KAUNAS UNIVERSITY OF TECHNOLOGY

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RESEARCH OF SINGLE PHASE EARTH FAULT IDENTIFICATION IN POWER DISTRIBUTION NETWORKS

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Linas Markevičius

INTRODUCTION

The process and quality control of electric energy power transmission and distribution has mainly concentrated on the energy transmission network where the energy trade process is performed and where modern control and supervision systems based on the latest technologies are being employed.

When environment protection became a subject of great importance, electric energy production from such renewable energy resources as wind, sun, biomass, etc. came to be foreground.

Electric energy consumers are also encouraged to change their old practices, i.e. to reduce energy consumption. Thus the unavoidable change of priorities is taking place in the electricity industry – which is the transition from big capacity power plants with extensive power transmission networks towards power generation from renewable sources in energy distribution networks.

The distribution network modeling and control in comparison with the transmission network is a fairly different and, in most cases, a more complicated subject as it is necessary to take into consideration the large amount of energy producers.

The part of the energy transmitted through the distribution network has been gradually increasing and in the future the distribution network is bound to evolve into small energy islands connected to one distribution network, or it may operate like a community of minute separate distribution networks.

The variability of distribution networks, the alternative pricing policies, the reduction of energy distribution costs, the optimization of reliability and operating expenses, the balancing of demand and supply as well as many other factors – have been posing new challenges for the distribution network control and imposing requirements to implement work-oriented modern technologies for network reorganization and maintenance.

The distribution network management system (DMS) has to simulate not a static or balanced distribution network operation in real time (such as a control system in the transmission network) but rather a radial non-harmonic network with changes of topology and variations of demand and supply simultaneously facing the issues of not synchronized recorded data.

DMS must also be able to evaluate such aspects of the technical distribution network as the variety of conductors, transformers, remotely controlled disconnectors as well as their influence on the network configuration as well as the impact of other temporarily or constantly connected devices used for operational work in order to provide electricity to individual consumers.

The modern DMS must help to reduce losses in the distribution network by optimizing the sorting-out of losses according to their specific features.

One of the main full-scale DMS functions is the detection of damaged parts within the distribution network, the identification of any faults and the energy supply restoration. The FLISR function includes the function of fault detection in the distribution network based on the analysis of remotely collected data. The relevant requirements include obtaining alternatives to the available network topology on the basis of preset and predefined priorities, load distribution opportunities, common consumers, etc. thus enacting the system to function as a self-healing entity with the automatic distribution network reconfiguration.

Even with the implementation of the latest state-of-the-art algorithms and modern expert systems, one of most complicated FLISR objectives is the identification of single phase earth faults in electric distribution networks.

Specific and volatile distribution network and load parameters, cases of determined short circuit fault parameters or selectivity and uncertainty of remote control functionality lead to false single phase earth fault identification.

Due to the necessity of obtaining a large amount of initial parameters, their measured values and data accuracy, time synchronization of different recordings or time-consuming measures of data processing, not a single one of single phase earth fault identification methods described in various publications and proceedings [1] - [6] has become widely used in practice. Simplification of the distribution network equivalent scheme by dissociating the impact of the external network structure influence and the high sampling frequency of electromagnetic transients helps to eliminate the issue of non-linearity and to optimize various network parameters thus opening opportunities to identify a single phase earth fault in the electrical distribution network.

Objective of the work

By using electromagnetic transient modeling technology for recorded processes with a high sampling frequency to simplify the equivalent diagram of a power distribution network and to create models allowing to adapt and optimize the parameters of the constituent parts of a power supply network exerting influence on the reliability of fast identification of the single phase earth fault location and allowing to identify the location of the single phase earth fault in the power distribution network.

Tasks of the work

1. To perform analysis of the fundamental methods and techniques for single phase earth fault identification in power distribution networks.

2. To perform the analysis of the fast electromagnetic transients parameters of the initial moment model caused by a fault in a single overhead line phase.
3. To create a simplified model of fast electromagnetic transients caused by the earth fault in complicated power overhead lines.
4. To create a model of single phase earth fault points in a power distribution network.
5. To create model structures of fast electromagnetic transients caused by a single phase earth fault in a power distribution network which could be applicable when solving the task of the identification of the single phase earth fault location.

Methodology of the work

Analysis of the single-phase earth faults in medium voltage power distribution networks with the insulated or compensated neutral and the evaluation of the parameters of electromagnetic transient processes and the research of parameters of propagation of electromagnetic waves caused by faults.

Scientific novelty of the work

The present thesis developed analysis techniques of the initial moment of electromagnetic transient caused by a single-phase fault (connection with an earthed object) thus enabling the creation of the primary electromagnetic transient analysis methodology on the grounds of which it is possible to quickly and accurately determine the location of the fault in the power line within a complex power distribution network.

Practical value of the work

Application of the initial transient's moment analysis methodology allows to evaluate the transient processes caused by the fault in the power distribution network more accurately; it also allows to quickly and accurately determine the line within the power distribution network where the fault has occurred and to identify the location of the single-phase earth fault in the power distribution network.

Identification models for the establishment of the location of the single phase earth fault place within the distribution networks have been presented. They make up a part of the technique which may be used as a practical fault location method for distribution systems. This technique serves as a basis of a software algorithm of experimental earth fault place identification devices installed in the Lithuanian power distribution network. Quick and well-timed single phase earth fault identification increases the reliability of the power distribution network and reduces the costs of the network service and maintenance. On the basis of electromagnetic transients identification method presented in this dissertation the invention has been patented [14], [15].

Defensive propositions of the dissertation

1. The initial moment model parameters of the fast electromagnetic transient caused by a fault in one of the power overhead line phases tend to reflect more quickly or more slowly fading processes. The modeling of their characteristics allows for calculations in order to optimize the line surge parameters and to estimate the influence of non-linear parameters of electrical network.
2. Modeling of the initial moment of fast electromagnetic processes allows:
   - to create a simplified model for the complicatedly structured overhead lines of the power distribution network,
   - to establish the location within the power distribution network line node model where the single-phase earth fault occurred.
3. On the basis of the analysis of characteristics of the initial moment of fast electromagnetic transients caused by the failure in the single phase of a power distribution network line, model structures can be created thus allowing to estimate the parameters of a faulty line and, specifically, the parameters of the fault point. This allows to find the urgent solutions when determining the distance to the fault location.

Approval of the work

7 scientific papers have been published on the basis of the material of this dissertation. The subject of the dissertation has been discussed in 6 scientific journals listed in International databases, while 1 publication has been posted in the Institute for Scientific Information database “ISI Web of Science”. The material of the dissertation has been presented in 5 scientific conferences. Three publications have been presented in scientific international conference proceedings. One invention has an international patent certificate.

Structure of the dissertation

The dissertation consists of an introduction, 3 chapters, conclusions, a list of references and an appendix. The text of the dissertation covers 98 pages including 59 figures and 10 tables. The list of references contains 87 items.

1. WORK METHODOLOGY. RESEARCH OF THE MODEL OF FAST ELECTROMAGNETIC TRANSIENTS FOR EARTH FAULT IDENTIFICATION

One phase short circuit connection to the grounded objects (i.e. the earth fault) of a medium voltage line takes place when the earthing through the poles circuit elements or branches of trees growing in the neighborhood due to electric discharge: in case of a lightning discharge, when the lightning overvoltage exceeds the residual electrical withstand value, or in the case of a branch touch when the line's phase voltage moment level reaches the amplitude value. These cases are excellent illustrations of earth fault accidents.

The initial voltage level change during incidental emergency earth faults in power distribution networks creates an intense transient process. The analysis of this transient process allows us to identify the earth fault location and to establish the authentication of certain specific parameters of the network. For the analysis, it is highly useful to search for specific resistance underneath the power line ground, the capacitances of electric equipment connected to the line, or even consider the network configuration.

Identification technologies in one or another way use the comparison of the measured electric parameters with estimation models or containing mathematical expressions involved in models. If a model represents processes in the power network which are as close as possible to the reality, the earth fault identification results are better and more precise. Therefore, it is crucially important to to define these processes as adequately as possible.

The initial processes are represented by slowly or fast damping components. The quantity of components engaged in the evaluation largely influence the quality of reiteration. The model of fast electromagnetic transients is of the type where fast damping components are reflected.

The modeling of fast processes features certain advantages: it is more informative than the modeling of partially or completely damped transients components, it is less sensitive to the nonlinear parameters of the power network and is generally more favorable for the modeling of the linearity characteristics.

1.1. Research of model parameters of fast electromagnetic processes in overhead power lines.

In the main and side diagonals of overhead line parameters (both structural and electrical), the matrix values of elements are unequal. Therefore, the widely used symmetrical [7] or Clarke [8] component methods in the modeling of transients or stationary processes in their formed sequences may reduce the identification accuracy.

Deep ground electric flux underneath the power line may even further reduce the accuracy if conventional methods of process transformation to sequences are employed. Because of the deep ground electric flux, the matrix of inductive specific parameters became dissimilar to the capacitive parameter matrix, and the electromagnetic waves propagating on the surface are supplemented by the field emanating in the transverse direction [9].

Therefore, fast processes are appropriate for transformation to the sequences that are adopted to the typical type of lines used in the network. In specific cases highly particularized or unique transformations and line equations may be required for certain power lines.

In transients analysis, the electric flux in the soil changes its depth and shape depending on the rapidity of decline of various frequency components of the field. In the model it responds to the change of the line's wave parameters. The approximation model suitable for the fast processes in the line are necessary to reach a certain estimation of these parameters.

In order to set up an earth fault identification model, studies of 10 and 20 kV power networks were performed. Power networks of indicated voltages are the most problematic as they are ramified and in most cases they are with the compensated neutral. The identification of earth faults by using voltage and current measurements of stationary processes is virtually impossible.

