CALCULATION OF TEMPORARY OVERVOLTAGE'S FACTORS IN POWER SYSTEMS

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INTRODUCTION

During the exploitation of electric power systems very often can occur the situations and conditions, which can endanger their normal exploitation. One of the most often effects which can influence on the normal electric power operation is the appearance of the high voltages, so called overvoltages. The causes for the appearance and existence of the different types of overvoltages and their consequences are numerous and different. High voltages can be very dangerous for insulation of electrical equipment. Appearance of the overvoltages causes increase of electric field through insulation. In the case when insulation can't withstand the effects of the overvoltage, at that time comes to the appearance of losses of the insulation's dielectric characteristics i.e. appearance of the flashover or the breakdown of the insulation. Because of that insulation begin to conduct electric current.

By means of techno-economic system optimization it is necessary to implement process of insulation coordination in order to limit damages caused by overvoltages appearances. Insulation coordination represents complex process of adjustment of equipment's insulation characteristics (insulation level) with protection device's protection characteristics (protection level) in order to decrease possibility that overvoltages cause insulation damages or to influence on operation continuations.

Surge arresters are primary (basic) protection devices against damages caused by the different overvoltages. Because of that, it is essential that the arresters accomplish their tasks under all possible system operating conditions. Therefore, it is very important to know characteristics of the system behavior that influence on the surge arresters operation. The large number of the system parameters influence on the proper selection of the different types of surge arresters for the defined location in the system and for the defined application. From that reason, large number of the arresters characteristics is defined for description of the arrester operation's behavior. Selection of an arrester for a specific application is compromise between protective level, temporary overvoltages capability and energy capability.

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Determination of maximum continuous operating voltage and rated voltage of the surge arrester are one of the most significant phases during the process of surge arrester selection. The values of these surge arrester characteristics directly depend on maximum values of temporary overvoltages that can appear on the location of the surge arrester in the power system.

According to existing practice [1] only temporary overvoltages in the case of single earth fault are taken into account. Also, values of the temporary overvoltage's factor during this fault (earth fault factor) are estimated on the value of 1.4 in solidly earthed power networks, and on the value of 1.73 in isolated neutral and impedance earthed power networks.

In the power systems, the series of the other disturbances that cause temporary overvoltages can appear. Some of these disturbances are: two phase to earth fault, one or two-phase conductors break, resonance, simultaneous appearance of more disturbances etc. In the node(s) of the disturbances temporary overvoltage's factors can have higher values in compare with earth fault factors in that node.

In the paper the possibility, which can make the calculations of temporary overvoltage's factors, for the cases of single earth fault and two phase to earth fault, faster and easier by using relatively simple, but exact enough, derived mathematical method and computer applications, has been presented and discussed. Program is written in MATLAB graphical user interface. This makes possible graphical input of the system graph elements, which represents the most simplified program interface. Input data of the program are lumped parameters of the system elements (generators, transformers, lines and customers) in sequence systems (direct, inverse and zero system), as well as their three-phase connections. In this way, application of the program enables enough accurate calculation of the temporary overvoltage's factors (for the cases of observed disturbances) in the different earthed networks. This is particularly very important for impedance-earthed network in which value of these factors cannot be properly estimated.

Application of the program is illustrated with calculation of temporary overvoltage's factors on example of part of power system of Montenegro (distribution system of town Tivat). The input data considering parameters of the elements are taken from accessible record in National Electric Power Industry of Montenegro. The obtained results are analyzed and compared with estimated values of the earth fault factors that are used for selection of built in surge arresters.

MATHEMATICAL MODEL

For the purpose of determination of maximum continuous operating voltage and rated voltage of the surge arrester, it is necessary to create appropriate model of power system. In the paper, calculation of voltage states in power system is performed by matrix methods [5]. It is well known that matrix methods of calculation of voltages and currents in the normal regime, as well as in the cases of symmetrical and nonsymmetrical disturbances of power systems, are the most convenient for applications of digital computers.

