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The etalon model for solving currents in ground wires at asymmetrical short circuits on overhead power transmission lines

The paper presents the etalon method for calculation of asymmetrical short circuit current distributions in ground wires on overhead power transmission lines. Proposed approach is based on presenting a line as multi-wire system, and allows taking into account factors that other methods based on the nmethod of symmetrical components ignore. This etalon model allows to determine the values of the currents on each wire, as well as to assess the applicability of using for this purpose, assumptions in simplified methods. The exact calculation algorithm is presented, the case in point example is showed as well.

Keywords: ground wire, wire, overhead power transmission line, tower, grounding, short circuit current, model, method, algorithm.

I. INTRODUCTION

When short circuit (SC) on earth (tower) on overhead power transmission line (PTL) with grounded ground wire (GW) occurs, part of the SC current is distributed to the earth through the tower (on which fault was happened), and part through ground wires and adjacent towers. The rate of current in the GW depends on the initial injected SC current value, induced current by phase wires and the some parameters like, tower grounding resistances and GW impedances that are part of a loop trough which SC current is distributed.

Determination of the maximally possible values of SC currents in a GW at a design stage is one of the important tasks, course of after installation GW, its section has to satisfy to thermal effect of SC currents. The choice of GW with a section which does not satisfy to technical requirements, i.e. when a GW with smaller section has been chosen during design stage, it can lead to loss of thermal stability (disconnection) of the GW itself, that might demand additional expenses for restoration and compensation of idle time of this overhead PTL.

Even bigger losses of resources from violation of thermal stability can arise when modern optical GW (OPGW) are installed [1], where in case of unreliable work (disconnection course of SC current thermal influence) there is a chance to damnification other spheres of economy (spheres that use communication channels, as the Internet, telecommunication, etc.). The installation of a GW with overestimated section, which thermal stability considerably exceeds real values of the coefficient of thermal effect on the line, can lead to unjustified overprizes of the project itself owing to that that the price of GW is determined by its section. Also additional expenses might occur for strengthening towers owing to increase in weight of the suspended GW.

Based on the aforesaid, there is a need to design etalon methods, which are capable to consider most influences of various factors on the values of currents in GW at asymmetrical SC on the earth (tower). Additionally, on the base of such etalon models to assess existed methods.

II. REVIEW OF THE EXISTING METHODS

For today a lot of works devoted to this subject have been accumulated, all methods introduced in them might be to some extent correlated to one of the groups presented below, which are conditionally divided according to the assumptions at calculations. It should be noted, that all methods offered by authors are based on the principles of Kirchhoff’s lows, difference consists in a methodology used for obtaining final solutions.

2.1 The method of using differential equations

In cases when long overhead PTL is considered, it is assumed that the line has infinite length, resistances of tower groundings, self and mutual impedances of phase wires and GW are assumed identical along the whole length of the line.

All final equations for determination of currents in GW and through tower grounding resistances are come out from initially worked out Kirchhoff’s loop and nodal equations to differential equations, which are solved proceeding from the boundary conditions. Results of the solution are proportional to exponential function.

The Indian scientists of R.Verna and D.Mukhedkar developed an analytical method for cases when fault is occurred near substations [2]. On the base of numerous questions of other engineers and scientists to authors and discussions of this subject, the method offered by authors is not suitable for determination of SC current distribution for cases when fault occurs between stations.

The Romanian scientist M.Vintan published a number of articles devoted to this subject [3,4,5]. In her works M.Vintan places emphasis on modification and addition of the methods which already had been developed by scientists R.Verna, D.Mukhedkar, J.Endrenyi, etc. but nevertheless her suggested model is based on differential equations.

In algorithms of the proposed method, the influence of the effects of mutual inductances are taken into account by special coefficient represented as a relation of specific mutual impedance between GW and an equivalent phase wire on the self-impedance of the phase wire.

M.Vintan in her works assumes that the value of the injected fault current in the considered node (on tower) is already known, and analytical equations are given only for determination of distribution SC current from the fault point.