For the modeling of fast electromagnetic processes in the time domain, D'Amaber's equations are used [10]. If considering these processes just by modeling the surface waves and excluding the electromagnetic field's dissipation phenomenon in the line wires and in soil (symmetrical and Clarke sequences), the equations will be as follows:

$$\begin{cases} U + wI = 2U^{+} \\ U - wI = 2U^{-} \end{cases}; \tag{1}$$

where U^{+} and U^{-} represent the values of vector-matrices columns of the reached and reflected voltage waves in sequences, U and I are sequence vectors of voltages and currents flowing to the wave's reflection point, *w* shows the sequence surge impedance diagonal matrix.

Equations (1) in Clarke's coordinates $\nu \in (\alpha\, \beta\, 0)$ in the linear transformation process produce the following modal matrix [11]:

$$T_c = \begin{pmatrix} 1 & 0 & 1 \\ -0,5 & \frac{\sqrt{3}}{2} & 1 \\ -0,5 & -\frac{\sqrt{3}}{2} & 1 \end{pmatrix}; \tag{2}$$

So, for example, the voltage and current phase value matrices are related to the sequence matrixes by expression:

$$\begin{cases} U_{\mathrm{f}} = T_c U \\ I_{\mathrm{f}} = T_c I \end{cases}; \qquad (3)$$

where U_f ir I_f are the voltage and current phase value matrices.

The square matrix of line impedances to the impedance diagonal matrix in Clarke's coordinates is associated by dependence:

$$w_f = T_c w T_c^{-1}. \qquad (4)$$

Finding the wave equations (1) by Clarke's transformation method is acceptable for slow process analysis when the investigation of electromechanic transients covers non-symmetrical short circuit faults or overvoltages in the power network, when the accuracy of the evaluation results is not that important. The identification of registered processes in the network requires a higher accuracy and adequacy in order to obtain the undistorted image of electromagnetic processes.

The direct application of matrix (2) for high voltage lines gives unacceptably big deviations because of two reasons:

- in reliance (4) $\mathbf{w}$ matrix is non-diagonal for the overhead line; therefore, when applying this transformation, one assumption is made – that in $\mathbf{w}$ matrix, all the elements except for the main diagonal are of zero value;
- because of the limited specific conductivity of the ground soil, power line wires and the cable sheath in dependencies (3), the modal matrices for voltages and currents are different, and the values of their elements depend on the process frequencies.

The duration of variable parameters in identification of fast processes covers only tens of microseconds; accordingly for the precise modeling frequency band the value of tens of kilohertz is exceeded.

In the above mentioned frequency band, the modal matrix dependence on the frequency is lower.

The structure of wire placing in overhead power lines in most specific cases geometrically is similar; the matrices of specific electric line parameters are also similar (modal matrixes are actually equal). These two circumstances provide an opportunity to detect line equations for fast processes. This is a better and more precise match for the real life processes.

Wave parameters are conformed by conductivities and surge impedances. Specific parameters for telegraph equations relate voltages and currents in line conductors. Values of surge impedances and conductivities increase when the current frequency increases as well; therefore, it is appropriate that the telegraph equations are presented in a complex environment for a fixed frequency (ω):

$$\begin{cases} -\dfrac{\mathrm{d}}{\mathrm{d}x}U_\mathrm{f} = Z_\mathrm{f} I_\mathrm{f} \\ -\dfrac{\mathrm{d}}{\mathrm{d}x}I_\mathrm{f} = Y_\mathrm{f} U_\mathrm{f} \end{cases}; \tag{5}$$

where U_f and I_f denote complex values of vector-matrix columns of line phase voltages and the current in $\boldsymbol{x}$ coordinate, Z_f and Y_f are square matrices of line surge impedances and conductivities in $\boldsymbol{x}$ coordinate.

Line specific conductivities are described by line transversal capacitances. Even if the frequency value is close to the fundamental frequency, these capacitances do not depend on the frequency change, and for the fast process modeling in the high frequency range it is useful to make an assumption that line conductivities are fully described by geometric parameters of line wires:

$$Y_\mathrm{f} = j2\pi\varepsilon\omega N^{-1}; \tag{6}$$

where ε represents the air dielectric constant, $\varepsilon = \frac{1}{36\pi 10^9}, \frac{F}{m}$.

$$N = (N_{ik});$$

$$\begin{cases} N_{ik} = \ln\dfrac{D_{ik}}{d_{ik}} \\ N_{ii} = \ln\dfrac{2h_i}{r_i} \end{cases} \tag{7}$$

where r_i is the phase ***i***- wire radius, h_i and d_{ik} stands for the ***i***-wire’s height above the earth surface and the distance between *i* -wire and *k*-wire.

$$D_{ik} = \sqrt{d_{ik}^2 + 4h_i h_k}.$$

Because of magnetic fluxes in the air, wires and the ground soil, surge impedances Z_f are described by specific inductances [12]:

$$\begin{cases} Z_f = \mathrm{j}\omega\dfrac{\mu}{2\pi} N_L \\ N_L = N + M + F \end{cases} \tag{8}$$

where μ denotes the air magnetic permeability constant;

$$\mu \approx 4\pi 10^{-7}, \frac{H}{m}.$$

M is the diagonal matrix of factors that are formed by magnetic fluxes in power line wires; *F* is the square matrix of factors formed by magnetic fluxes in the soil.

As a result of the process frequency growth, values of matrix factors due to the skin effect gradually decrease; therefore the values of elements of matrix N_L approach the values of the elements of matrix *N*.

In order to locate closest pole to the earth fault place, the most accurate measurements and the most adequate modeling in the high frequency range above 100 kHz is required.

Processes in the lower frequency ranges are less informative; therefore, they require less accuracy for analysis.

In such circumstances it is favorable that in higher frequency N_L matrix elements are less dependent on the frequency. Such conditional matrix invariance from the frequency permits the researcher to make unifications and simplifications and to receive a more accurate model structure. Table 1.1 shows how matrix norm N_L alters with the change of frequency to different ground resistivity levels for different types of power lines.

The following table shows that when frequency increases 100 times from 100 Hz, the matrix norms change by about 40% and in cases when in the high frequency range the frequency increases 100 times from 0.1 MHz, matrix norms change by about 12-20%.

Table 1.1. N_L matrix norm dependence on the process frequency.

Line category	Ground specific conductivity, Ωm	Process frequency					
		0.1	1.0	10	0.1	1.0	10
		kHz			MHz		
10 kV line with wire positions in isosceles pyramid shape	100	25.58	21.64	18.32	15.83	14.42	13.87
	300	27.15	23.19	19.71	16.85	14.95	14.06
	1000	28.89	24.93	21.35	18.21	15.79	14.41
	3000	30.49	26.54	22.90	19.60	16.82	14.93
20 kV line with portal type towers	100	25.03	21.09	17.80	15.36	14.02	13.51
	300	26.60	22.63	19.17	16.36	14.51	13.68
	1000	28.34	24.37	20.80	17.69	15.32	14.01
	3000	29.94	25.97	22.34	19.06	16.32	14.50

In Table 1.1, data is presented for the typical distances between poles and the line wire positions on the poles (figures 1.2 – 1.4) by using the Euclidean norm calculation method:

$$norma = \sqrt{\sum_{\forall i,k} |N_L\,(i,k)|^2}. \quad (9)$$

It is known that some matrices with different elements possess the same modal matrix, such matrixes are considered to be similar, and if the modal matrices of such different element matrices at the level of structure and element values are similar, then these matrixes are close to similarity. Their extent of closeness can be found by using the matrix difference norm. The model of electromagnetic processes can be improved when having relatively close matrices of power network parameters. This may be achieved with more accurate modeling results, and the common analysis algorithm can be simplified.

For example, if a network consists of only three core cables, then for the matrices of lines, capacitances can be found for a modal matrix similar to

Clarke's matrix (2). The matrix of cable capacitances is relatively close to the matrix with a specific structure:

$$A = \begin{pmatrix} a & b & b \\ b & a & b \\ b & b & a \end{pmatrix}, \text{ and}$$

$$T_c A\, T_c^{-1} = \begin{pmatrix} a-b & 0 & 0 \\ 0 & a-b & 0 \\ 0 & 0 & a+2b \end{pmatrix}.$$

An attempt to diagonalize $N_L$matrix of 20 kV lines with horizontally positioned wires when the frequency $f=$ 1 MHz and the ground surge impedance $\rho = 100$ Ωm gives the following result:

$$T_c N_L\, T_c^{-1} =$$
$$= \begin{pmatrix} 5.9437 - j0.0159 & 0.3980 - j0.0007 & -0.2298 - j0.0004 \\ 0.3980 - j0.0007 & 5.4841 - j0.0151 & 0.3980 - j0.0007 \\ 0.1149 + j0.0002 & 0.1990 - j0.0003 & 13.9952 - j0.6032 \end{pmatrix}.$$

The closeness of the result to the diagonal matrix can be evaluated on the grounds of the percentage error,

$$\Delta = 100\ \frac{|T_c N_L\, T_c^{-1} - \ diag(T_c N_L\, T_c^{-1})|}{|diag(T_c N_L\, T_c^{-1})|}, \%. \tag{10}$$

For the presented sample when using the expression above, an error of 4,69 % is given, which can be considered as a fairly large error for earth fault identification in power distribution network with long lines.

What concerns modeling processes in the time domain, processes are considered as multifrequency; therefore it would be easier to perform diagonalization of the propagation constants matrix Γ by using the modal matrix found at one basic frequency f_0 and by employing the matrix part of real figures.

It is appropriate to have a model, which – with acceptable accuracy – can simulate processes in a wide range of frequencies. Analysis shows that in identification tasks concerning overhead line networks it is optimal to use the basic frequency of $f_0 = 23$ kHz.

For diagonalization, not only accuracy but also ground soil resistivity is important. Figure 1.1. shows the error curve of diagonalization. This curve was received by changing the ground soil resistivity at frequency $f = 23$ kHz and by performing the diagonalization of a modal matrix of the basic frequency with real figures $\widetilde{T_u} = real\ (T_u)$, or $\widetilde{T_i} = real\ (T_i)$.