Value of the earth fault factor represents ratio between (over)voltage of the healthy phases during single earth fault and phase to ground voltage in normal working conditions at the observed location in the system. For the single earth fault at the phase "a", earth factor is given with:

$$K_f \equiv \max\left(\frac{U_b}{U_{ra}}, \frac{U_c}{U_{ra}}\right) \tag{1}$$

where:

U_b, U_c - are stationary voltages at the healthy phases during single earth fault at phase "a". These voltages depend on value of equivalent sequence impedance of the system (direct and zero sequence impedance $\underline{Z}_\alpha$ and $\underline{Z}_o$) measured at the place of earth fault, which can be expressed as:

$$\frac{U_b}{U_{ra}} = \left| e^{-j\frac{2\cdot\pi}{3}} + \frac{1-\frac{\underline{Z}_0}{\underline{Z}_\alpha}}{2+\frac{\underline{Z}_0}{\underline{Z}_\alpha}} \right|$$

$$\frac{U_c}{U_{ra}} = \left| e^{j\frac{2\cdot\pi}{3}} + \frac{1-\frac{\underline{Z}_0}{\underline{Z}_\alpha}}{2+\frac{\underline{Z}_0}{\underline{Z}_\alpha}} \right| \tag{2}$$

where:

U_{ra} - is phase to ground voltage in normal working conditions.

For two phases earth fault (phases "b" and "c"), temporary overvoltage's factor is given with [2]:

$$k_e = \frac{U_a}{U_{ra}} = \left| \frac{3\underline{Z}_o}{\underline{Z}_\alpha + 2\underline{Z}_o} \right| \tag{3}$$

Relations (2) and (3) are very important for selection of insulation level of network, because they define the value of temporary overvoltages in the cases of single earth and two phase earth faults. The voltages at the healthy phases in the case of single earth fault also determine rated voltage of the surge arresters, which are placed in the network, as well as they determine the protection level of surge arresters.

Temporary overvoltage's factors priory depend on the way of networks neutral point connections (which directly has influence on the value of equivalent zero impedance), but also depend on the value of network parameters (especially on ratio between equivalent zero and direct reactance X_o/X_α).

Within isolated neutral networks, value of the earth fault factor is, in the most cases, 1.73; although it can has higher values if ratio X_o/X_α is negative. In the cases when $k_e \leq 1.4$ usually is considered that the network is solidly earthed.

In the paper, the calculation of the equivalent sequence impedances is performed by using matrix algebra and application of the relations for calculation of the equivalent impedance between any two points (nodes) of the system. If work of the system is represented in bus frame of reference, it can be shown that equivalent impedance for one sequence system between nodes "p" and "q" is given with relation:

$$Z_{p-q} = Z_{pp} + Z_{qq} - Z_{pq} - Z_{qp} \tag{3}$$

where:

Z_{ij} - is element of the bus impedance matrix Z_{BUS}.

It is obvious that, for calculation of the equivalent impedance of the direct and zero sequence systems for given input nodes, it is necessary to calculate the node (bus) impedance matrices of direct and zero sequence system. These matrices can be derived from [5]:

$$[Z] = \left(A^t \cdot [y] \cdot A\right)^{-1} \tag{4}$$

where:

$[A]$ - is bus incidence matrix,
$[y]$ - is primitive admittance matrix.

For selected node in which temporary overvoltage's factors should be determined, equivalent impedances of direct and zero component system between selected node and ground are calculated using relation (4). After that, temporary overvoltage's factors in healthy phase(s) is/are computed using relations (2) and (3).

PROGRAM DESCRIPTION

Previously presented mathematical model is used for writing the computer program (written in MATLAB Graphical Interface), which enables calculation of the temporary overvoltage's factors for the cases of single earth and two phase to earth faults. The program is used for further analysis. Block diagram of program algorithm is given in Figure 1.
Program enables graphical input of system elements (generators, transformers, lines and consumers) and creation of the system graph. On this way, very simplified interface for data entry is created (example is given in Figure 2.). Additional windows, which enable input of element parameters in sequence component systems, open after graphical entry of the single element. System elements are modeled with equivalent schemes using lumped parameters. On the basis of entered elements and theirs parameters, bus incidence matrices and admittances matrices of the sequence component systems are created. Bus impedance matrices are created using relation (5). Depending on selected node in which temporary overvoltage's factors should be calculated, equivalent impedances of sequence component systems for selected node are determined using relation (4). After that, temporary overvoltage's factors in healthy phases are calculated and displayed as final result.
Program also enables changes of any of elements parameters. Parameters of the system as well as its configuration remains in the computer memory, so it is possible that temporary overvoltage's factors for observed disturbances can be calculated for every node in formed system graph. This is, beside very user-friendly interactions with program, also one of the advantages of the developed program.

