ARTICLE

DOI 10.36074/grail-of-science.25.06.2021.025

FEATURES OF TRANSIENT RESEARCH IN THREE-PHASE HIGH-VOLTAGE POWER TRANSMISSION CABLE LINES

RESEARCH GROUP:

Lobodzinskiy Vadim
Ph.D, associate professor, department of theoretical electrical engineering
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine

Chybelis Valeriy
Ph.D, associate professor, department of theoretical electrical engineering
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine

Petruchenko Oleg
Senior Instructor, department of theoretical electrical engineering
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine

Illina Olga
Assistant Lecturer, department of theoretical electrical engineering
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine

Chunyak Yuliya
Assistant Lecturer, department of theoretical electrical engineering
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine

Babenko Viktoriia
Higher education applicant department of computing engineering
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine

Summary. *The methods of analysis of transients in three-phase circuits with distributed parameters and interphase connections are considered on the basis of representation of such circuits by multipoles, finding their corresponding concentrated parameters and determination of boundary and initial conditions of transients. The formulation of this scientific problem is justified by the current trend in theoretical electrical engineering to consider multiphase circuits as a series-parallel*

connection of different n-poles, which improves the calculation of transient electromagnetic processes in multiphase circuits with distributed parameters and interphase connections. Using the theory of multipoles allows us to represent the elements of the electric circuit by macromodels that reflect their external connections and the impact on the rest of the circuit. The main difficulty in applying this principle is to resolve emerging electromagnetic bonds.
Keywords: *distributed circuits, multipole, three-phase electric circuits, transients, interphase connections, cables.*

Calculation and prediction of transient electromagnetic processes is not an easy task. Transients that occur in multiphase electrical circuits with concentrated and distributed parameters require in-depth study. In addition, this problem is static, which requires consideration of a large number of options in which different factors and their combinations change. Consideration of such problems and bringing them to a technical solution is not always possible without the use of modern computing tools. The use of computer modeling is an understanding and interpretation of the results that can be obtained if you first solve the problem in a simplified form, which allows you to bring it to an analytical solution [1–114].

In modeling and analysis of a complex multiphase electric circuit, a set of algorithms and software techniques is used, in which the electric circuit is represented by a set of multipoles, the outputs of which, called the branches of the electric circuit, are connected in nodes. The branches of the electric circuit with numbers 1, 2, ... are matched with the vector of currents $i^{T} = (i_1, i_2, i_M)$, the nodes of the electric circuit with numbers 0, 1,..., N are the potential vector $u^{T} = (u_1, u_2, u_N)$. The vector $V = (u,i)$ is called the vector of variables of the electric circuit or coordinate basis. The sum $L = M + N + 1$ is determined by the dimension of this electric circuit.

The mathematical model of the component of an electric circuit is an open system of equations that connects the variables on the conclusions of this component. The mathematical model of an electric circuit is a closed system of equations that define the topological law and the relations of mathematical models of the components of an electric circuit. The task of modeling an electric circuit is to summarize all equations into one system, the task of analysis is to determine the vector of variables of an electric circuit.

In this approach, Kirchhoff's law for currents is chosen as the topological law. It is known that the set of Kirchhoff's laws for all nodes forms a linearly dependent system, so Kirchhoff's law for currents applies to all nodes except zero. In the general case, the number of this node does not matter. As a reference point for voltages, a zero node is selected, the potential of which is equal to zero. Then the mathematical model of the electric circuit is represented by a system of equations:

$$\begin{gathered} u_0 = 0, \\ [\mathrm{A}] \cdot \mathrm{i} = 0, \\ F\left(\frac{d\mathrm{u}}{dt}, \frac{d\mathrm{i}}{dt}, \mathrm{u}, \mathrm{i}, t\right) = 0 \end{gathered} \tag{1}$$

where [A] – dimensional incidence matrix M x N.

The equations that determine the mathematical models of the components of an electric circuit are generally nonlinear differential and algebraic equations. The sampling of ordinary differential equations is carried out by implicit Euler or trapezoidal methods. A linearized system of equations is compiled for each component of the electric circuit and connects the variables u and i at the terminals of this component only. Partial derivatives, which are elements of the Jacobi matrix, are calculated by analytical expressions selected from a mathematical model of the components of an electric circuit. The initial approximation of the decision vector is its value in the previous time step, which ensures the convergence of the iterative process with quadratic velocity.