From Figure 1.1. it is seen, that in the resistivity range to 3000 Ωm (this corresponds to the real life conditions), the biggest error gives high resistivity close to 3000 Ωm. Therefore, the diagonalization of propagation constants matrix calculations when using modal matrices $\widetilde{T_u}$ or $\widetilde{T_\iota}$ is done for the specific ground resistivity of 3000 Ωm

Table 1.2 shows errors of diagonalization of propagation constants with adopted $\widetilde{T_u}$ or $\widetilde{T_\iota}$, matrices and Clarke's matrix T_c for various wire positions in power lines.

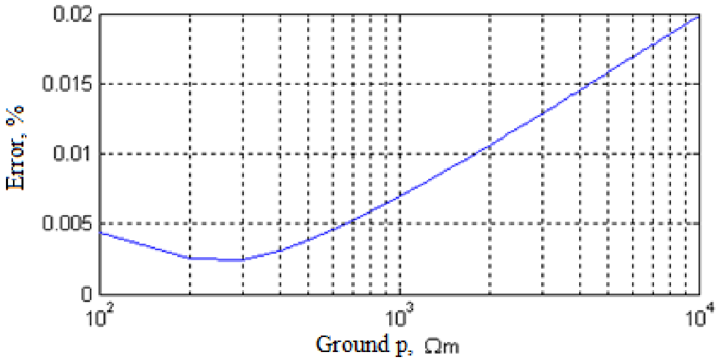


Fig 1.1. Errors of diagonalization of the dependence of propagation constants on the ground resistivity.

Errors of propagation constants matrix diagonalization when using $\widetilde{T_u}$ or $\widetilde{T_\iota}$ modal matrices do not exceed the 2% value in the low frequency range. Errors in the high frequency range are the most informative for the fast process modeling: 0.1 – 10 MHz do not exceed 0.2%.

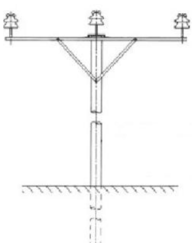


Fig. 1.2. Parallel interpolation of wires to the earth surface

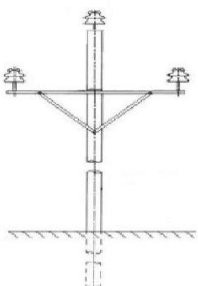


Fig. 1.3. Pyramid interpolation of wires

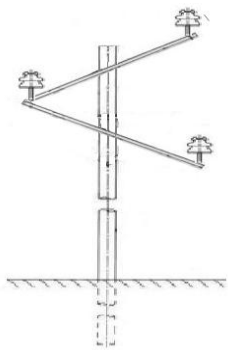


Fig 1.4. Delta interpolation of wires

Table 1.2. shows errors in using Clarke modal matrix, and even if the values are bigger, they are also acceptable for modeling. However, it is still necessary to define if the model simplification method when using the conventional matrix diagonalization will be acceptable for finding surge impedances.

Table 1.2. The percentage of propagation constants diagonalization errors

Modal matrix	**Line wires interpolation**	**Process frequency**					
		0.1	**1.0**	**10**	**0.1**	**1.0**	**10**
		kHz			**MHz**		
$\widetilde{T_u}$ and $\widetilde{T_i}$ at **23** kHz	Parallel (fig 1.2.)	1.2565	0.2204	0.0530	0.0206	0.0176	0.0104
	Pyramid (fig. 1.3.)	0.3773	0.0686	0.0392	0.0628	0.0913	0.0731
	Delta (fig. 1.4.)	0.6683	0.1591	0.0928	0.1446	0.2068	0.1640
T_c	Parallel (fig. 1.2.)	3.1054	1.4910	1.1366	0.8269	0.5111	0.2458
	Pyramid (fig. 1.3.)	0.5758	0.5262	0.4880	0.4280	0.3277	0.1907
	Delta (fig. 1.4.)	0.6238	0.4898	0.4541	0.4031	0.3131	0.1841

The diagonal matrix of surge impedances may be expressed in the following way:

$$w = \sqrt{\frac{\mu}{\varepsilon}\,(T_u^{-1}\,real\,((N_L\,+\,N)N^{-1})T_u)^{-0,5}\,T_u^{-1}real\,(N_L\,+\,N)\,T_i}. \qquad (11)$$

1.2. Fast overhead line process model structure

Wave equations (1) do not reflect the propagation of electromagnetic waves along the line dissipation and dispersion aspects. With the change of the frequency of harmonic processes, propagation constants and surge impedances alter as well. Due to the frequency increase, absolute values of propagation constants and surge impedances decrease. Such multi-harmonic influence formed during the initial transients process stage shall be reflected in the power lines model structure.

1.2.1 Analysis of surge impedance changeability

For a complicated configuration, the model structure of a multi-sectored power distribution network is acceptable for simplicity purposes as being the closest to the wave equations (1) where the prorogation of electromagnetic waves is simulated by delay functions. This condition is also acceptable because the main part of the waves in the line are damped surface waves which can be expressed by equations (1) while taking into consideration the wave damping correction factor.

In order to determine the influence of the imaginary part diagonalized matrix of surge impedances to the current and voltage distribution in the wires, the change of surge impedances in terms of the absolute values is investigated.

Errors are assessed by their expression on the basis of disparity of non-diagonal elements in the absolute values matrix derived by (11) and by the matrix produced on the grounds of modal matrices $\widetilde{T_u}$ and $\widetilde{T_\iota}$.

Furthermore, the present disparity is transformed to phase coordinates thus giving a better view of the impact to the phase parameters.

Error calculation can be performed by employing the following expression:

$$\Delta_1 = 100\,\frac{\left|\tilde{T}_i^{-1}\left[\!\left[abs\left(w - diag\,(w)\right) - \left(\widetilde{w} - diag\,(\widetilde{w})\right)\right]\!\right]\tilde{T}_u^{-1}\right|}{\left|\tilde{T}_i^{-1}\,abs(w)\widetilde{T_u}\right|}, \qquad (12)$$

Calculation results for the cases specified in Table 1.2 are presented in Table 1.3.

As the calculation results show, using adequate modal matrices $\widetilde{T_u}$ and $\widetilde{T_\iota}$,
errors stemming from the disregard of the imaginary part of matrix elements in the surge impedance matrix merely reach hundredths of per cent across the wide frequency range from 100 Hz up to 10 MHz.

In Figure 1.5, the curves of diagonalized surge impedance dependences on the frequency are shown; they were produced by using the adequate modal matrix found at the basic frequency value of 23 kHz. It shows the character of the alteration of power line surge impedances in all three sequences for the wire interpolations: specifically, pyramid in curve 1 and parallel as curve 2.

In Figure 1.5, the stability of surge impedances of the first two sequences can be seen across the frequency range equaling or exceeding the value of 10 kHz.

Table 1.3. Percentage error values due to disparity of non-diagonal elements

Modal matrix	Line wires interpolation	Process frequency					
		0.1	1.0	10	0.1	1.0	10
		kHz			MHz		
$\widetilde{T_u}$ and $\widetilde{T_i}$ at **23** kHz	Parallel (Fig. 1.2.)	0.0274	0.0476	0.0035	0.0124	0.0114	0.0062
	Pyramid (Fig 1.3)	0.1147	0.0536	0.0108	0.0409	0.0700	0.0515
	Delta (Fig 1.4)	0.1274	0.0654	0.0212	0.0484	0.0791	0.0593
T_c	Parallel (Fig 1.2)	2.6641	2.7205	2.9248	3.1538	3.3880	3.5739
	Pyramid (Fig 1.3)	0.4440	0.4680	0.4971	0.5417	0.6139	0.7059
	Delta (Fig 1.4)	0.5424	0.5801	0.6203	0.6743	0.7494	0.8381

This case shows the advantage of the fast process analysis as the surge impedance correction in terms of the time dimension is unnecessary. Alteration of the surge impedance third sequence is of uniform character; therefore, it facilitates approximation based on a single standardized curve.

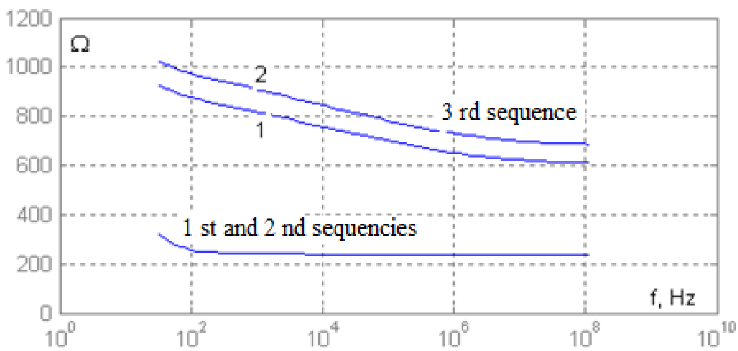


Fig .1.5. The real part of sequence surge impedance dependency on the frequency: the 1st and the 3rd curves represent line wire interpolation in the pyramid while the 2nd curve shows the third sequence, specifically, the line wire interpolation going parallelly above the ground.

1.2.2 Analysis of the changeability of electromagnetic waves propagation characteristics

Electromagnetic waves propagating along the lines lose a part of their energy and change their parameters. High frequency process components reach the line's end with a smaller amplitude thus lowering their frequency. Such uneven damp depends on the line constructive parameters and on ground soil electrotechnical conductivity features. Analysis of dispersion characteristics can be useful in order to discover more convenient methods for model adaptation.

In spite of frequency being linked to good shielding properties of the ground and wire surfaces to the electric fields, the ratios of wire potential and comparative charges are expressed by potential energy coefficients in matrix [13] with minimal errors:

$$A = (\alpha_{ik}); \tag{13}$$

where $\alpha_{ik} = \frac{1}{2\pi\varepsilon} N_{ik}$;

Therefore the matrix of comparative conductivities of capacitances (6) obtains the expression:

$$Y_f = j2\pi\varepsilon\omega N^{-1};$$

$$N = (N_{ik});.$$

The relation of the magnetic field created by the flowing currents in the wires and ground soil to the currents in the wires is expressed as a matrix of inductances:

$$L = (L_{ik}); \tag{14}$$

where $L_{ik} = \frac{\mu}{2\pi} (N_{ik} + M_{ik} + F_{ik})$, $M_{ik} = 0$, kai $i = k$.

