will lead to a limitation of the switching voltage.

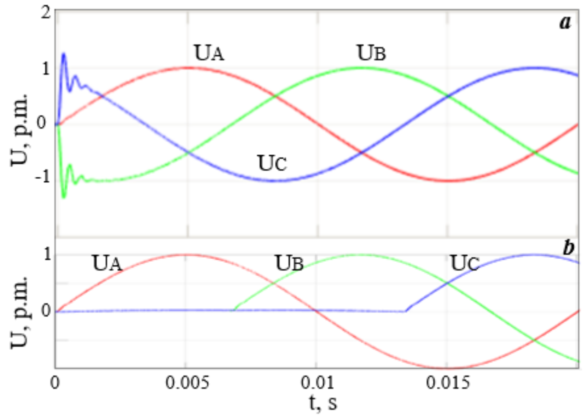

Fig. 5. Oscillograms of voltage and currents in a three-phase cable line at the moment of connection to the power source: with phase shift (*a*); at the switching angle φ=0^O (*b*).

Changing the initial angle of each phase during switching does not affect the increase in voltage on the cable screen (Fig. 6), but at the same time, induced currents appear in the screens (Fig. 7), the transition process curves of which are subject to investigation in order to understand the processes, happening in cable screens.

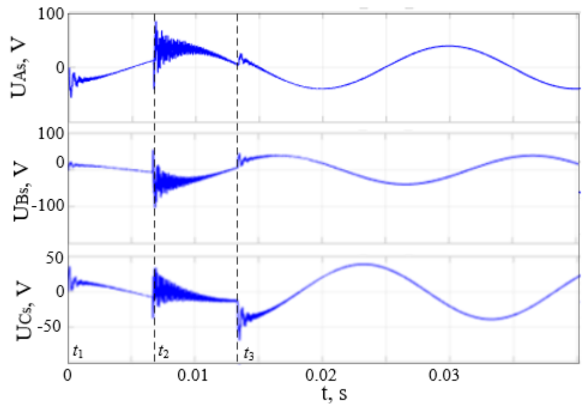

Fig. 6. Voltage curves in the screens of each phase when changing the initial angle.

From fig. 6, 7, it can be seen that at the first moment of time at t_1, phase A is turned on and a current begins to flow through the conductive core, as a result of which a variable magnetic field is created around the conductor, which leads to the appearance of a current in the screen of Fig. 7. The current in the screen causes a drop in the voltage of its phase, under the action of magnetic induction, causes a drop in the voltage on the screens of phases B and C (Fig. 6). Similarly, the voltage on the screens of phases B and C, which are not turned on, is due to the capacitive and electromagnetic connection with phase A.

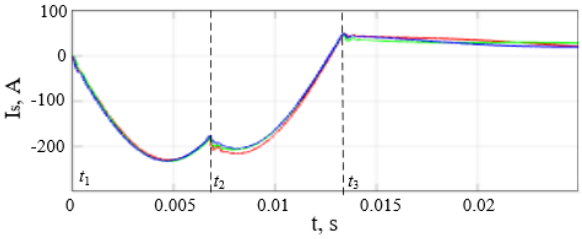

Fig. 7. Transient current curves when the initial angle changes.

At the moment of switching on one phase, induced currents begin to flow in all screens of each phase. Since only the voltage of phase A acts, the transposition of the screens does not compensate for the EMF of the mutual induction, which leads to a strong increase in the current.

At the moment of time t_2, phase B is connected, which leads to an increase in the EMF of the mutual induction on the phases. This can be seen from the oscillogram (Fig. 6), the voltages U_A and U_B have a large initial amplitude compared to the disconnected voltage U_C.

The appearance of voltage on phase B, as a result of the transposition of the screens, compensates for the longitudinal currents flowing through the screens, but does not lead to a balance of phase voltages.

At the moment of time t_3, all three phases are connected to the line, and therefore the EMF of the mutual induction, which is shown in the screens of the three sections of the transposition, due to the phase shift by 120° and 240°, is zero. Therefore, the currents induced in the screens, after a slight transient process, take values close to zero.