The discrete form of the system (1) has the form:

$$\begin{gathered} u_0^{m+1} = 0, \\ \left[\mathrm{A}\right] \cdot \mathrm{i}^{m+1} = 0, \\ \left[\mathrm{B}^n\right] \cdot \mathrm{u}^{n+1} + \left[\mathrm{C}^n\right] \cdot \mathrm{i}^{n+1} = \mathrm{D}^n \end{gathered} \qquad (2)$$

where $\left[\mathrm{B}^n\right]$, $\left[\mathrm{C}^n\right]$, D^n *– parametric matrices and vectors, respectively.*

Multiphase circuits are characterized by the presence of electromagnetic and electrostatic relationships between the elements of the individual phases of the components of the electrical circuit. A discrete mathematical model of such a multipolar component can be represented in the form

$$\mathrm{u}^{n+1} + \left[\mathrm{C}^n\right] \cdot \mathrm{i}^{n+1} = \mathrm{D}^n \qquad (3)$$

has a symmetric matrix [C^n] with non-zero diagonal and non-diagonal terms. If we If you make the matrix diagonal the matrix [C^n], then system (3) can be represented by a set of independent equations.

Go to the diagonal matrix is associated with the problem of finding eigenvalues. The diagonal matrix is a matrix of eigenvalues of the original matrix, and the transformation matrix will be a matrix of eigenvectors. Denoting the matrix of the corresponding linear transformation by [Λ], we can represent system (3) as a system of independent equations:

$$\tilde{\mathrm{u}}^{n+1} + \left[\tilde{\mathrm{C}}^n\right] \cdot \tilde{\mathrm{i}}^{n+1} + \tilde{\mathrm{D}}^n \qquad (4)$$

where the relationship of the converted variables with the phase is represented by the relations

$$\tilde{\mathrm{u}}^{n+1} = \left[\Lambda\right]^{-1} \cdot \mathrm{u}^{n+1}, \; \tilde{\mathrm{i}}^{n+1} = \left[\Lambda\right]^{-1} \cdot \mathrm{i}^{n+1} \qquad (5)$$

and the diagonal matrix $\left[\tilde{\mathrm{C}}^n\right]$ is defined by the expression

$$\left[\tilde{\mathrm{C}}^n\right] = \left[\Lambda\right]^{-1} \cdot \left[\mathrm{C}^n\right]\left[\Lambda\right] \qquad (6)$$

Thus, the multipolar component of an electric circuit, the mathematical model of which (3) is an interdependent system of equations for variable circuits in phase coordinates, can be replaced by a set of bipolar components whose mathematical models in the transformed coordinate systems are independent of equations (4), and additional multipolar components described by equations (5). Analysis of the electrical circuit including such components is performed in the extended coordinate basis

$$V = (u), \tilde{u}, i, \tilde{i}$$

which increases the dimension of the electric circuit. However, with the help of a limited set of basic components, the converters allow to form schemes of the original multipoles and to include components, the mathematical description of which is the most rational in the non-phase coordinate system.

When calculating transient electromagnetic processes in three-phase electric circuits, phase (*A, B, C*) coordinates are used, modal (*α, β, 0*) coordinates are used, and rotating (*d, q, 0*) coordinates are used.

Information about the topology, component composition of the electrical circuit and the values of the parameters can be set by the components of the subroutines, indicating the numbers of branches and nodes of the component, as well as their parametric data. In matrix form, system (2) has the form

$$[F] \cdot V = W \qquad (7)$$

For circuits that contain complex mathematical models with a high relationship between the elements (for example, the inductive relationship), the matrix [F] may appear complete.

The model method is a kind of topological methods of circuit analysis, which include methods of contour currents, nodal potentials, state variables. Their difference is determined by the choice of coordinate basis. The dimension of the electric circuit L in the model method exceeds the dimension of the coordinate basis in such methods as the method of nodal potentials or state variables. Accordingly, the calculation speed is reduced. However, the advantages of the model method are: no restrictions on the type of components of the electrical circuit (bi- and multipolar, linear and nonlinear, controlled by current and voltage); simplicity of modeling an electric circuit due to the use of Kirchhoff's law for currents, the application of which does not require the concepts of a closed circuit and voltage drop in the circuit; algorithmic simplicity of mathematical models of electric circuit components, which consists in filling the matrix [F] and the vector W with data according to the topology and parameters of linearized equations.

The waveguide method is used to analyze electrical circuits consisting of long lines. The presence of a coordinate converter and a single-phase (single-channel) line allows the calculations of transients in multi-wire lines, which consist of any number of phase wires. In a separate case, a three-phase symmetric line is represented by a transformation from phase (*A, B, C*) coordinates into modal (*α, β, 0*) and a system of three single-channel lines with parameters in straight and zero sequences [15].

To analyze the transients in three-phase electrical circuits with distributed parameters, various methods are used, presented in Fig. 1 [16].