2.2 The method of using correction coefficient for short overhead PTL

In cases when the line has short length, or its consideration as a long is unacceptable, the method with the distributed parameters described above is corrected by correction coefficient. This method was offered by J.Endrenyi and assumes considerable simplifications in a model. Detailed technique of this method is presented in [6].

2.3 The method of using conventional short-circuit calculation technics

The current distribution from the SC point can be calculated without essential simplifications by application of the Thevenin's theorem. The matrix methods of nodal or loop equations can be implemented, where currents and nodal voltages for different types of asymmetrical SC can be calculated by solving that equations with direct or iterative methods.

One of such works is paper of the Chinese and working together with Korean scientists Jun Zou, Jae-bok Lee, JunJie Li, Sughun Chang [7]. Authors suggest to apply nodal equations and for their solving recommend to use iterative methods. In the technique proposed by authors, mutual inductance between wires (phase and GW) are taken into account by their representation as equivalent electro motive forces (EMF). During the process of solving equations, where all EMF sources included, the nodal voltages are changed iteratively until the convergence of the process is provided.

This method can be applied to any kind of schemes without any difficulties and take into account the influences of all essential mutual inductances. Authors however, with minor reservation of this method's features, say that it occupies considerable amount of computer memory and respectively demand more computer time for calculation in comparison with other methods. Claiming about simplicity of the offered method and convenience of its application in comparison with other methods authors offer its application as alternative to the method of double-sided elimination of the scheme designed by Dawalibi [8,9,10].

A little bit different approach was offered by Ljubivoje M.Popovic [11] which allows as the author shows, quickly and with rather reliable accuracy to calculate SC current distribution on the earth, independently on what tower it was occurred. Its advantage the author explains as simplicity of formulas for the solution of uniformly distributed ladder networks of any size. Formulas received by applying the equations of a line with lumped parameters, for the scheme with a GW in the SC point.

2.4 The methods of one and double-sided elimination

The methods of one and double-sided elimination are in very details given in works of F.Dawalibi [8,9,10]. Also, the author gives comparisons with other methods in computer memory consumption and time spent by computer for the solving process by using these algorithms. In contrast with other scientists, F.Dawalibi offers to consider each span of the overhead PTL as a separate link, thus parameters of the overhead PTL such as ground resistance and tower grounding resistances, types of phase and ground wires have to be considered by real values. The loop equations for spans are equated and by solving these equations, SC current distribution from the fault point is defined. He offers two ways of solving these equations – one sided elimination of the scheme and - double sided elimination of the scheme. Earlier, before he published these works some other authors had already offered similar methods, but with certain simplifications that was improved and validated by measurements carried by F.Dawalibi and B.Niles [10].

Despite on a large number of works devoted to this theme, which were supplemented and improved for many years, in all of the presented above methods authors consider three-phase system of wires as an equivalent single-phase that can bring certain errors when overhead PTL parameters are asymmetrical. I.e. when different phase wires are suspended on towers and/or GW with large cross sections are installed, etc. The methods with application of the differential equations also assume that injected current in a SC point is known, and the methods assume only calculation of its distribution through GW and a tower to the earth. In advance known value of the injected asymmetrical SC current is calculated by the use of the method of symmetrical components, the use of which already assumes simplifications that are not always justified and brings initially put errors in a calculation process. These defects might be eliminated by application of the method of multi-wire coordinates [12, 13], which besides the accounting of all factors causing asymmetry of the initial three-phase system of wires and mutual inductances between all wires in a system, is differed in simplicity and ease of visualization.

III. THE MODEL OF AN OVERHEAD PTL IN THE SYSTEM OF MULTI-WIRE COORDINATES

Overhead PTL is divided into the sections, according to the ground characteristics, span lengths, types of suspended wires on towers along the whole length. After that, for all sections of the n-wire transmission line (for example if one GW and three phase wires are suspended on towers - the system is considered as four wire, if two GW as five wire system, etc.) with the help of John R.Carson's equations and their modifications [14,15] matrices of self and mutual series specific impedances with earth return ($Z_{0\,section}$), and self and mutual specific shunt capacitive susceptances ($B_{C0\,section}$) each with the size of n×n are calculated.