Oscillations caused by the connection of each phase at times t_1, t_2, t_3 by the recharging of the capacitors, and by the electromagnetic connection between the cores and shields of the three-phase cables.

CONCLUSION

Optimal conditions of controlled switching when switching on a three-phase cable line prevent the appearance of an aperiodic current component, which allows limiting switching overvoltage.

It is convenient to analyze the switching processes of each phase by bringing the initial conditions to zero. Given that the very principle of controlled switching rids the current in the line of free components, the analysis of controlled switching can be carried out in the schemes of the established mode.

Synchronization of switching processes is carried out with the voltage of phase A and is carried out in the sequence A→B→C when switching the three-phase cable line to the generator. Such sequences are due to the desire to minimize the total switching time.

The oscillograms of the transient processes of currents and voltages in the shields of a three-phase cable line of single-phase execution when the cable line is turned on to a three-phase voltage source when the starting angle is changed are considered. When each phase of a three-phase cable line is connected to a three-phase source with a time delay equal to 0.006(6) (1/150) of a second, the angle of inclusion of all phases is zero, which makes it possible to limit switching voltages.

The significance of the obtained results lies in the possibilities of the proposed method to select optimal conditions of controlled switching, which allows it to be used in the design of switching nodes, as far as in controlled switching to eliminate unwanted electrical transients during planned switching.

Changes in the initial angle of each phase during switching does not lead to an increase in the voltage on the cable shield, but at the same time, induced currents appear in the shields, the transition process curves of which are subject to additional research to analyze the processes occurring in the cable shields.

REFERENCES

[1] Chaban A., Lis M., Szafraniec A., Levoniuk V. Mathematical Modelling of Transient Processes in a Three Phase Electric Power System for a Single Phase Short-Circuit *Energies*, 2022, *15*(3), 1126. doi.org/10.3390/en15031126

[2] Vijaya Tharani C., Nandhini M., Sundar R., Nithiyanantha K. MATLAB based Simulations model for three phases Power System Network. *Int. J. Res. Appl. Sci. Eng. Technol*. 2016, 4, 502–509. ISBN-13: 978-1540513212

[3] Pruski P., Paszek S. Analysis of transient waveforms in a power system at asymmetrical

short-circuits. Prz. Elektrotech. 2020, 2, 26–29. doi.org/10.15199/48.2020.02.05

[4] Colqui, J.S.L., de Araújo A.R.J., Kurokawa, S.; Filho, J.P. Optimization of Lumped Parameter Models to Mitigate Numerical Oscillations in the Transient Responses of Short Transmission Lines. *Energies.* 2021, 14, 6534. doi.org/ 10.3390/en14206534

[5] Marius Fișcă, Mihail Abrudean, Vlad Mureșan, Iulia Clitan, Mihaela-Ligia Ungureșan, Roxana Motorga, Emilian Ceuca. Modeling and Simulation of High Voltage Power Lines under Transient and Persistent Faults. *Mathematics* 2023, 11(1), 21. doi.org/10.3390/math11010021

[6] Nuricumbo-Guillén R., Cortés F.P.E., Gómez P., Martínez C.T. Computation of Transient Profiles along Nonuniform Transmission Lines Including Time-Varying and Nonlinear Elements Using the Numerical Laplace Transform. *Energies* 2019, 12, 3227. doi.org/10.3390/en12173227

[7] Kizilcay M., Teichmann K., Papenheim S., Malicki P. Analysis of Switching Transients of an EHV Transmission Line Consisting of Mixed Power Cable and Overhead Line Sections. *In Proceedings of the International Conference on Power Systems Transients (IPST2017)*, Seoul, Korea, 26–29 June 2017.