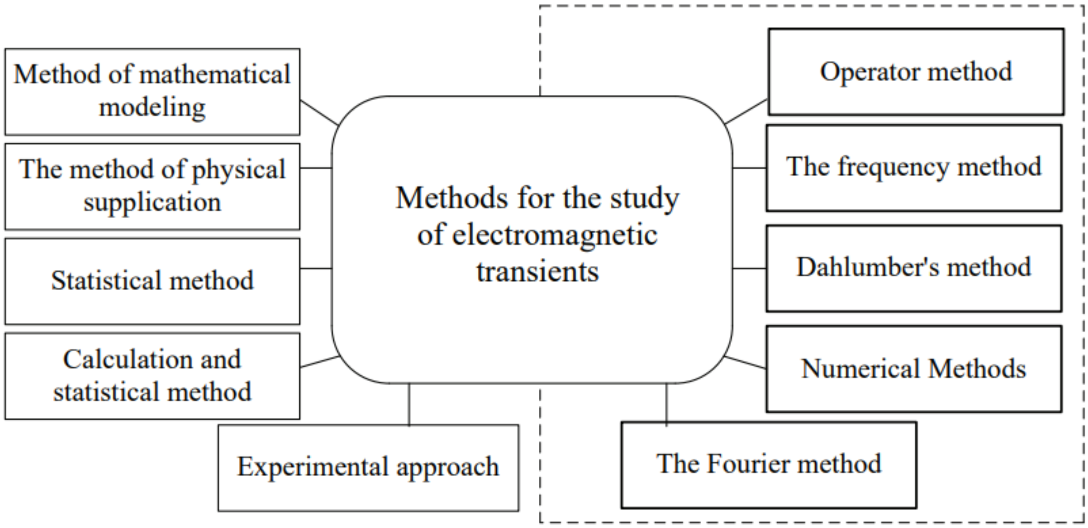

Fig 1. Methods of research of electromagnetic transients

The analysis of these methods shows that: an experimental approach based on monitoring and observation of over voltages that occur in cable transmission lines. These methods are typical for different ways of selecting protective devices and monitoring the level of insulation. But they do not take into account the duration, the amplitude of the overvoltage at different switching modes.

Consider a method of physical modeling that has limitations for high voltage cable lines. It allows you to accurately analyze the processes in the full-scale models of cable lines and to study the physical phenomena occurring in the cable. However, there are a number of difficulties associated with the implementation of full-scale models in practice, which are associated with technical conditions and financial costs.

The method of mathematical modeling is to implement a scheme for replacing a three-phase cable line with known parameters, which limits its application.

The statistical method is based on the statistical planning and processing of a large number of experiments and the development of recommendations for the assessment of over voltages and the choice of protection against their consequences. However, it is not always possible to generate the necessary statistical arrays.

Calculation and statistical method, using a cable line is a homogeneous long line or circuit diagram, and the parameters of the substitution circuit are calculated by simple engineering formulas. Similarly, this includes statistical parameters of over voltages that occur in mathematical experiments, with multiple calculations of modes in mathematical models of the system, taking into account different values of parameters and switching.

In calculation methods based on the study of a mathematical model of a three-phase circuit with distributed parameters, in all cases the coefficients included in the equation are determined by the parameters of the substitution scheme, which are either experimentally or by calculating design data, which is not always possible.

The frequency method is based on the fact that in its application, the expression of the transfer function is composed in the circuit substitution scheme and then (through the Fourier integral) expressions for voltages and currents in the transient mode are constructed. For the practical calculation of the Fourier integral it is necessary to know the dependences of the parameters in a wide range of frequencies, starting from ω=0.

The Fourier method (ie standing waves) involves the use of a solution in the form of an infinite sum of harmonics - standing waves. The disadvantage of this method is the production of orthogonal eigenfunctions, as a result of which it is impossible to determine the Fourier coefficients independently of each other. Since the initial voltage and current functions that satisfy the boundary conditions of the mode before switching, are decomposed into series by their own functions, which satisfies the boundary conditions of the mode after switching. Practical calculation in the presence of such a phenomenon can be performed by summing the series by arithmetic mean or the method of Lanzosh factors. The advantage of the method is the relatively fast determination of the natural frequency spectrum of the system, the value of which is necessary for further calculation of the amplitude of over voltages.

When using the Fourier method to calculate transients, it is sufficient to have the value of the discrete natural frequency spectrum and the value of the wave parameters of the system at these frequencies.

In particular, the method of D'Alembert (traveling waves). This method reflects the physical content of transients in circles with distributed parameters. The application of this method is usually used for lossless lines and for non-distorting lines. In other cases, the shape of the propagating wave is strongly distorted when moving. In these cases, proceed to the calculation in modal channels, each of which is characterized by its own speed of propagation, which allows to take into account the dependence of the wave parameters of the line on the frequency. This method can calculate the amplitude of over voltages during the first wave path, as taking into account the reflected and refracted waves leads to the complexity of algorithms and increase the amount of calculations.