The computational etalon model is based on the representation each span of an overhead PTL as π-circuit (Fig. 1) with their matrices of series impedances Z_{ij} and shunt capacitive susceptances $B_{C\,ij}$.

Block matrices of self and mutual series and shunt admittances for each of the spans are calculated according to the (1) and (2).

$$Y_{ij} = \left(L_{span} Z_{0\,section}\right)^{-1} \quad (1)$$

$$B_{Cij} = L_{span}\, B_{C0\,section} \quad (2)$$

Where:

L_{span}-the length of the span between two neighboring towers.

The equivalent circuit of an overhead PTL is represented by the chain of span circuit sequences along the whole length of the line (Fig. 2). Tower groundings are presented by resistances R_i ($i = \overline{1 \ldots m+1}$), where R_1 and R_{m+1} equivalent resistances of the respective substation groundings.

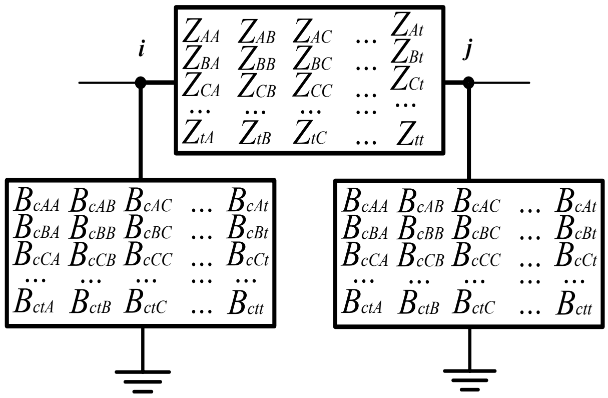


Figure 1. π-shaped equivalent circuit of the overhead PTL span

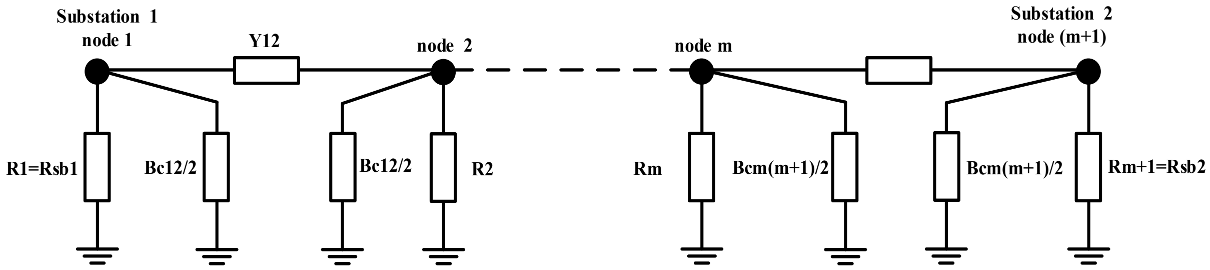


Figure 2. Equivalent circuit of an overhead PTL

IV. THE MODES CALCULATION

4.1. Network circuit

A power network is presented by a line, with equivalent system parameters on its ends Fig.3.

For calculations of modes, Power Flow Equations are formed, where the state equation is written as in (3).

$$YU = I \tag{3}$$

Here:

- Y – the nodal admittance matrix of the network, which is formed on the basis of block matrices $Y_{series\,ij}$ and $B_{C\,ij}$;
- U – the column vector of nod voltages, where each element consists of the matrix of voltages on the wires in the i-th node: $\dot{U}_i = [\dot{U}_{i1}^w,\ \dot{U}_{i2}^w, \dot{U}_{i3}^w, \dots, \dot{U}_{i(k-1)}^w, \dot{U}_{ik}^w]^T$ where $\dot{U}_{ik}^w$ – the voltage value on the k-th wire in the i-th node ($k = \overline{1 \dots n}$; $i = \overline{1 \dots m+1}$;
- I – the column vector of the nod injected currents where each element is presented as: $\dot{I}_i = [\dot{I}_{i1}^w,\ \dot{I}_{i2}^w, \dot{I}_{i3}^w, \dots, \dot{I}_{i(k-1)}^w, \dot{I}_{ik}^w]^T$, where $\dot{I}_{ik}^w$ the value of the current in the k-th wire directed into the i-th node ($k = \overline{1 \dots n}$; $i = \overline{1 \dots m+1}$).