The matrix of comparative impedances (8) has the expression:

$$Z_f = \mathrm{j}\,\omega \frac{\mu}{2\pi} (N + M + F).$$

Matrix component part $M = diag(M_{ik})$ characterizing the internal magnetic flux of the wires for each wire (i.e. for the main diagonal component of the matrix) can be expressed as:

$$M_{ii} = \frac{k\rho J_o(kr_i)}{j\omega\mu r_i J_1(kr_i)}; \tag{15}$$

where J_o and J_1 represent Bessel zero first rate and primary functions, ρ is the wire's metal-specific resistivity, Ωm, μ represent the air magnetic permeability whereas k stands for the electromagnetic waves wavelet number inside the wire:

$$k = \omega\sqrt{\mu_i\left(\varepsilon_i - j\frac{1}{\omega\rho}\right)}; \tag{16}$$

where ε_i and μ_i are the wire's metal dielectric constant and its magnetic permeability.

Impedance $F = (F_{ik})$ is a component part defining the internal magnetic flux in the ground soil. It is expressed as:

$$F_{ik} = \frac{\pi}{2x_1}\left(H_1(x_1) - Y_1(x_1)\right) - \frac{1}{x_1^2} + \frac{\pi}{2x_2}\left(H_1(x_2) - Y_1(x_2)\right) - \frac{1}{x_2^2}; \tag{17}$$

where H_1 are Y_1 the primary functions of Struve and Neumann

$$\begin{cases} x_1 = [(h_i + h_k) + j(b_i + b_k)]\sqrt{-k_g^2 + k_0^2} \\ x_2 = [(h_i + h_k) - j(b_i + b_k)]\sqrt{-k_g^2 + k_0^2} \end{cases};$$

h_i and h_k: - i- and k-wire height above the ground surface,
b_i and b_k: - i- and k-wire horizontal coordinates,
k_g and k_0:- ground soil and air wavelet numbers;

Influence of the wire internal impedance and the ground soil impedance component in the comparative impedance are largely significant. Figure 1.6. shows the typical relationship between all three impedance components (impedance modules): curve 1 stems from N, curve 2 is caused by from F while curve 3 is derived on the grounds of M.

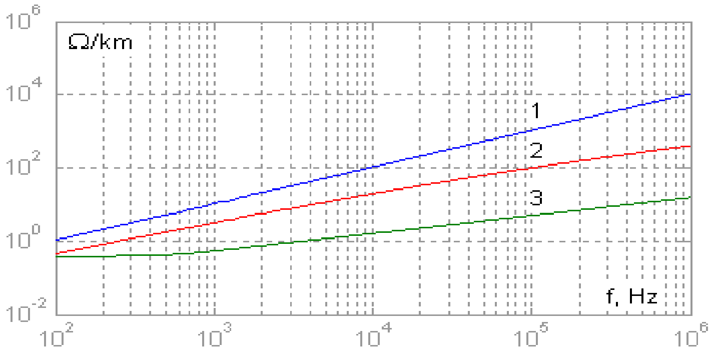


Fig 1.6. Time impedances

Figure 1.6. illustrates the character of the 3rd sequence exhibiting the highest surge impedance value. In the case of equal phase parameters, in a perfectly completely transponse line, the 3rd sequence in symmetrical or Clarke's coordinates would be the ordinary zero sequence.

Alteration of the electric field voltage during electromagnetic wave propagation in sequences, is characterized by the vector of frequency response functions:

$$G = \exp\,\{-l\,(\mathrm{diag}(T_u^{-1} N_L N^{-1} T_u - V)\varepsilon\mu)^{0,5}\}; \tag{18}$$

where l is the length of the line, m, V are represented as a matrix of ones; $V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$.

Figures 1.7. shows 5 km-long lonely wires above the ground and their G frequency response function graphs (amplitude AmpG and imaginary ImG). According to the amplitude-frequency characteristic, above 100 kHz the electromagnetic wave in the channel "ground – wire" damps more that 50% of the voltage level. In this computational model, the value of the soil-specific resistivity was taken as $\rho = 100$ Ωm. In the cases of higher soil-specific resistivity, dissipation damping of electromagnetic waves is only slightly more intensive, while in the case of tenfold resistivity increase, the amplitude-frequency characteristic at 100 kHz decreases by about 20%.

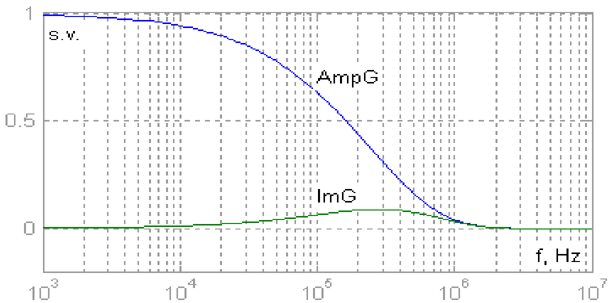


Fig. 1.7. Frequency response function graphs

Wires in the gaps between poles are parabolic banded; therefore, with the change of wires above the ground level, the wavelet parameters and wave damping intensity of the 3rd, channel "ground-wire" sequence are also changed.

First of all, the modeling of parameters with a consideration of the wire height ***h*** in the range from **0.3** ***h*** to ***h*** showed that modal matrices are essentially invariant to the height, and this is important for identification purposes.

Wavelet parameters of the 1st and 2nd sequences (i.e., the channel between the wires) remain essentially unchanged while the surge impedance for the 3rd sequence (channel-to-ground) is unstable. Therefore the regularities of this parameter must be analyzed in order to find out the equivalent and stable height along the whole line at which the researched current and voltage processes of this model would be adequate for the purpose of identification.

Table 1.3. Dependency of the surge impedance 3rd sequence (channel-to-earth) to the ground soil-specific resistance and the height above the ground surface.

Ground soil resistance, Ωm	**Height of wires h/h_{max}**					
	0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**
100	585	595	603	610	616	622
300	595	605	613	620	626	631
1000	605	614	622	629	635	640
3000	615	624	632	639	645	650

In Figure 1.8., three-dimensional space surge impedance (channel-to-earth) dependency from the ground soil specific resistance and the wire height above the ground surface is shown. The surge impedance reaches the minimum value at the smallest soil resistivity and when line wires are the most prominently bent.

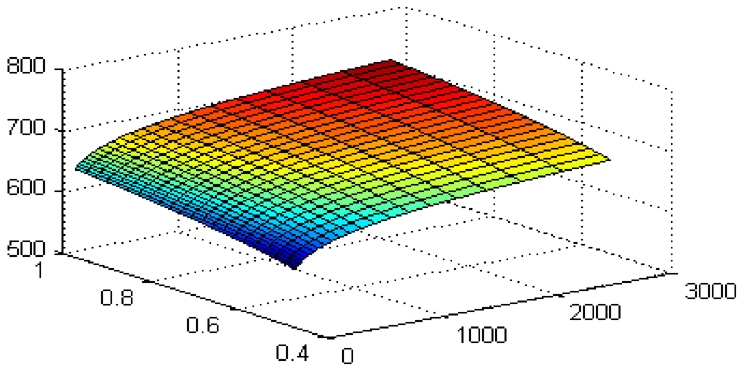


Fig 1.8. Wire 1st sequence surge impedances

The optimal equivalent height of a wire may be derived by researching the reflected electromagnetic waves in the lines with bent wires and detecting the line where the wires are at a constant height and the waves most closely correspond to the ones found in the line with the bent wires.

A simulation was performed for a lonely wire line by using equations (1).

The lines in which the wires in the gaps between the poles get bent according to the regular parabola was divided into equal sections; the heights in the sections correspond to the parabola's average ordinate value while in the section merger places, wave break and reflection coefficients were calculated.

The break coefficient is calculated as follows:

$$\alpha = \frac{2w_2}{w_1 + w_2}. \quad (19)$$

The reflection coefficient is produced by the formula below:

$$\beta = \frac{w_2 - w_1}{w_1 + w_2};$$

where w_1 and w_2 are sections of surge impedances to and from which the wave reaches the breaking point in the section merger location.

The optimal height was sought by changing (here, increasing) the number of sections. The optimal height of the wire (Fig. 1.9) was produced on the basis of the formula:

$$h_{opt} = h_{max} - \frac{2}{3}(h_{max} - h_{min}); \quad (20)$$

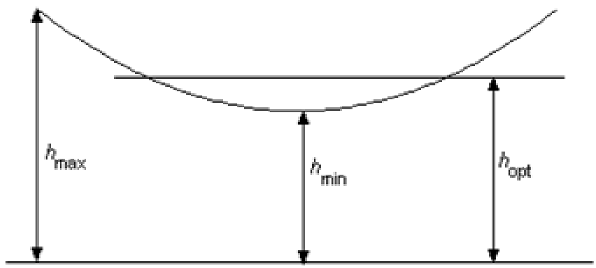


Fig 1.9. Detection of the equivalent height

Variations in the height also affect the frequency characteristic; however, this change is relatively insignificant. Figure 1.10 shows the amplitude-frequency characteristics in the channel "ground-wire" for h_{max} and $h_{opt} = h_{max} - 0,3\,\frac{2}{3}\,h_{max}$ cases assuming the wire banding of 0,3 h_{max}.

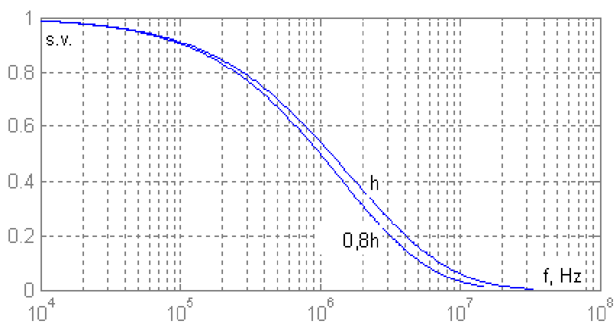


Fig 1.10. Amplitude-frequency characteristics

During the propagation of an electromagnetic wave, the height of the wire may vary within h_{opt} value; therefore, the resultant amplitude-frequency characteristic is close to its optimal value.