A common disadvantage of numerical integration methods is the complexity of the step-by-step analysis of the results and the three-dimensional formulation of the original data in programming tasks. In the presence of the oscillatory nature of the processes under consideration, these methods are unstable.

The finite element method allows you to divide the areas of integration into identical finite elements with simplified properties. In the considered problems the method of finite elements on the physical maintenance corresponds to representation of a line by the chain scheme. Similarly, numerical methods include: finite difference method and Z transformation method, which allow constructing the original and do not requiring determination of roots (natural frequencies), by replacing the exact image of the voltage and current functioning by pulse.

The operator method is the most effective method of obtaining solutions, as its use does not need to take into account the sequential obtaining of coefficients of series, and therefore the accuracy of this method does not depend on the orthogonality of eigenfunctions.

The solution by this method can be represented in the form of forward and reverse waves. To obtain the original by the decomposition theorem, it is necessary to determine the natural frequency spectrum. When solving problems, a mandatory recording of the entire image is required, this leads to an increase in the amount of calculated data. The operator method allows you to automatically take into account the initial and boundary conditions.

Given the methods of studying electromagnetic transients, it is concluded that for the calculation of transient voltages and currents in multiphase electrical circuits, the most appropriate is the use of calculation methods. These methods allow to increase the accuracy of the results of the calculation of transients, which requires in some practical cases to abandon the assumptions of line symmetry and move on to the development of methods for calculating transients in asymmetric modes [17–21].

In the analysis of dynamic processes in electric circuits with concentrated and distributed parameters, considerable attention is paid to the choice of the mathematical model that best meets the requirements.

Currents and voltages in circles with distributed parameters are functions of two independent variables – time *t* and spatial coordinate *x*. Accordingly, the equations describing the processes in circles with distributed parameters can be represented as equations in partial derivatives:

$$\begin{aligned} \frac{\partial u}{\partial x} &= R_0 i + L_0 \frac{\partial i}{\partial t} = 0 \\ \frac{\partial i}{\partial x} &= G_0 u + C_0 \frac{\partial u}{\partial t} = 0 \end{aligned} \tag{8}$$

where R_0, L_0, G_0 ,C_0 – linear primary parameters, assigned per unit length.

Fragments of an electric circuit with concentrated parameters, described by ordinary differential equations, can in turn be multi-element circuits with a rather complex structure. Thus, the mathematical description of such a circle with dissimilar elements combines two groups of differential equations – in partial derivatives of type (8) and groups of ordinary differential equations.

When developing a mathematical model of transient electromagnetic processes, the reduction of a system of equations in partial derivatives to a system of differential equations in complete derivatives is usually used. In this approach, the line with distributed parameters is replaced by a circuit substitution circuit, the number of links which is determined by the required accuracy of the solution. As a result, a mathematical model is built in the form of a system of ordinary differential equations, which is then solved by any numerical or numerical-analytical method.

The difficulty in obtaining a mathematical model of a circle with dissimilar elements is that the fragments of the circle, described by different types of equations, are calculated separately - specific to each type of equation methods and then agree solutions for individual fragments of the circle. To solve the system of ordinary differential equations, one of the numerous or numerical-analytical methods is used. For the analysis of fragments of a circle with distributed parameters can be used or classical methods for calculating long lines, or one of the finite-difference methods for solving equations in partial derivatives. Traditionally used classical methods of studying electric circuits with distributed parameters are of two main classes: methods based on the wave representation of the solution (wave methods) and methods that do not take into account the wave nature of the processes in the line. Both of these approaches have their pros and cons. Thus, wave methods (for example, methods of characteristics, traveling waves) well represent the physical nature of the transition process, but do not allow considering it for a long time. Wave methods do not make it possible to present solutions in analytical form at a certain interval. Methods that do not take into account the wave character (for example, the method of standing waves), allow you to represent analytically or numerically-analytically the transition process in the line, without considering the propagation of waves. In addition, both approaches require significant simplification of the original data (for example, by replacing the real line without distortion with a line or a line without loss).

The problem of reconciling the calculations of sections of the electrical circuit with concentrated and distributed parameters can be solved in different ways. For example, the sequential transition from fragment to fragment of the circle in a step-by-step solution, or the organization of parallel calculations using the diacoptic approaches.