The system parameters corresponding to the nodes of the overhead PTL connections to the Networks are accounted by three-phase equivalent EMF and per phase impedance matrices. In practice, for calculations of asymmetrical modes, the input parameters of the systems are usually set by single-phase equivalent EMF E_{S1}, E_{S2} and equivalent impedances of positive, negative and zero sequences [15] $Z_S = [Z_1, Z_2, Z_0]$ corresponding to each of substation buses, as well as equivalent mutual impedance between substations Z_{S12}. For calculations of modes in a multi-wire system, it is necessary to convert symmetrical components of initial data to the phase values and system equivalent EMF represent as separate EMF for each of the phases.

Transformation of the symmetrical component impedances into the phase values, for each of the sides of the Network are made by (4).

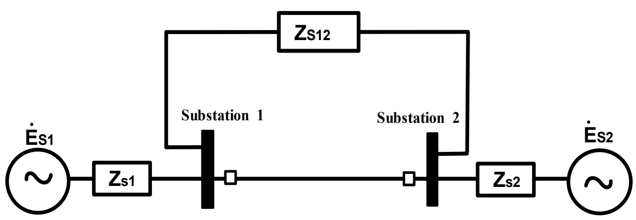


Figure 3. Equivalent circuit of a power network

$$Z_S^{phase} = \begin{vmatrix} Z_{AA} & Z_{AB} & Z_{AC} \\ Z_{BA} & Z_{BB} & Z_{BC} \\ Z_{CA} & Z_{CB} & Z_{CC} \end{vmatrix} =$$

$$\left(\begin{vmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{vmatrix}\right)^{-1} \mathrm{x} \left(\begin{vmatrix} Z_1 & 0 & 0 \\ 0 & Z_2 & 0 \\ 0 & 0 & Z_0 \end{vmatrix}\right) \mathrm{x} \left(\begin{vmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{vmatrix}\right) \tag{4}$$

Presenting EMF of the Network in phase values are made by (5).

$$E_S^{phase} = [E_A,\ E_B,\ E_C]^T = [E_S,\ aE_S,\ a^2E_C]^T \tag{5}$$

Where $a = exp(j120^0)$ in (4) and (5) — the coordinate transforming operator.

4.2. The formation of the bus admittance matrix

The bus admittance matrix Y is formed according to [15], in particular:

Any off-diagonal element Y_{ij} of the bus admittance matrix in (3) is equal to series admittance of the branch between nodes i and j taken with negative sign, so $Y_{ij} = -Y_r$ where $r = \overline{1 \dots m}$; $i \neq j$. In case there is no connection between branches, than the admittance matrix element $Y_{ij} = 0$.

The diagonal elements Y_{ii} of the bus admittance matrix are calculated as the sum of every branch admittances, which are connected with the node i, so for the first node the element of the bus admittance matrix is formed as:

$$Y_{11} = Y_{S1}^{phase} + Y_{S12}^{phase} + Y_{12} + B_{c12}$$

For the second node:

$$Y_{22} = Y_{12} + B_{c12} + Y_{23} + B_{c\,23}, \text{ etc.}$$

And for the node from the side of the second Network i.e. (m+1) node, as:

$$Y_{(m+1)(m+1)} = Y_{S2}^{phase} + Y_{S12}^{phase} + Y_{m(m+1)} + B_{c\,m(m+1)}$$

Where:

$$Y_S^{phase} = \left[Z_S^{phase}\right]^{-1}$$

4.3. The forming of the column vector of the nod injected currents

The values of the elements in the matrix of nod injected currents for all phase wires with the exception for the nodes where overhead PTL is connected to the substations are considered to be zero, whereas for GW, elements are set to be zero for all nodes.

The values of non-zero elements for phase wires in the matrix of nod injected currents are determined on the base of the Network equivalent parameters.