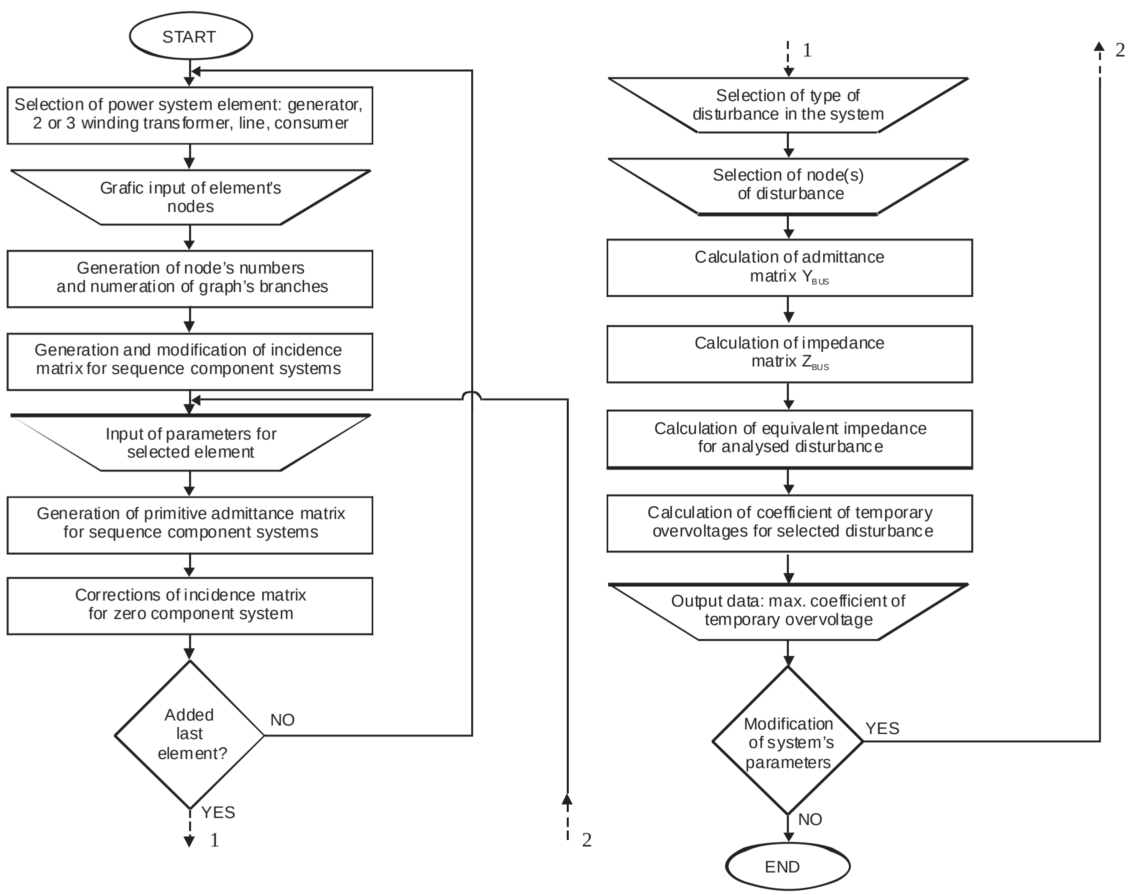

Figure 1. Block diagram of program's algorithm

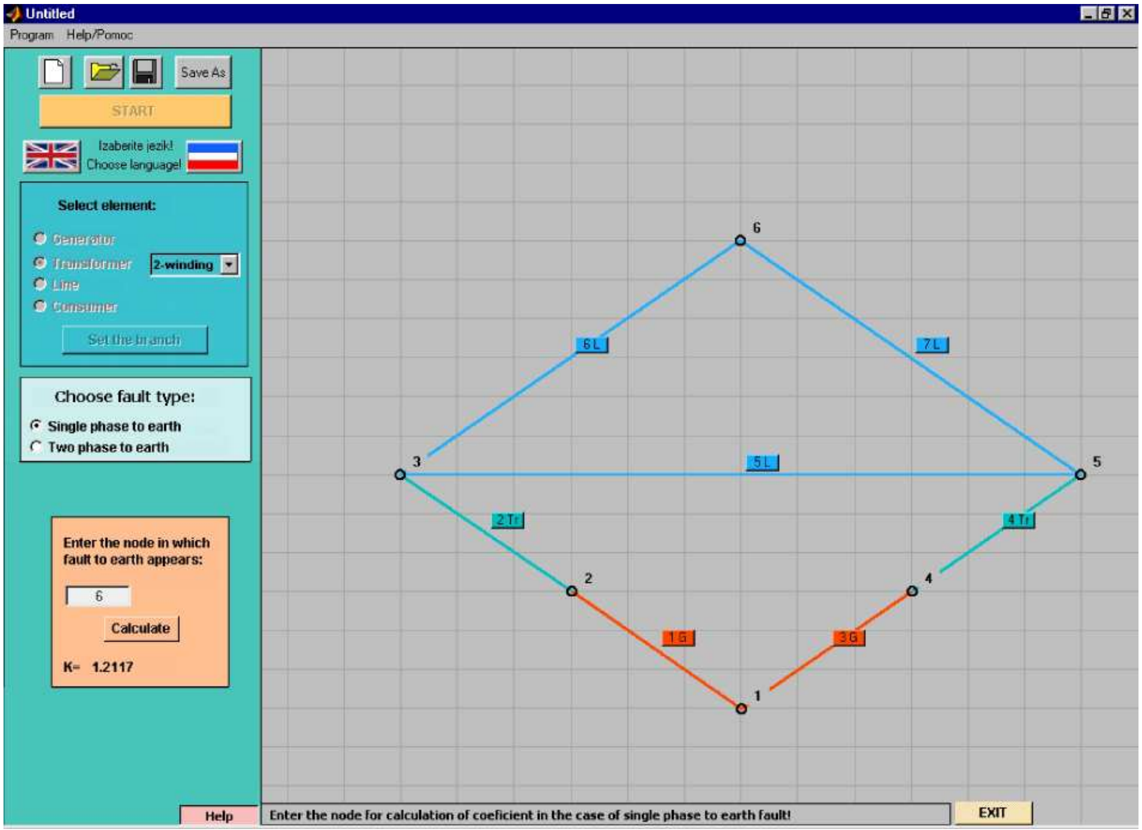

Figure 2. Program interface

EXAMPLE OF PROGRAM APPLICATION

For the purpose of illustration of the application of the developed program, it has been used for calculation of temporary overvoltage's factors (for the cases of single earth fault and two phase to earth fault) of one distribution system (of town Tivat) of Power system of Montenegro (Figure 3.).