1.2.3 Power line model equations

For the power line model equations, various factors have to be taken into account: multichannel electromagnetic wave structure with their specific modal matrix, wave propagation and their change in time, the value of the impedance variable in the transient channel to the ground characteristic, boundary conditions at the line ends, etc.

A model, reflects the power line processes in the time domain simulate the propagation of electromagnetic waves with the time delay functions for every channel (see sequences $s\{1,2,3\}$). The discredit process is performed on the grounds of presumptions discrediting step Δt corresponding to the section through which the electromagnetic waves passed:

$$\Delta x = \Delta t\sqrt{\mu\varepsilon}. \quad (21)$$

It is considered that the speed of electromagnetic waves in the channels is the same:

$$\mathcal{V} = \frac{1}{\sqrt{\mu\varepsilon}}.$$

The processes of energy dissipation in the line channels are reflected by transient characteristics stemming from the real part of frequency characteristics ((18) by employing the digital conversion to the time domain technology.

The propagating current wave in every sequence in the model algorithm is performed by the following function:

$$J^{-} = \frac{2u}{w_{\min}} - J_{\mathrm{rez}}; \quad (22)$$

where w_{min} stands for the surge impedance minimum value, u denotes thevoltage of the node from which the reflected electromagnetic wave propagates to the line side, J_{rez} marks the delay function, received from the function of the line end reflection delay (22) in convolution with the transient characteristic and surge impedance alteration correction:

$$J_{\mathrm{rez}} = f_G * J\left(t - \frac{l}{\Delta x}\Delta t\right) - f_w * i; \quad (23)$$

where $\boldsymbol{i}$ is the current flowing to the node, $J\left(t - \frac{l}{\Delta x} \Delta t\right)$ denotes the delay function found at a specific time moment $t - \frac{l}{\Delta x} \Delta t$; formula (22), it is only based on the line's other end values; l indicates the length of the line.

Binomial function convolution expression (23) for each moment in time is replaced by distinction:

$$J_{rez} = F_{1n} - F_{2n};$$

where $F_{1n}$and F_{2n} are results of digital convolution procedures for *t* time moment:

$$\begin{cases} F_{1n} = \sum_{j=2}^{n} (F_j - F_{j-1}) J_{n-j}\,, \\ F_{2n} = \sum_{j=2}^{n} (F_{W,j} - F_{W,j-1}) i_{n-j}\,; \end{cases} \qquad (24)$$

$F_{G,j}$ and $F_{W,j}$ are transient function values at $\boldsymbol{j}$ discredit step of the electromagnetic wave and surge impedance alteration; J_{n-j} and i_{n-j} stand for the delay function and the current $n - j$ discredit step.

The accuracy of digital convolutions performed by the digital filtering methodology (25) depends on the size of the discredit step and on the sum of n polynomial members in matrix rows. Digital filtering yields the positive result when the number of rows in a matrix is equal or higher than $n \geq \frac{2l}{\Delta x}$; . The required accuracy is thus achieved by reducing the size of the discredit steps. When a line in its end is connected to ***N*** lines of a similar type (lines with the same modal matrix), then the voltage is calculated as follows:

$$u = \frac{\sum_{\mathrm{k}=1}^{\mathrm{N}} J_{rez\,k}}{\sum_{\mathrm{k}=1}^{\mathrm{N}} \frac{1}{W_{\min k}}}. \qquad (25)$$

and the current flowing to the node is described as:

$$i = J_{rez} - \frac{u}{W_{min}}. \qquad (26)$$

For illustration purposes, Figures 1.11 and 1.12 show the transient alteration curves of the voltage waves reaching the beginning of the power line.

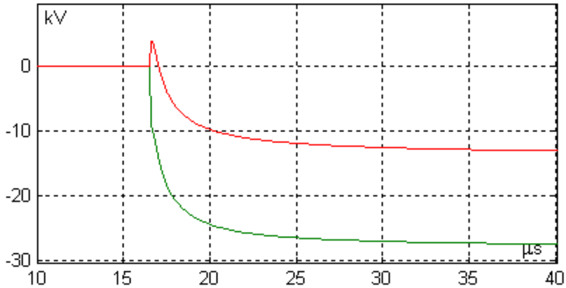


Fig 1.11. Transient alteration curves of voltage waves which reached the beginning of a power line.

These waves are formed by the short connection in phase *a* at a distance of 5 km from the beginning of the power line. Below in the figures, the voltage waves in the faulty phase are shown while above they are represented in the healthy phase.

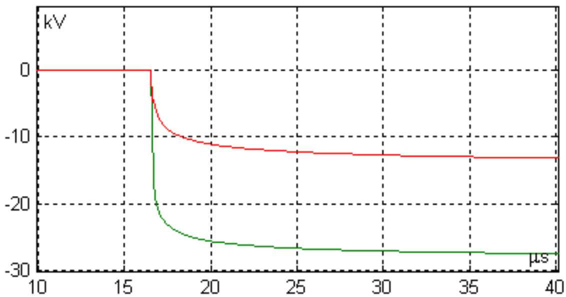


Fig 1.12. Curves of traveling voltage waves reaching the beginning of the line

In Figure 1.12, the curves were produced by using Clarke's modal matrix of entirely symmetrical parameters just before the matrix of inductances and capacitances transformed into the matrix of equal parameters in the phases. For that purpose, parameter average values were found separately for the parameters in the main diagonals and for the parameters in other diagonals. As it is evident, the complete unification of parameters performed with the intent to enable the use of traditional diagonalization methods essentially yield a changed image of the initial process. Simplification of a complicated power network structure, and the calculation of average values for phase parameters change voltages and the character of currents vibrations was performed. Therefore, in order to obtain clear identification of ongoing processes, it is recommended to use line pole type-corresponding matrixes.

1.3 Summary of chapter 1 analysis

1. A specific way was developed to find the modal matrix for fast processes identification in the power distribution network overhead lines. The basic frequency of 23 kHz is defined as optimal for finding these matrices.
2. Analysis of parameters matrix diagonalization errors for different construction type lines, and for 100 – 3000 Ωm ground soil resistivity range, shows that at the basic frequency of 23 kHz, errors of diagonalization of propagation constants are aggregated because of the remaining non-zero non-diagonal elements which do not exceed 0.2% in the whole frequency range of fast processes spanning from 10 kHz to 10 MHz.
3. The errors of diagonalization of propagation constant get aggregated because of the remaining non-zero non-diagonal elements and disregarding the imaginary part in the matrix figures reaching up to 1% in the whole fast process frequency range from 10 kHz to 10 MHz
4. The analysis of line surge impedances shows that surge impedances take place in wavelet channels between wires changing the ground soil's resistivity. They remain almost unchanged, and in practical calculations it is appropriate to refer to them with constant values.
5. Surge impedances for the channel-to-ground convolution to time domain allowed to find the linear dependence on time in the argument's logarithmic scale.
6. The impedances of the impact of an individual line surge on the line's model parameters were discovered. The minimum and non-essential (about 1000 times weaker) influence features the ground soil impedance component between the phase channels in comparison to other components, and the simulation of results in between the phase channels is less dependent on the ground soil resistivity.

7. The equivalent height of a wire for the line model was discovered, and assuming the constant value for the height above the ground surface, this discovery allows to simplify the model.
8. Equations in the wavelet processes in power lines were formed so that to assess electromagnetic waves alternation processes over time and to consider the dependence of the line sequence surge impedances on the process frequency thus forming the basis for fast process simulation and earth fault identification in the power distribution network.

2. ANALYSIS RESULTS. FAST EARTH FAULT IDENTIFICATION MODELS IN EXTENSIVE POWER DISTRIBUTION NETWORKS

A power distribution network is typically denoted by the radial type configuration. Quite frequently, the outgoing overhead lines are connected to the substation busbars via cable insertions.

Generally, the network consists of lines with different modal matrices. This condition requires a specific consolidation method for line equations.

Processes in the line are also affected by the power supply system as well as by other lines connected to the same switchgear busbars. In order to reduce their influence on the fault identification, it is necessary to apply a specific analysis algorithm.

The fast processes simulation technology permits to make simplification of the network diagram lets us use linear features for the process describing equations (i.e., proportion and superposition principles) thus letting us adopt and optimize the parameters of diagram elements.

2.1. Fast process model of the lines within a complicated network

The voltage finding expression (25) cannot be used for the connection point of line sections if lines have different modal matrices, for example, this happens in the case of an overhead line being connected in the node with a cable line. In such a case, node voltages are appropriate to be expressed in any conventional type coordinates. The modal matrix which is the closest in terms of configuration to the distribution network lines and which serves the objective to diagonalyze matrices in the same parameters phases (for example, cables), is:

$$T_f = \begin{pmatrix} -\frac{1}{2} & -1 & 1 \\ 1 & 0 & 1 \\ -\frac{1}{2} & 1 & 1 \end{pmatrix}. \quad (27)$$

For example, for parallel or pyramid wires interpolation cases, the modal matrix for the matrix of specific conductivities and surge impedances can take the following form:

$$T_f = \begin{pmatrix} t_1 & -1 & t_2 \\ 1 & 0 & 1 \\ t_1 & 1 & t_2 \end{pmatrix}. \quad (28)$$

Coefficient values t_1 and t_2 in this matrix are determined by only one coefficient. For example, in the impedance matrix:

$$Z_f = \begin{pmatrix} Z_S & Z_M & Z_N \\ Z_M & Z_D & Z_M \\ Z_N & Z_M & Z_S \end{pmatrix}; \quad (29)$$

The coefficient values are defined by factor:

$$k = \frac{Z_S + Z_N - Z_D}{Z_W}; \quad (30)$$

Then, coefficients t_1 and t_2 are calculated:

$$\begin{cases} t_1 = \dfrac{k - \sqrt{k^2 + 8}}{4} \\ t_2 = \dfrac{k + \sqrt{k^2 + 8}}{4} \end{cases} \quad (31)$$

However, the main advantage of the matrix of the canonical form (27) is the clear and balanced nature of the physical power lines of the electrical field channel. The inverse matrix for (27) acquires the form:

$$T_f^{-1} = \begin{pmatrix} -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{pmatrix}. \quad (32)$$

The first row of this matrix forms the 1st channel (r) between the line middle phase and the other two remaining phases while the 2nd row represents channel (s) between the first and the third phases and the 3rd row stands for the traditional zero sequence channel to the ground (o) for all the three phases

The canonical form (28) for matrix $\dddot{T}$ presented in the general manner can be obtained on the grounds of the following expressions:

$$\begin{cases} T_f = \dfrac{\dddot{T}}{\dddot{T}_{13}}, \\ \text{for all}: \; T_{i1} = \dfrac{\dddot{T}_{\iota 1}}{\dddot{T}_{21}}, T_{i2} = -\dfrac{\dddot{T}_{\iota 2}}{\dddot{T}_{12}}, \; T_{i3} = \dfrac{\dddot{T}_{\iota 3}}{\dddot{T}_{23}}; \end{cases} \tag{33}$$

where $\dddot{T}_{\iota k} \in \boldsymbol{\dddot{T}}$; and $T_{ik} = \boldsymbol{T_f}$.