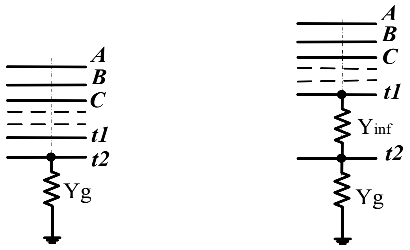
$$I_i = Y_{Si}^{phase}\, E_{si}^{phase}\ (i = 1, m+1)$$

4.4. GW grounding simulations in the nodes

GW grounding simulations in the nodes on the overhead PTL are fulfilled by adding the total tower admittance and its grounding calculated as $Y_{gi} = R_i^{-1}$ $(i = \overline{1 \ldots m+1})$ to the corresponding element of the GW's self-admittance, in the block matrices of the diagonal elements of the bus admittance matrix Y in (3). I.e. in case of grounding only wire t_2 on a tower as shown on (Fig.3 *a*) the self-admittance of the element in the block matrix is formed as $Y_{t2\,t2} = Y_{t2\,t2} + Y_g$.

In the case of suspension on an overhead PTL two grounded GW, electrical connection between them is simulated by adding an infinitely big admittance Y_{inf}, whereas their grounding is simulated by adding admittance Y_g.

According to the rule of forming nodal equations, admittance Y_{inf} is added to the mutual connections between grounded GW in the block matrices, i.e. for grounding GW t_1 and t_2 mutual element between wires in the block matrix is formed as $Y_{t2\,t1} = Y_{t1t2} = Y_{t1\,t2} - Y_{inf}$, whereas Y_{inf} and Y_g are added to the self-admittance one of the grounded GW. According to the Fig.4 b. the element of the self-admittance of the GW t_2 is formed as: $Y_{t2t2} = Y_{t2t2} + Y_g + Y_{inf}$; of the GW t_1 as: $Y_{t1t1} = Y_{t1t1} + Y_{inf}$.



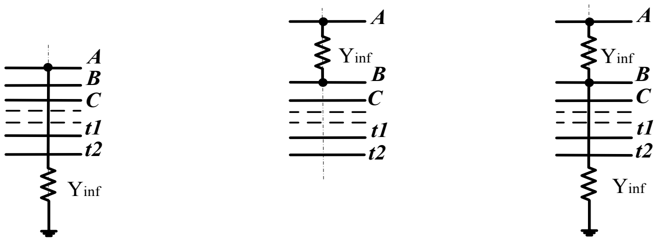
a) b)

Figure 4. The models of grounding GW in nodes of PTL: a) grounding of one GW; b) grounding of both ground wires

4.5. Modeling of asymmetrical SC in the node on overhead PTL

Sort-circuit by itself is presented as an electrical connection of two (or more) phase wires between each other, or one (or all) of them to the earth (tower). The simulations of sort-circuits are made by adding an electric connection represented as infinitely big admittance Y_{inf} between faulted nodes. So, for modeling:

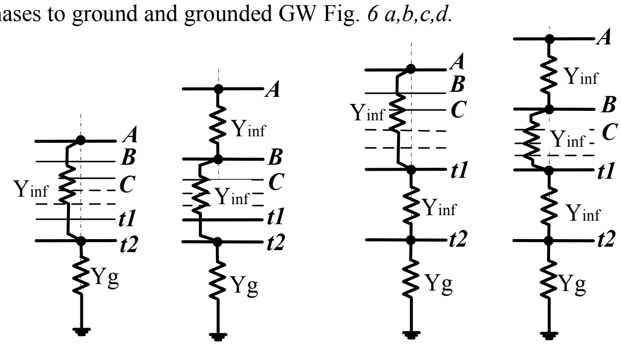
- single phase fault, Fig.5 *a,* the admittance Y_{inf} is added to the element of self-admittance of the faulted phase wire in the corresponding block matrix;
- line-line fault, Fig.5 *b,* the admittance Y_{inf} is added to the self elements, and $-Y_{inf}$ to the mutual elements of the faulted phase wires in the corresponding block matrix;
- double line-ground fault, Fig.5 *c,* the admittance $-Y_{inf}$ is added to the mutual elements between faulted phase wires in the corresponding block matrix, and also to one of the self-admittance elements of the faulted wires Y_{inf} is added, whereas to the second self-admittance element $2Y_{inf}$ is added. So according to the Fig.5 *c* the element of self-admittance for the phase A is formed as $Y_{AA}=Y_{AA}+Y_{inf}$, for the phase B as $Y_{BB}=Y_{BB}+Y_{inf}+Y_{inf}$.