[8] Kuchanskyy Vladislav. "The application of controlled switching device for prevention resonance overvoltages in nonsinusoidal modes." *2017 IEEE 37th International Conference on Electronics and Nanotechnology (ELNANO)*. IEEE, 2017, 394-399. doi.org/10.1109/ELNANO.2017.7939785

[9] Nidhi Parmar, Chetan Kotwal, Tarang Thakkar, Prakash Makhijani. "Switching Overvoltages in Offshore Cable Connections."*ICRISET2017*, 2017, 586-592. doi.org/10.29007/d2q7

[10] Garbelim Pascoalato, Tainá Fernanda, et al. A comparison of frequency-dependent soil models: Electromagnetic transient analysis of overhead transmission lines using modal decomposition. *Energies* 15 (5), 2022, 1687. doi.org/ 10.3390/en15051687

[11] Shen Hong, Zhonghao Dongye. "Modeling of high-frequency electromagnetic oscillation for DC fault in MMC-HVDC systems." *CSEE Journal of Power and Energy Systems* (2022). doi.org/10.17775/CSEEJPES.2021.06370

[12] Peng Lu, Xu Liu, Lijuan Wang, Jiajia Fu, Xinwen Hu, Xiaoang Li. "Influence of operation mode on HGIS fast transient overvoltage and enclosure overvoltage." *4th International Conference on Information Science, Electrical, and Automation Engineering (ISEAE 2022)*. Vol. 12257. SPIE, 2022. 658-665. doi.org/10.1117/12.2640282

[13] Zychma Daria, Paweł Sowa. "Electromagnetic Transients in Multi-Voltage Transmission Lines during Non-Simultaneous Faults." *Energies* 15(3) (2022): 1046. doi.org/10.3390/en15031046

[14] Ye Zhihong, Yanchao Shi, Zhiwei Gao, Xiaolin Wu. "Time-Domain Hybrid Method for the Coupling Analysis of Power Line Network with Curved and Multidirectional Segments." *IEEE Transactions on Electromagnetic Compatibility* (2022). doi.org/10.1109/TEMC.2022.3222208

[15] Zalhaf Amr S., et al. Evaluation of the transient overvoltages of HVDC transmission lines caused by lightning strikes. *Energies* 15.4 (2022): 1452. doi.org/10.3390/en15041452

[16] Zhang Shun, Nannan Zhou. Extraction of Multiple Electrical Parameters from IP-affected Transient Electromagnetic Data based on LSTM-ResNet. *IEEE Transactions on Geoscience and Remote Sensin* (2023). doi.org/ 10.1109/TGRS.2023.3266258

[17] Mutukutti Ravi, Jose Marti. "Modelling of water conduit dynamics using the electromagnetic transient program line model." *Electric Power Systems Research* 212 (2022): 108401. doi.org/10.1016/j.epsr.2022.108401

[18] Jiaxin Yuan, Weizhe Zhang, Jiajun Mei, Zaoshen g Ye, Dongliang Gan, Yuankun Zheng, Liwen Pe ng. A novel multiline fast electromagnetic unified power flow controller topology for distribution network. *IEEE Transactions on Industry Applications* 58(3) (2022): 3238-3249. doi.org/10.1016/j.egyr.2023.04.097

[19] Wenying Yang, Yuhang Pan, Zilan Qiu, Guofu Z hai. "Electromagnetic transient model and field-circuit coupling numerical calculation of Sen transformer based on finite-element method. *Electric Power Systems Research* 214 (2023): 108941. doi.org/10.1016/j.epsr.2022.108941

[20] Boumous S., Boumous Z., Anane Z., Nouri H. Comparative study of 220 kV overhead transmission lines models subjected to lightning strike simulation by using electromagnetic and alternative transients program. *Electrical Engineering & Electromechanics*, (4), 2022, 68–74. doi.org/10.20998/2074-272X.2022.4.10

[21] Ghassan Bilal, Pablo Gómez, Reynaldo Salcedo, Juan Villanueva. Electromagnetic transient studies of large distribution systems using frequency domain modeling methods and network reduction techniques. *International Journal of Electrical Power & Energy Systems* 110 (2019): 11-20. doi.org/ 10.1016/j.ijepes.2019.02.043