Coordinating solutions for heterogeneous sections of a circle is a rather difficult task, and does not always have a solution. When forming a model of a heterogeneous electric circuit, the same mathematical description of its elements must be used. The elements of an electric circuit, which are considered as multipoles, can be both lines with distributed parameters and sections of the circuit with concentrated elements. The relationship between the input $u(t)$ and the output $i(t)$ values of the multipoles in this case are integral operators, the transient conductivities of which $g(t\text{-}\tau)$ are completely determined by the internal properties of the system elements:

$$i(t) = \frac{d}{dt}\int_0^t g(t-\tau)u(\tau)d\tau \qquad (9)$$

In classical theory of electric circuits, this approach is applied to a circuit with concentrated parameters, which is known as the Duhamel integral method. The application of integro-differential equations (9) to the description of circuit elements allows obtaining a mathematical model in the form of a system of integral equations describing transients in circles containing both elements with concentrated and distributed parameters.

If the scheme of the section of the circuit is quite complex, then its transient conductivities can be determined through the transient conductivities of its individual parts. The intrinsic and mutual transient conductivities of a line with distributed parameters can be obtained through the transient conductivities of infinitely long lines. In this case, they are expressed through relatively simple and well-studied transcendental functions. The transient conductivities of the lines are carriers of information about the wave nature of the process, naturally reflecting the physical features of the transient process, inherent in the circles with distributed parameters.

The use of integral equations for the analysis of dynamic modes allows solving the problem of heterogeneity of the mathematical description of different elements included in the electric circuit, because in this case the elements with concentrated and distributed parameters are described equally.

There are a number of significant advantages to using a transition from a line with distributed parameters to circuit substitution circuits. Since elements with different properties are described uniformly, the proposed approach allows you to build a single numerical scheme for the analysis of objects containing segments of long lines and fragments of a circle with concentrated parameters.

Explicitly expressed circuits with distributed parameters are three-phase cable power lines. Many years of research at the Department of Theoretical Electrical Engineering of the National Technical University of Ukraine "Kyiv Polytechnic Institute named after Igor Sikorsky" (Kyiv, Ukraine), Institute of Electrodynamics of NAS of Ukraine (Kyiv, Ukraine) and "Yuzhcable" plant (Kharkov, Ukraine), showed that to make optimal decisions that ensure efficiency and high operational reliability of cable lines. For this purpose it is necessary to consider as much as possible the greatest number of factors (sometimes mutually exclusive to each other) which will allow to realize the maximum reliability, throughput and resource of such lines. [7,10,11,17,22,23].

However, the relatively high cost of modern cables with cross-linked polyethylene (SPE) insulation requires the selection of the optimal design of the cable line, as well as a systematic approach to these operating conditions, which must take into account all factors affecting efficiency, operational reliability and cases and environmental friendliness of the cable line. Since these factors are interdependent (sometimes with negative feedback), along with the optimal choice of cable design (adapted to a specific project) for rational design decisions, a certain compromise should be found between the individual factors.

During operation, the insulating design of cables with SPE insulation is exposed not only to the electric field of industrial frequency and high-frequency over voltages, but also the thermal field and electromechanical forces arising in the normal mode and overload modes.

The high demand for ultra-high voltage (UHV) cables has determined the relevance of scientific research to improve the design of UHV cables to meet the growing demands of consumers. The Ukrainian "Yuzhcable" plant has especially succeeded in mastering the industrial production of world-class UHV cables.

Improving and manufacturing cable power lines for different voltages (including ultra-high) requires solving a number of scientific problems, from which we can distinguish:

- increasing the safety and reliability of cable lines by determining the conditions that prevent the occurrence of unacceptable currents and voltages at a given level of transmitted power;

- determination of conditions for ensuring the required quality of transients in cable lines in the occurrence and disappearance of short-term allowable currents and voltages;

- analysis of features of long-extinguishing currents and voltages, in particular long and quasi-steady over voltages, the source of which is the electricity accumulated in the cable.

UHV cables are now increasingly used to strengthen the connection of local power systems with the unified European one. To increase the resilience of the UK power system in London and Nantorpe, two cable lines with a total length of 125 km, with a capacity of 1600 MVA for 400 kV.

In Berlin, Bewag has built a 380 kV overhead cable transmission line, the main purpose of which is to create a reliable external power supply system in the central part of the city, taking into account the future prospects for the development of urban cable networks. Another purpose of cable transmission is to strengthen the 380 kV connection of the Berlin area with the main network of power systems in Central Europe, as the constructed line is an element of this network.

The existing electricity grid in central Sydney is no longer able to cover loads with the required reliability. Therefore, the Haymarket substation (3 x 400 MBA 330/132 kV) and the 330 kV cable lines that supplies this substation were built and put into operation.

The parameters of the largest cable facilities built in recent years are shown in Table 1 [24, 25].