a) b) c)

Figure 5: The models of short circuit simulations in nodes on overhead PTL: a) single phase fault (phase A); b) line-line fault (phases A and B); c) double line-ground fault (phases A and B)

In the models of overhead PTL when asymmetrical SC on ground (on tower) are calculated and there are grounded GW on towers, the connection in the form of $-Y_{inf}$ is added between one of the faulted phases to ground and grounded GW Fig. *6 a,b,c,d.*



a) b) c) d)

Figure 6. The models of short-circuits in nodes on overhead PTL when grounded GW are suspended on towers

Assuming that block matrices of the diagonal elements of the matrix Y in (3) have already been corrected according to the type of SC and the number of grounded GW on the tower, the only essentially thing remained is to retreat the block matrices with respective connections Y_{inf}. Than for:

- single phase fault with one grounded GW (Fig.6 *a*). The admittance Y_{inf} is added to the element of the self-admittance of the grounded wire in the corresponding block matrix. $-Y_{inf}$ also is added to the elements of mutual-admittances between faulted phase wire and grounded GW in the corresponding block matrix;
- line-line fault to earth with one grounded GW (Fig.6 *b*). The admittance Y_{inf} is added to the element of the self-admittance of the grounded wire in the corresponding block matrix. $-Y_{inf}$ also is added to the elements of mutual-admittances between one of the faulted phase wires and grounded GW in the corresponding block matrix;
- single phase fault with wo grounded GW (Fig.6 *c*). The admittance Y_{inf} is added to one of the elements of the self-admittances of the grounded wires in the corresponding block matrix. $-Y_{inf}$ also is added to the elements of mutual-admittances between faulted phase wire and one of the grounded GW in the corresponding block matrix;
- line-line fault to earth with wo grounded GW (Fig.6 *d*). The admittance Y_{inf} is added to one of the elements of the self-admittances of the grounded wires in the corresponding block matrix. $-Y_{inf}$ is also added to the elements of mutual-admittances between one of the faulted phase wires and one of the grounded GW in the corresponding block matrix;

After the bus admittance matrix Y with taking into account GW groundings on different sections of the line and the type of SC in the corresponding node has already been formed, by solving (3) the nod voltages are defined. The sparse structure of the matrix Y in (3) allows to operate during solution only with two ribbon structure matrices (nodal-self admittances, and branch-mutual admittances) what makes the solving algorithm even less computer memory consuming. Calculated values of the voltages on the wires in the nodes allow to define the currents in each of the wire directed to the both sides from the SC point.

V. THE ALGORITHM OF SOLVING IN THE SYSTEM OF MULTYWIRE COORDINATES

The sequence of steps for solving asymmetrical short circuit currents on overhead PTL with taken into account the asymmetry of the system is presented by the algorithm below:

1. Overhead PTL is divided on the sections according to the ground characteristics, span lengths, types of suspended wires on towers along the whole length;
2. For each section of the overhead PTL, matrices of self and mutual series specific impedances, and self and mutual specific shunt capacitive susceptances are calculated;
3. The network equivalent parameters are transformed into phase coordinates, where nodal injected currents for phase wires are determined and the matrix of nodal injected currents is formed;
4. The block matrices of self and mutual impedances, and self and mutual shunt capacitive susceptances for each of the span taking into account span lengths and specific parameters of the corresponding section are calculated, after that on the base of rule of forming nodal equations for each of the node (tower), the block matrices of nodal admittances are formed;
5. In case of grounded GW are suspended on towers, the block matrices are corrected according to the paragraph 4.4;
6. The type of short circuit in the node is modeled by changing its elements in the block matrix of nodal equation in the corresponding node according to the paragraph 4.5;
7. By solving equation (3) nodal voltages on each of the wire and each of the node are determined.
8. The currents in each of the wire and each of the spans directed from the fault point are determined.