Line voltages and currents can be transformed to canonized coordinates ($v = r, s, o$) by employing the following matrix:

$$\begin{cases} T_U = T_f \widetilde{T_u^{-1}} \\ T_I = T_f \widetilde{T_\iota^{-1}} \end{cases}; \tag{34}$$

The constant part of the surge impedance matrix from (22) can be transformed with the matrix triad:

$$W = T_U \,\text{diag}(w_{min}) T_I^{-1}. \tag{35}$$

As an illustration, žTable 2.1. presents (34) matrices for various wire interpolations in the power lines. The obtained matrices are close to a matrix of ones but with minor 6% voltage and current redistribution in individual sequences.

Table 2.1. Transformation matrices for transforming currents and voltages to canonical coordinates

Matrix type	**Wire interpolation in the lines**		
	Parallel (fig 1.2)	**Pyramid (fig 1.3)**	**Delta (fig 1.4)**
T_I	$\begin{pmatrix} 0{,}94 & -0{,}06 & -0{,}06 \\ 0 & 1 & 0 \\ -0{,}06 & -0{,}06 & 0{,}94 \end{pmatrix}$	$\begin{pmatrix} 0{,}97 & -0{,}04 & -0{,}03 \\ 0 & 1 & 0 \\ -0{,}03 & -0{,}04 & 0{,}97 \end{pmatrix}$	$\begin{pmatrix} 0{,}99 & -0{,}02 & -0{,}03 \\ 0{,}01 & 1 & -0{,}02 \\ 0{,}02 & 0{,}04 & 1{,}02 \end{pmatrix}$
T_U	$\begin{pmatrix} 1{,}03 & -0{,}06 & 0{,}03 \\ 0 & 1 & 0 \\ 0{,}03 & -0{,}06 & 1{,}03 \end{pmatrix}$	$\begin{pmatrix} 1{,}01 & -0{,}04 & 0{,}01 \\ 0 & 1 & 0 \\ 0{,}01 & -0{,}04 & 1{,}01 \end{pmatrix}$	$\begin{pmatrix} 1{,}00 & -0{,}02 & -0{,}01 \\ 0{,}03 & 1 & -0{,}03 \\ 0{,}02 & 0{,}02 & 0{,}97 \end{pmatrix}$

In a complicated network consisting of different wire interpolation types, expression (25) acquires the form of the following matrix:

$$U_E = (\sum_{k=1}^{N} T_{I\,k}\, J_{rez\,k})\, W_Z \;; \qquad (36)$$

where W_Z is the aggregate node surge impedance matrix,
U_E represents the node without load (no capacitive elements or without earth fault current sources),

$$W_Z = \left(\sum_{k=1}^{N} W_k^{-1}\right)^{-1} \;;$$

Expression (22) gets the form of the matrix:

$$J_k^- = 2\, diag\left(\frac{1}{w_{\min k}}\right) T_U^{-1} U - J_{rez\,k}; \qquad (37)$$

The balanced (21, 23, 24, 27-37) expressions and components convert complicated and branched line models into fast processes.

In order to simulate the current and voltage procession, a line model must be supplemented by models of structures connected to the nodes and by the earth fault source initiating these processes.

When a line from one type of wire interpolation switches to another (i.e., wire transposition is performed), it is useful for add the additional node to the transposition location point so that to maintain the algorithm integrity , where voltages could acquire canonical ($v = r, s, o$) coordinates.

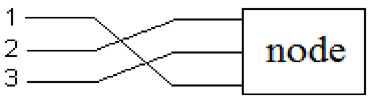
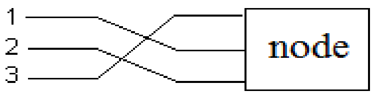
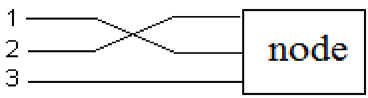
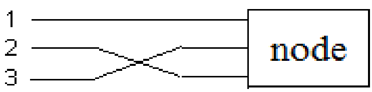
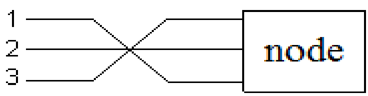
2.2. Transpositions in the line model

In order to keep the algorithm in integrity to the transposition location point in an equivalent scheme it is appropriate to provide an additional node. Then at one line's end, at the transposition point, expression (34) structures change:

$$\begin{cases} T_U = T_f T_{TR} \widetilde{T_u^{-1}} \\ T_I = T_f T_{TR} \widetilde{T_i^{-1}} \end{cases}; \quad (38)$$

where T_{TR} matrix determines the transposition type (table 2.2).

Table 2.2. Transposition type referring matrix

Transposition type	**Corresponding matrix**
	$T_{TR}= \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$
	$T_{TR}= \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$
	$T_{TR}= \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$
	$T_{TR}= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$
	$T_{TR}= \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$

2.3. Capacitive node model

The impact of inductive elements on the fast process model is relatively minor. At the initial moment during the fast process changes in transformers, the windings are negligible and cannot affect the common process picture. However, the incoming capacitances of switchgear busbars, transformers and apparatuses influence the picture of this common process. In the general case, capacitances can form the equivalent scheme node capacitances matrix with which a system of differential equations is associated:

$$T_f^{-1} C_f T_f \frac{d}{dt} U + W_{\Sigma}^{-1} U = U_E. \tag{39}$$

After every digital step, the solution, i.e. vector U_1 (assuming that during interval Δt, vector U_E is a constant ($U_E = const$)) can be expressed as:

$$U_1 = AU_0 + BU_R; \tag{40}$$

where U_0 represents the value of the voltage vector at a time moment $t - \Delta t$; $A = \exp(-\Delta t \cdot T_f^{-1} \cdot C_f^{-1} \cdot T_f \cdot W_{\Sigma}^{-1})$, $B = V - A$, V is a matrix of ones, $V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$.

The accuracy of solutions (40) depends on vector U_E alteration within the discreditation time period; therefore, the required accuracy can be achieved by minimizing the discreditation step. Figure 2.1. shows how the internal capacitance of a 10 kV transformer connected at the line's end softens the fronts in ($\nu = r, s, o$) sequences. Incoming capacitances are at the level of 1 nF.

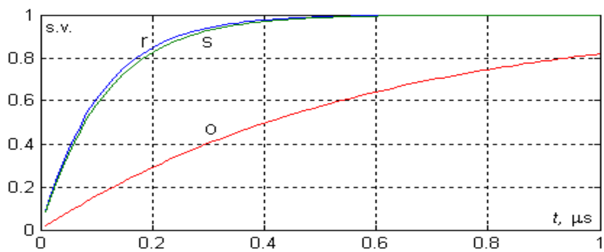


Fig 2.1 Voltage fronts in ($v = r, s, o$) sequences of a 10 kV transformer stemming from a single pulse wave's form.

2.4. Single phase earth fault's node model

During the fast processes, the forced component of fundamental frequency remains practically unchanged; hence, in identification devices it is appropriate to filter this frequency out.

The transient part remains; it depends on the moment voltage values of normal operation at the moment of the earth fault and on the resistivity of the earthing point.

At the point of a single phase earth fault (pole fittings, a tree branch, etc.), voltages in canonized coordinates ($v = r, s, o$) are simulated by matrix expression;

$$U = T_f \cdot \left(T_f^{-1} + \frac{W_\Sigma \cdot (T_f^{-1} \cdot K) \cdot K^T}{R} \right)^{-1} \cdot \left(U_E + \frac{W_\Sigma \cdot (T_f^{-1} \cdot K) \cdot (U_N^T \cdot K)}{R} \right); \quad (41)$$

where U_N stands for the vector-column of phase voltage moment under normal operation conditions (voltages before the moment of earth fault), R represents the resistivity of the earthing point; K denotes the vector defining the faulty phase:

$K = (k_i)_{3x1}$;; $k_i =$ 1, when i-phase is faulty, otherwise k_i = 0.

Figure 2.2. illustrates the dependence of the initial voltages on the earthing point R resistivity when the earth fault happens in 10 kV line's 1st side wire. The line wire interpolation is in the "pyramid" shape.

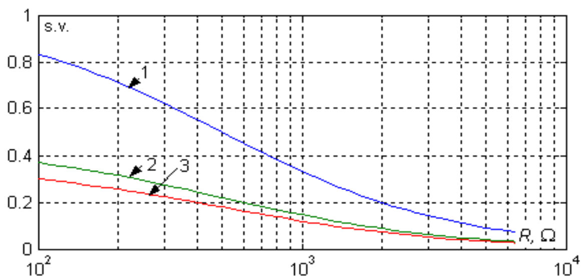


Fig. 2.2 Initial voltages in line phases just after the 1st side wire's earthing through R resistance; curves 2 and 3 represent the initial voltages in the remaining phases.