Improvements in design and manufacturing technology have made it possible to create more advanced cables of the traditional type and actively pursue new developments. So, now European manufacturers of cable products have developed, tested and created industrial samples of cable UHV record bandwidth voltage:

• up to 1000 kV, oil-filled, with a cross section of the conductive part of 2500 mm^2, having a capacity of 3 million kW;

• up to 550 kV with cross-linked polyethylene (XLPE) insulation with a cross-section of current-carrying parts of 2500 mm^2, having a capacity of 1.9 million kW.

Table 1

Country, Project name	Number of lines, voltage, type of cable insulation, cross section	Type of cable laying	Length, km (in single-phase calculation)
Denmark, Aarhus-Aalborg	2 x 400 kV, XLPE, 1 x 2000 mm^2	in the ground	84
USA, Sun Jose	2 x 230 kV, XLPE, 1 x 1267 mm^2	in the pipes	57
Great Britain, Nunthorpe	1 x 420 kV, XLPE, 1 x 2000 mm^2	in the ground	65
Great Britain, London	2 x 420 kV, XLPE, 1 x 2500 mm^2	in the pipes	60
Spain, Madrid	2 x 400 kV, XLPE, 1 x 2500 mm^2	in the pipes	72
Republic of Singapore	1 x 400 kV, XLPE, 1 x 2000 mm^2	in the ground	51
Germany, Berlin	2 x 400 kV, XLPE, 1 x 1600 mm^2	in a deep tunnel	75
Arab Emirates, Abu Dhabi	2 x 400 kV, XLPE, 1 x 800 mm^2	in a deep tunnel	16
Qatar	2 x 400 kV, XLPE, 1 x 1600 mm^2		141
Denmark, Copenhagen	1 x 420 kV, XLPE, 1 x 1600 mm^2		104
China, Guangzhou	1 x 500 kV, oil filled insulation, 800 mm^2, 1600 mm^2	tunnel, height difference 200 m	3 4

data generated from [24,25]

Ukraine has already created 330 kV ultra-high voltage cable transmission line [26], which ensures the continuity of electric steel production.

At the same time, the design of ultra-high voltage cable transmission lines requires a large amount of preliminary scientific and technical developments, electrical calculations, development of special technical solutions related to the route of the line, the construction of cable structures. It is also necessary to follow the electrical calculations by choosing the cross section of the conductors of the cable to ensure the required capacity of the cable, voltage losses in the cable, the allowance of long loads under heating cable in normal and emergency modes, grounding parameters, etc.

Cost-effectiveness, operational reliability and the actual service life of the cable with SPE insulation depend on the thermal mode of operation of cables, which is determined by the method of laying cables, the scheme of grounding screens, the presence or absence of transposition of screens.

Available publications on modeling and analysis of transients occurring in cable transmission lines do not fully describe the features of their occurrence. The obtained models are mainly designed to analyze only the current values of currents and voltages of steady state, which does not allow analyzing and studying transients at different commutations. In addition, most often the calculation of longitudinal and transverse asymmetry, is based on symmetrical components, where due to assumptions, many factors are not taken into account.

The task of calculating transients in three-phase cable transmission lines is complicated by the lack of available methods for its solution, taking into account the peculiarities of power switching. Currently, the solution, the task of calculating the transients in the CL should be carried out using software and hardware-software systems, such as Matlab / Simulink, PS-CAD, COMSOL Multiphysics and others. When modeling cable lines, simple substitution schemes are usually used, as the tasks of calculating transients require the adaptation of existing application packages. Most often, the task of modeling ultra-high voltage cable lines is to calculate the steady state to determine the voltage level and power losses.

In the domestic and foreign literature there are models of individual elements of cable lines, which are usually considered as cables in single or three-phase design without taking into account the mutual inductances and capacitances between conductors, which does not give accurate results and does not fully analyze the processes.

At the same time, the transient modes of the cable are due to load switching and emergency modes. The presence of mutual induction and capacitance between the wires of the phases leads to the complexity of the calculations, which leads to difficulties in the analytical description. Widely used in practice methods of calculating transients in cable transmission lines do not allow with sufficient accuracy to obtain the shape of the curves of current and voltage transients in complex types of switching and manifestations of nonlinearity.

Usually when calculating transients is either qualitative or quantitative analysis of process parameters, such as current values of currents and voltages, symmetrical components, harmonic components of current and voltage signals, and does not consider the whole picture of the transient process as a whole, taking into account the mutual influence of phases for one.

The study of electromagnetic transients in cable lines is devoted to works in which the solution of problems of ensuring the reliability of objects at the design stage is considered. The solution of such problems is associated with the study of transients in three-phase circuits with distributed parameters that occur during operational and emergency switching.