On the base of this algorithm, the program was written on the Matlab Software, some examples are presented in the next paragraph below.

VI. CASE IN POINT OF THE ASSYMETRICAL SHORT CIRCUIT CURRENT CALCULATIONS

As an example, the 500 kV overhead PTL with the length of 50 km (125 towers), with two suspended GW on towers - steel GW and OPGW is considered. It was assumed that line is presented by one section, i.e. tower types, phase wires and GW, tower groundings and span length between neighboring towers are the same across the whole length of the line. The system equivalents from each of the side of the network (Fig. 3) are presented in the table 1.

TABLE I
Network equivalent parameters

	For substation 1	For substation 2	Mutual connections between substations
EMF (kV)	E_{S1}=500	E_{S2}=500	
Positive sequence impedance (Ohm)	Z_{s1}^{1}=j24.15	Z_{s2}^{1}=j21.83	Z_{s12}^{1}=j524.41
Zero sequence impedance (Ohm)	Z_{s1}^{0}=j22.23	Z_{s2}^{0}=j12.6	Z_{s12}^{0}=j14390.31
Span between substation terminals and the end towers (m)	75	75	
Substation equivalent groundings (Ohm)	0.05	0.05	

The tower types are taken equal along the whole length of the line Fig. 7.

The phase wire types along the length of the line are taken as follows:

— for phase A — 3×ACSR-300/66;
— for phase A — 3×ACSR-400/51;
— for phase A — 3×ACSR-300/66.

Such arrangement of phases with different wires, is widely used in mountain areas in order to eliminate loses for corona, and therefore attracts interest cause of it provides even bigger asymmetry of the system.

The ground wire types are taken as follows:

— from the left side of the tower OPGW;
— from the right side of the tower steel GW.

Technical characteristic of the wires are presented in the table 2.

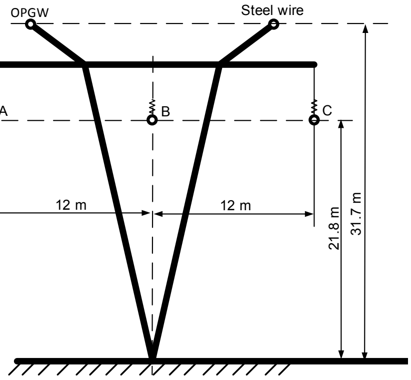


Figure 7. Tower geometry

TABLE II
Technical characteristics of the wires

Wire type	Outside diameter D (mm)	T/D* ratio	Specific resistivity to the direct current ρ (Ohm/km)
Steel GW (PT-70*)	11	0,5**	2.33
OPGW-DABB 12E9/ 125 AA/ACS 092/44	16.0	0.3844	0.28
3×ACSR-300/66	24.5	0.4285	0.10226
3×ACSR -400/51	27.5	0.3327	0.075

* PT-70 - PT-the abbreviation "PT" stands for the type of contact between the layers of wire - Point Touch.

**T/D value of 0.5 indicates a solid conductor.

Span lengths are taken as L_{span}=400 (m) across the whole length of the line, tower resistances R_g=10 (Ohm), ground resistance $\rho = 100\ (\text{Ohm} \times m)$.

On the base of presented parameters of the initial data by using of J.Carson formulas, the matrix of specific self and mutual impedances and matrix of self and mutual capacitance susceptances are calculated each with the size of 5×5. The corresponding calculated matrices are presented in the table 3.

The mode calculations were performed on the model presented as five wire system (three phase wires and two ground wires).

Single-phase fault (phase A) on the tower number 20 (from the substation number 1) were calculated. The calculation results as current distribution characteristics are presented on Fig. 8.

TABLE III
The matrices of wire specific parameters.