As shown in Figure 2.2., in other wires (the 2nd in the middle, and the 3rd on the opposite side), voltages are induced electrostatically. Due to the difference of parameters, voltages are unequal.

2.5. Summary of Chapter 2 analysis

1. A fast process identification model for the development of the single earth fault electromagnetic process in a distribution network has been developed.
2. The most acceptable form of transformation to canonical matrices, the coordinates of the distribution network's currents and voltages and simplified algebraic formulae of their detection have been produced.
3. In order to maintain the integrity of the process model algorithm for the places of the transposition within a line, a modal matrix recalculation method has been created.
4. For the impact of equivalent scheme capacitances to the model, an approved proximity digital filter has been formed.
5. A single phase earth fault node's model has been derived thus assessing the resistivity of the point of the earth fault point.

3. ANALYSIS RESULTS. STRUCTURES OF FAST PROCESS SIMULATION MODELS FOR PRACTICAL IDENTIFICATION OF EARTH FAULT LOCATION

Recordings of electric parameters of fast electromagnetic transients can be used for the identification of characteristics of various faults: earth fault in the line, earth fault point location, estimation of the distance to the earth fault, estimation of the earth fault resistivity, ground soil specific conductivity, etc. Different goals of identification inherently require different mathematic models and structures.

The automatic network control system must quickly respond to fault events; therefore, the electronic devices performing the function of protection and control must perform digital fault identification models within a very short period. This can be achieved by coordinating the productivity of control devices denoted by the efficiency of digital simulation.

3.1. Earth fault identification and influence of differences of line electromagnetic parameters in phases

For earth line identification, the connection of a part of the distribution network system to the earth is usually used, i.e. when the power transformer's neutral is artificially connected to the earth via a resistor for a short period of time. However, the resistor's connection and disconnection operations prolong the earth fault identification time and generate undesirable switching over voltages in the network.

In comparison with the stationary regimes, the initial part of the fast electromagnetic transient caused by earth faults is distinct, and it features visible voltage and current amplitudes. Usually, earth fault currents are cut by compensation coils; earth fault identification from the evaluation of stationary process parameters leads to inaccurate and frequently erroneous results.

Earth fault in the line can be identified by the estimating current zero sequence direction and the polarity of the voltage at the beginning of the power line: when one phase connects to the earth and the voltage has a positive polarity, the current at the initial earth fault moment flows to the line, and vice versa, if the earthing point has the negative polarity voltage.

The illustration in Fig 3.1. shows the curves of typical recordings: 1) – 2) transient alterations in phase voltages, 3) – 6) currents in incoming phases and zero sequence in faulty and non-faulty lines. The component of 50 Hz frequency is filtered out. The voltage of faulty phase A at the moment of the fault had a negative polarity. Therefore, the negative voltage alteration reached the busbars of phase A. Such voltage alteration initiates the current flow towards busbars in the zero sequence channel. In non-faulty lines, the direction of the zero sequence current has the opposite direction (6).

Directions of the difference allow to exactly detect the faulty power line: at the initial fault moment, the zero sequence current flows from the line when the alteration of zero sequence voltage is positive while it flows the other way and the current flows to the line when the alteration of zero sequence voltage is negative.

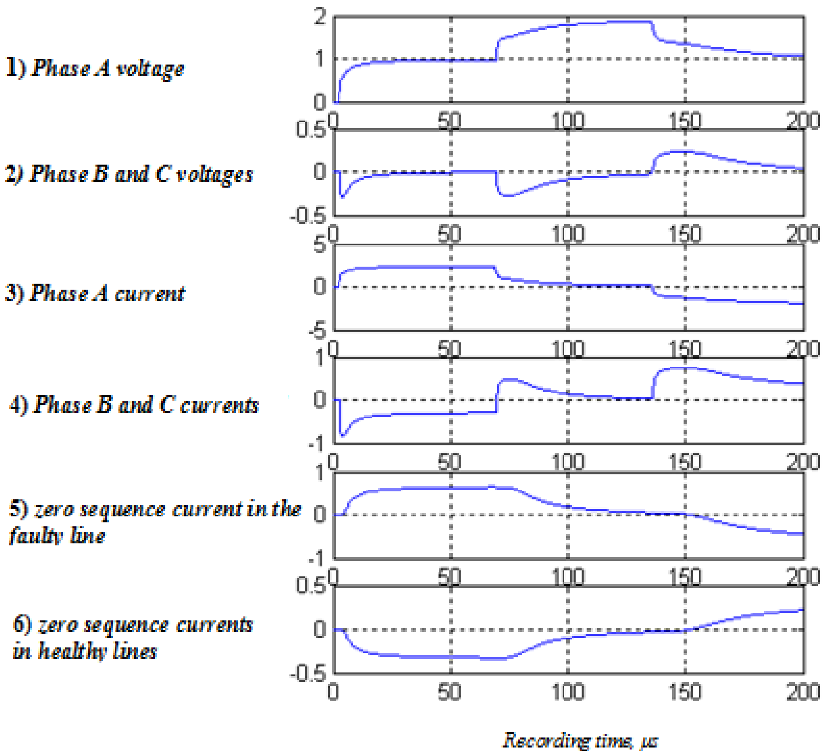


Fig 3.1. Recording results of the initial process after the earthing moment in the line:

1 – 2 – voltages in the power supply busbars; 3 – 5 – currents in the faulty line; 6 – zero sequence voltages in healthy lines. Recordings are presented in relative values.

The analysis of measurements and recordings of transient processes in an operating distribution network led to the observation that the current at the beginning of the line at the initial moment may have the opposite direction (Fig. 3.2.). Recordings of the current in phase A and recordings of the transformer's zero sequence indicates that during the time interval between t_0 and t_1 currents have opposite directions. Transient simulations showed that short-term direction alteration of the zero sequence current is only possible in the case of disparity of electromagnetic parameters in phases.

The size of interval t_1- t_0 mainly depends on the ground resistivity and on the distance to the fault. If the distance to the fault is larger and the resistivity is higher, then the time interval is bigger as well. In Fig 3.2., recordings were made at the ground resistivity of 320 Ωm while the distance from busbars to the earth fault place was 600 meters.

The earth fault identification device must compare the binary relation of discrete marks of the voltage and current zero sequences, i.e. either to comply or fail to do it. Therefore, the recording of the above mentioned binary pairs must be delayed by an interval of the t_1- t_0 size value. In order to define this interval value, it is necessary to perform transient process simulations at different levels of ground resistivity. The identification accuracy depends on the properly recorded quantities of voltage and current pairs.

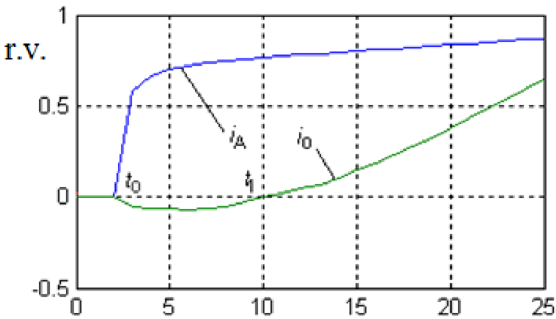


Fig 3.2. Current (i_A) in phase A and in zero sequence (i_0) at the initial moment of electromagnetic transients caused by an earth fault in phase A. The earth fault location is 600 meters away from the switchgear.

The reliability of the earth fault identification depends on the ratio of positive and negative records of binary pairs:

$$reliability = \frac{n^+}{n^+ + n^-} \tag{42}$$

or

$$reliability = \frac{t^+}{t}; \tag{43}$$

where $n^+$and n^-represent the quantity of positive and negative binary pairs, $t^+$and t stand for the duration of recordings during which positive binary pairs were detected and for the whole recording time.

Major influence on the correct identification is exerted by the recording quality during the initial moment. The factual recording showed that various interferences have direct influence on voltage measuring circuits. Thus it is highly sensible to postpone the recording start time as much as possible. For example, a delay of up to 30 μs offers 40 ns of the recording frequency and allows to receive about n^+ = 1000 positive records thus achieving a good identification result.

3.2. Possibilities of the investigation of distance to the detectable fault

In order to locate the place of the earth fault, the identification device must concentrate and focus its "look" on the earth fault's environment. Fault currents are weak and various previously suggested identification methods do not yield satisfactory results.

Recording and analysis of fast processes allow us to locate the fault place even in compensated distribution network configurations. The electromagnetic wave reaches the busbars with the speed of light but the electromagnetic wave is denoted by zero sequence channel "delays". Fig 3.3. shows the front part of the wave in zero sequence. Due to the energy dissipation during the initial moment, the front part acquires the inclined shape. The tangent of the curve by crossing the abscise coordinate line yields the delay parameter .

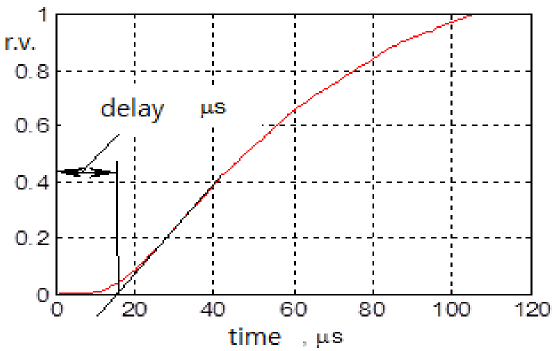


Fig 3.3. The delay parameter of the zero sequence electromagnetic wave.

The delay parameter is dependent on the length of the traveling electromagnetic wave, ground resistivity and on the interpolation type of the wires the in power distribution line . Having estimated the ground resistivity value and the wire interpolation type, it is already possible to find out the distance the traveling wave had already passed. There are also some positive circumstances:

- The primary energy of electromagnetic transients has the highest value; therefore, the initial part of the voltage and current recordings is the most prominently expressed;
- The front part of the wave gets shaped in the parameter linear medium; and is not affected by various network nonlinear parameters,
- The wave in line branch places decreases all the parameters equally and proportionally to the wave reflection coefficient with no impact on the delay parameter.