Switching overvoltage is a dangerous phenomenon that leads to equipment failure, danger to service personnel and economic losses. They have a gradual destructive effect on the cable insulation. The need to ensure high quality of the cable transmission line requires measures to limit switching over voltages.

The need to anticipate possible levels of switching over voltages is especially emphasized in the works, which emphasize the difficulties that arise when using the designed cable, up to the complete impossibility of ensuring its reliable operation. A large number of works is also devoted to the experimental study of switching over voltages in cable lines. There are many theoretical works in the calculations of which the experimental frequency characteristics of the system are used, which increases the accuracy, but does not allow studying the object at the stage of its design.

In the study and analysis of overvoltage curves, the task of determining the characteristics of the transient process (multiplicity, steepness of the front, frequency spectrum). As well as the geometric parameters of the designed line are particularly difficult [7, 11 17].

Thus, despite significant advances in theoretical and experimental studies, the scientific problem of calculating the transients of three-phase circuits with distributed parameters is especially relevant.

Such researches are more convenient to carry out on mathematical models of transients in three-phase electric circuits which further give the chance to integrate the received settlement models into packages of computer application programs, such as Matlab / Simulink.

Conclusions. Based on the analysis of known specialized publications, the need to improve the methods of analysis of steady-state and transient processes in three-phase power lines and their mathematical models is scientifically substantiated, based on the development of multipole theory in the direction of interphase interconnection in cable lines.

From the analysis of known methods for the study of electromagnetic transients in electric circuits with distributed parameters such as long cable lines, the most appropriate is the use of classical and operator methods and the theory of multipoles. The convenience of these methods lies in the possibility of automatic accounting of initial and boundary conditions. But when solving this class of a problem requires a mandatory record of the entire image, which leads to an increase in the amount of calculated data.

When modeling electrical circuits, which consist of a cable, containing disparate elements – with both concentrated and distributed parameters - there is a need to choose the form of the model, analysis methods adapted to the selected model, and build a numerical procedure for computer implementation of the method.

Using the theory of multipoles allows us to represent the elements of the electric circuit by macromodels that reflect their external connections and the impact on the rest of the circuit. The main difficulty in applying this principle is to resolve emerging electromagnetic bonds.

Despite significant advances in theoretical and experimental research, the calculation and analysis of transients in three-phase circuits with distributed and concentrated parameters remain relevant. Such studies are more conveniently carried out on mathematical models of transients in three-phase electrical circuits, represented by circuit substitution circuits, the links of which are modeled by multipole equivalents, which further makes it possible to adapt the obtained calculation models into computer application packages.

References:

[1] Schött-Szymczak, A., & Walczak, K. (2020). Analysis of Overvoltages Appearing in One-Sidedly Ungrounded MV Power Cable Screen. *Energies*, *13*(7), 1821.

[2] He, B., Zhou, Y., Li, H., Ye, T., Fan, S., & Wang, X. Fault Identification of High-voltage Cable Sheath Grounding System Based on Ground Current Analysis. In *2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2)* (pp. 3248-3251). IEEE.

[3] Kharlamov, V. V., Romanov, S. E., Shkarin, Y. P., & Merkulov, A. G. (2019, June). Characteristics of PLC Channels over High Voltage Power Cables and Mixed Cable-Overhead High Voltage Power Lines. In *2019 1st Global Power, Energy and Communication Conference (GPECOM)* (pp. 35-40). IEEE.

[4] Chi, Q., Pu, L., Sun, H., Duan, W., Hou, Z., Zhao, X., Deng, J. (2020, September). Research on the Characteristics of Transient Sheath Overvoltage in Underground Cable Lines. In *2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE)* (pp. 1-4). IEEE.

[5] Burlakov, E. S., Evdokunin, G. A., & Karpov, A. S. (2017, February). Transients and overvoltages in single-phase high-voltage cable lines. In *2017 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)* (pp. 260-264). IEEE.

[6] Shaban, M., Salam, M. A., Ang, S. P., & Voon, W. (2014). Calculation of sheath voltage of underground cables using various configurations.

[7] Lobodzinskiy, V., & Maślak, L. (2015, September). Mathematical modeling of the three-phase high-voltage cable lines under the theory of multiterminal networks. In *2015 16th International Conference on Computational Problems of Electrical Engineering (CPEE)* (pp. 96-98). IEEE.

[8] Ohno, T., Bak, C. L., Ametani, A., Wiechowski, W., & Sørensen, T. K. (2013). Statistical distribution of energization overvoltages of EHV cables. *IEEE transactions on power delivery*, *28*(3), 1423-1432.