The matrix of wire self and mutual specific impedances $Z_{0\,section}$ (Ohm)					
	A	B	C	Steel GW	OPGW
A	0.0738+ j0.63504	0.0488+ j0.34225	0.0488+ j0.29872	0.0487+ j0.35302	0.0487+ j0.30399
B	0.0488+ j0.34225	0.0738+ j0.63504	0.0488+ j0.34225	0.0487+ j0.34067	0.0487+ j0.34067
C	0.0488+ j0.29872	0.0488+ j0.34225	0.0738+ j0.63504	0.0487+ j0.30399	0.0487+ j0.35302
Steel GW	0.0487+ j0.35302	0.0487+ j0.34067	0.0487+ j0.30399	2.3785+ j0.84543	0.0485+ j0.32406
OPGW	0.0487+ j0.30399	0.0487+ j0.34067	0.0487+ j0.35302	0.0485+ j0.32406	0.3785+ j0.82445
The matrix of wire self and mutual specific capacitance susceptances $Bc_{0\,section}$ (Siemens)					

	A	B	C	Steel GW	OPGW
A	$j3.44x10^{-6}$	$-j4.37x10^{-7}$	$-j1.05x10^{-7}$	$-j4.03x10^{-7}$	$-j1.20x10^{-7}$
B	$-j4.37x10^{-7}$	$j3.51x10^{-6}$	$-j4.35x10^{-7}$	$-j2.92x10^{-7}$	$-j3.04x\ 10^{-7}$
C	$-j1.05x10^{-7}$	$-j4.35x10^{-7}$	$j3.44x10^{-6}$	$-j1.15x10^{-7}$	$-j\ 4.19x10^{-7}$
Steel GW	$-j4.03x10^{-7}$	$-j2.92x10^{-7}$	$-j1.15x10^{-7}$	$2.04x10^{-6}$	$-j\ 1.72x10^{-7}$
OPGW	$-j1.20x10^{-7}$	$-j3.04x10^{-7}$	$-j4.19x10^{-7}$	$-j1.72x10^{-7}$	$2.12x10^{-6}$

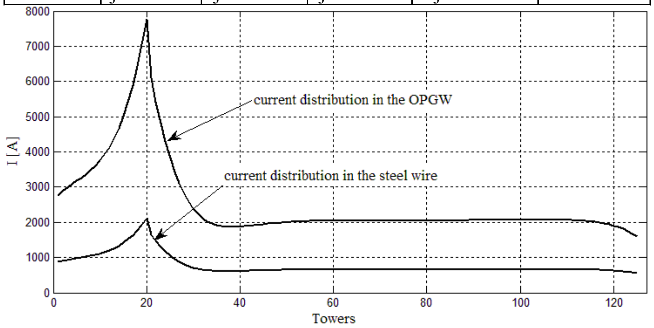


Figure 8. Current distribution during the single-phase fault on the tower № 20

The maximal current values in the steel wire during the single-phase fault on the tower № 20 is 2.1055 [kA], in the OPGW 7.7542 [kA].

VII. CONCLUSION

The algorithm for solving modes of asymmetrical short circuits in multi-wire overhead PTL is presented. The use of the performed approach for the calculation of the currents in GW allows taking into account factors, ignoring of which by using other methods based on the MSC might be course of errors, to be exact:

- Asymmetry of the original three phase system of wires;
- Suspension different types of phase wires and GW on towers;
- Installing different types of towers on the line;
- Difference of ground resistances along the line;
- Differences of GW groundings.

The implementation of the presented algorithm can be found when solving thermal stability of the GW to short circuit currents. In particular when designing expensive OPGW.

Developing of the etalon method for solving currents in multi-wire overhead PTL based on the presented approach, gives the ability to estimate the implementation of other methods based on the use of the MSC.

ACKNOWLEDGMENT

A special thanks to the main specialist Utkur Sharipov and chief Evgeniy Drobov of the «Elcetrical Power Networks‘ modes management» department of the Desighn Surveying and Scientific Research company «Sredazenergosetprojekt» for their unique and priceless ideas in helping to improve solving-algorithms, providing necessary data for making example calculations and making sure this paper is technically accurate.

To the head of “Electrical Power Stations, Networks and Systems” department of the Power engineering faculty of the Tashkent State Technical University Tulkin Gayibov for his constant support and encouragement.

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