Figure 3.4 shows the dependency of the delay parameter on the ground resistivity and denotes the distance which the zero sequence wave along the 15 kV power distribution line. The average height of the wire is 11 meters.

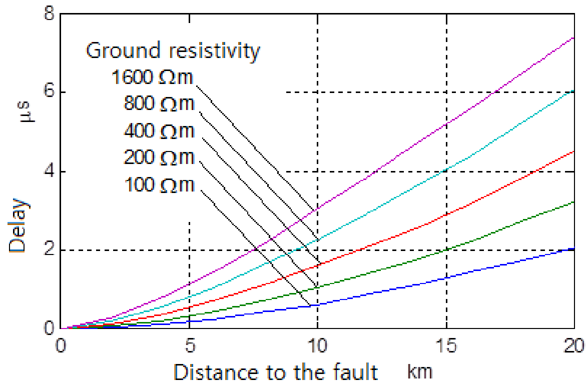


Fig 3.4. Dependency of zero sequence electromagnetic wave delay parameters on the ground resistivity and the passed distance when a wave travels along the 15 km line.

3.3. Identification structure of earth faults in distribution networks

In order to eliminate the influence of the switchgear, non-faulty lines and the electricity supplying external network on the earth fault identification result, it is appropriate to simulate electromagnetic transients with the wave reflected from the busbars. In the time domain, these values are sourced from the recorded data of currents and voltages at the beginning of the outgoing line:

$$U^{-}(t) = u(t) - w \cdot i(t); \qquad (44)$$

where $u(t)$ and $i(t)$ are zero sequence time function values of currents and voltages at the beginning of the outgoing line; w is the beginning of the line zero sequence surge impedance.

Possible various earth fault location zones are simulated starting from the discovered fault point and analyzing the reflection of zero sequence waves reaching the switchgear busbars.. Wave time functions were established and compared with the traveling wave received from registrations:

$$U^{+}(t) = u(t) + w \cdot i(t). \tag{45}$$

The best correlation results are the most probable earth fault location according to the model.

The described technology is installed in devices in different power distribution network places. The software structure is oriented towards the earth fault line identification, the detection of the possible earth fault zones, the establishment of the most probable earth fault places and the tracing the average ground specific resistivity.

3.3 Summary of chapter 3 analysis

1. Line single earth fault identification method was discovered; the reliability of the estimated possible identification was established.
2. The homogeneity cause of the initial process was identified in and the homogeneity elimination principle was defined.
3. The zero sequence traveling wave delay parameter concept was introduced. It enabled us to stipulate the identification of the close earth fault location.
4. Clauses concerning the distance to the detected location of an earth fault were formulated.
5. The zero sequence traveling wave dependability on the essential factors: traveling distance, ground specific resistivity and the height of the power line wires was estimated.
6. Statistic simulations of processes after the earth fault allowed to estimate the zero sequence traveling wave delay parameters dispersion limits, and to discover the possible earth fault zone.
7. Single phase earth fault location algorithm was developed; it was utilized specifically for the earth fault identification; devices were developed and designated for power distribution utilities.

CONCLUSIONS

1. The conducted study covering various scientific and technological solutions for the identification of single phase earth faults in power distribution networks allowed to establish the advantages and drawbacks of these solutions thus leading to an estimation that there is no universal and commonly integrated solution, based on which a quick identification of earth faults in the power distribution network can be performed, and with sufficient accuracy the earth fault's location in overhead lines can be identified.
2. Equations of waving processes in power lines where electromagnetic waves change over time were formulated, assessed, the frequency of a power line's surge impedance was allowed; the discovery of the dependence permitted to form the foundations for the methodology enabling to solve the location problems of single-phase earth faults in a power distribution network, because in the calculations:
   - for the overhead lines of various constructional solutions and changing the earth ground resistance range up to 3000 Ωm, the most accurate velocity of electromagnetic wave propagation and most accurate power line surge impedance can be found by selecting the optimum frequency of 23 kHz in the entire 10 kHz - 10 MHz frequency range of fast transient processes,
   - cross-wired wave channels surge impedances can have constant values, because it almost does not when changing ground impedance is changing,
   - for the line model's simplification can be found an equivalent wire height, making it constant over the entire line length.
3. Using the linearity characteristics in equations, that describe fast electromagnetic processes, can be adapted and optimized the parameters of elements of power supply scheme, and for the complex configuration overhead line can be found the equivalent simplified model of the electricity network, because in the calculations can be:
   - the initial transient process moment was established, and the inhomogeneity causes of the initial moment of the process were determined. principles of the inhomogeneity elimination principles were investigated,
   - a specific analysis algorithm was created with the objective to reduce the influence of the ongoing extrinsic processes from the busbars section,
   - the power overhead line design parameters, the wire curve in the gaps between the poles, cable insertions, transformer capacities, impedances of the ground and of the object itself via which the

connection with the ground occurred were established; thus reduced influence of non-linear electrical network parameters was defined,

- the influence of electromagnetic parameters of phases heterogeneity in the line where the failure occurred was estimated, and the node model for the fault location identification was developed.

4. A fault location identification model was developed which according to the recorded characteristics of fast electromagnetic processes and based on the zero-sequence wave initial front-delay parameter allows to identify the distance to the fault location search area. When the specific resistance of the ground soil is within the range of 100Ωm to 300Ωm, according to accrued recordings of single phase earth faults in the overhead lines with distances up to 20 km, the distance to the fault location error does not exceed 10%.

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REZIUMĖ

Darbo tikslas − taikant greitųjų elektromagnetinių pereinamųjų vyksmų modeliavimo technologiją, supaprastinti skaičiuojamąją elektros skirstomojo tinklo schemą ir sukurti modelius, kurie leistų adaptuoti ir optimizuoti elektros tinklo schemos elementų parametrus, turinčius įtakos gedimo vietos vienoje fazėje greito nustatymo patikimumui, ir leistų nustatyti gedimo vietą vienoje elektros skirstomojo tinklo fazėje.

Mokslinis naujumas

Išplėtoti vienos fazės gedimo (susijungimo su įžemintu objektu) sukeltų elektromagnetinių pereinamųjų vyksmų pradinio momento analizės metodai leido sukurti pirminių elektromagnetinių pereinamųjų vyksmų analizės metodiką, kurią taikant galima greitai ir tiksliai nustatyti gedimo sudėtingo skirstomojo elektros tinklo linijoje vietą.

Rengiant disertaciją atliktus mokslinius tyrimus apibendrina išvados:

1. Tyrimas, kuriuo įvertinti skirtingais moksliniais ir technologiniais sprendimais grindžiamų gedimų vienoje elektros skirstomojo tinklo fazėje atpažinimo technologijų privalumai bei trūkumai, parodė, kad nėra vieno kompleksinio metodo, kurį taikant būtų galima greitai atpažinti gedimą elektros skirstomajame tinkle ir pakankamai tiksliai nustatyti gedimo elektros oro linijoje vietą.
2. Suformuotos banginių vyksmų linijose lygtys, padedančios įvertinti elektromagnetinių bangų kitimą per laiką bei linijos sekų banginių varžų priklausomybę nuo dažnio, leidžia sudaryti pagrindą metodikos, kuria vadovaujantis galima spręsti gedimo vienoje elektros skirstomojo tinklo fazėje atpažinimo uždavinius, nes atliekant skaičiavimus:
    - įvairių konstrukcijų linijoms ir žemės grunto varžoms kintant diapazone iki 3000 Ωm tiksliausiai elektromagnetinių bangų sklidimo pastoviąsias ir linijų bangines varžas galima rasti pasirinkus optimalų 23 kHz dažnį visame greitųjų vyksmų 10 kHz–10 MHz dažnio diapazone,
    - bangines varžas tarplaidiniuose banginiuose kanaluose galima laikyti pastoviaisiais dydžiais, nes jos beveik nekinta keičiantis grunto varžai,
    - linijos modeliui supaprastinti galima rasti ekvivalentinį laidų aukštį, laikant, kad jis vienodas visoje linijos dalyje virš žemės.
3. Naudojantis greituosius elektromagnetinius vyksmus aprašančių lygčių tiesiškumo savybėmis, galima adaptuoti bei optimizuoti elektros tinklo schemos elementų parametrus ir sudėtingos konfigūracijos elektros oro linijai surasti ekvivalentinį supaprastintą skaičiuojamojo elektros tinklo modelį, nes atliekant skaičiavimus galima:

- įvertinti pradinį vyksmo momentą, nustatyti pradinio vyksmo nehomogeniškumo priežastis ir surasti šio nehomogeniškumo pašalinimo principus;
- sudaryti specifinį analizės algoritmą, kuris leistų sumažinti šynų sekcijoje vykstančių pašalinių procesų įtaką;
- įvertinti elektros oro linijos konstrukcinius parametrus, laidų išlinkimą tarpstiebiuose, kabelinius intarpus, transformatorių talpas, žemės grunto ir objekto, per kurį įvyksta susijungimas su žeme, varžas ir taip sumažinti netiesinių elektros tinklo parametrų įtaką;
- įvertinant linijos, kurioje įvyko gedimas, elektromagnetinių parametrų fazėse nevienodumo įtaką, sukurti mazgo modelį gedimo vietai nustatyti.

4. Sukurtas gedimo vietos nustatymo modelis, kuris pagal užregistruotas greitųjų elektromagnetinių vyksmų charakteristikas ir remiantis nulinės sekos krintančiosios bangos fronto trukmės parametru leidžia nustatyti atstumo iki gedimo vietos paieškos zoną. Žemės grunto specifinei varžai esant diapazone nuo 100 iki 300 Ωm, remiantis gedimų vienoje fazėje registracijų elektros skirstomojo tinklo linijose iki 20 km duomenimis, atstumo iki gedimo vietos nustatymo paklaida neviršija 10 %.

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