[9] da Silva, F. F., Bak, C. L., & Holst, P. B. (2011, June). Switching restrikes in HVAC cable lines and hybrid HVAC cable/OHL lines. In *Proc. The International Conference on Power System Transients*.

[10] Shcherba, A. A., Podoltsev, A. D., & Kucheriava, I. M. (2013). Electromagnetic processes in 330 kV cable line with polyethylene insulation. *Teknichna Elektrodynamika*, *1*, 9-15.

[11] Chibelis, V., Lobodzinskyi, V., & Illina, O. (2016). Research on transposition efficiency of screens of three-phase cable lines with consideration of mutual phase disposition. *Computational problems of electrical engineering*, (6,№ 2), 63-66.

[12] MV, D. (2010). Zazemlenie ekranov odnofaznih silovih kabelei 6-500kV [Single-phase power cables 6-500kV screens grounding]. *Saint Petersburg, ZEU Publ*. (rus).

[13] Daud, M. Z. (2009). Transient behaviour modelling of underground high voltage cable systems.

[14] Wedepohl, L. M., & Wilcox, D. J. (1973, February). Transient analysis of underground power-transmission systems. System-model and wave-propagation characteristics. In *Proceedings of the institution of electrical engineers* (Vol. 120, No. 2, pp. 253-260).

[15] Naumkin, I. E., CHelaznov, A. A., SHkuropackij, D. A., CHubarov, L. B., & SHokin, YU. I. (1998). The general concept and principles of the implementation of an interactive graphical environment for calculating the parameters of complex power networks. [Obshchaya koncepciya i principy realizacii interaktivnoj graficheskoj sredy dlya rascheta parametrov slozhnyh energeticheskih setej] *Computing technology*, *3*(3). (rus).

[16] Lobodzinskyi V. (2020). Analysis of methods for calculating electric circuits with distributed parameters and interphase connections. *Science, research, development. Technics and technology*, (26), 5–7.

[17] Lobodzinskyi V.U. (2019) Transients in represented by multipoles three-phase circuits with distributed parameters and electromagnetic coupling (avtoref. dys. … kand. tekhn. nauk). National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute". Kyiv, Ukraine. (ukr)

[18] Irina, K., Roman, M., & Olga, M. (2018, October). The use of interactive methods and computer technologies for increasing the motivation for in-depth study and obtaining long-term knowledge in the course theoretical foundations of electrical engineering. In *2018 IV International Conference on Information Technologies in Engineering Education (Inforino)* (pp. 1-5).

[19] Kim, K. K. (2017). Theoretical foundations of electrical engineering.

[20] Poyasok, T., Bespartochna, O., Grytsiuk, O., & Sivyakova, G. (2017, November). On the expediency of introducing the "mathematics—theoretical foundations of electrical engineering" integrated course into the educational process. In *2017 International Conference on Modern Electrical and Energy Systems (MEES)* (pp. 332-335). IEEE.

[21] Zhokhova, M. P., Putilova, I. V., & Karpunina, M. V. (2021, March). Application of the distance learning technologies when mastering the discipline "Theoretical foundations of electrical engineering". In *2021 3rd International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE)* (pp. 1-4). IEEE.

[22] Chulieiev, V., Zolotarov, V., Chulieieva, O., & Pakharenko, V. (2014). Aging of polymer compositions based on polyvinyl chloride and complex calcium-zinc stabilizers: research results [Starinnia polimernykh kompozytsii na osnovi polivinilkhlorydu ta kompleksnykh kaltsii-tsynkovykh stabilizatoriv: rezultaty doslidzhennia]. *Standartyzatsiia. Sertyfikatsiia. Yakist,* (6), 47-51. (ukr).

[23] Shcherba A.A., Zolotarev V.M., Podoltsev A.D., Kucheriavaia Y.N. (2010) Principles of construction and development trends of fireproof cables [Principy postroeniya i tendencii razvitiya pozharobezopasnyh kabelej]. *Technical electrodynamics*, (2), 73–80. (rus).

[24] Fajbisovich D. L. Extra-high voltage cable lines. Foreign construction experience [Kabel'nye linii sverhvysokogo napryazheniya. Zarubezhnyj opit stroitel'stva]. (rus). Removed from: http://www.news.elteh.ru/arh/2004/25/12.php.

[25] Extra High Voltage Cable Lines in the Word. Removed from: https://www.tdworld.com/.

[26] Lyah V.V., Molchanov V.M., Sudakova I.V., Pavlichenko V.P. (2009) Cable line with voltage of 330 kV – a new stage in the development of electrical networks of Ukraine [Kabel'naya liniya napryazheniem 330 kV – novyj etap razvitiya elektricheskih setej Ukrainy]. *Electrical networks and systems*, (3), 16–21. (rus).