[22] Rooney R. A. Coelho, Domingos T. da Silva Neto, José Roberto Cardoso. Electromagnetic Transients in Multiconductor Transmission Lines. *Journal of Microwaves, Optoelectronics and Electromagnetic Applications* 21 (2022):

508-526. doi.org/10.1590/2179-10742022v21i4268097

[23] Xiangxiang Wei, Dechang Yang, Xiaowei Wang, Bin Wang, Jie Gao, Jie Wei. "Faulty feeder detection based on fundamental component shift and multiple-transient-feature fusion in distribution networks." *IEEE Transactions on Smart Grid* 12.2 (2020): 1699-1711. doi.org/10.1109/tsg.2020.3026390

[24] Akifumi Yamanaka, Naoto Nagaoka, Yoshihiro Baba. "Circuit model of vertical double-circuit transmission tower and line for lightning surge analysis considering TEM-mode formation." *IEEE Transactions on Power Delivery* 35.5 (2020): 2471-2480. doi.org/10.1109/EEEIC/ICPSEurope49358.2020.9160536

[25] Meng, X. K., Jia Y. B., Liu Z. H., Yu Z. Q., Han P. J., Lu Z. M., Jin, T. High-Voltage Cable Condition Assessment Method Based on Multi-Source Data Analysis. *Energies*, 2022,*15*(4), 1369. doi.org/10.3390/en15041369

[26] Pournabi M., Mohammadi M., Afrasiabi S., & Setoodeh P. Pournabi, Mehrdad, et al. Power system transient security assessment based on deep learning considering partial observability. *Electric Power Systems Research*, 205, 2022. 107736. doi.org/10.1016/j.epsr.2021.107736

[27] Chaban A., Lis M., Szafraniec A., Levoniuk V. Mathematical Modelling of Transient Processes в Три фазе Electric Power System для Single Phase Short-Circuit. *Energies*, *15* (3), 2022. 1126. doi.org/10.3390/en15031126

[28] Varetsky Yuriy, Michał Gajdzica, Beata Kushka. Study of transient overvoltages on CSI adjustable speed drives under arcing SLGF in the industrial cable grid. *Electric Power Systems Research*. 209, 2022: 107954. doi.org/10.1016/j.epsr.2022.107954

[29] Wang, Jingya, Yongchun Liang, and Chunyu Ma. A novel transient thermal circuit model of buried power cables for emergency and dynamic load. *Energy Reports*. 9, 2023. 963-971. doi.org/10.1016/j.egyr.2022.11.097

[30] Shcherba, A. A., Podoltsev, A. D., & Kucheriava, I. M. The reduction of magnetic field of underground cable line in essential areas by means of finite-length composite magnetic shields. *Tekhnichna elektrodynamika*. 1, 2022. 17-24. doi.org/10.15407/techned2022.01.017

[31] Wedepohl L.M., Welcox D.J. Transient analysis of underground power transmission systems. *Proc. Inst. El. Eng*, 1973. vol. 120, №2. P. 253–260. doi.org/10.1049/piee.1973.0056

Information about authors.

Lobodzinskiy Vadim Yur'evich – PhD, Associate Professor. Research interests: energy modelling of smart grids; analysis of steady-state, pulsed and transient electromagnetic processes in electric circuits of different types.
E-mail: v.lobodzinskiy@gmail.com

Buryk Nikolay Petrovich – PhD, Associate Professor. Research interests: Research of methods of control of interconnected electromechanical systems in the conditions of uncertainty of mathematical model of object.
E-mail: burykm@ukr.net

Spinul Lyudmila Yur'evna – PhD, Associate Professor. Research interests: theoretical and applied aspects of the theory of identification of objects of different nature.
E-mail: spinul20@gmail.com

Chibelis Valeriy Ivanovich – PhD, Associate Professor. Research interests: development of scientific and technical nondestructive diagnosis of highvoltage cables.
E-mail: toe209@gmail.com

Illina Olga Aleksandrovna – assistant Professor. Research interests: research on the energy characteristics of the charge and discharge circuits of capacitors at non-zero voltage.
E-mail: illina.olga@lll.kpi.ua