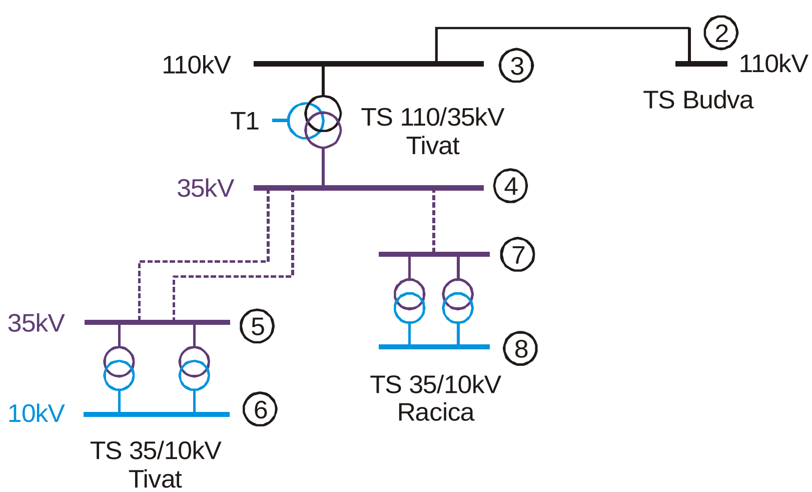

Figure 3. Single line diagram of the observed system

Input data of the program, which represent parameters of the power system's elements and which are necessary for the program application, are given in Table 1.

TABLE 1 – ELEMENT'S PARAMETERS FOR OBSERVED SYSTEM

Elements:										
Generators:	Generators data:									
	U_n	S_n	R_d	X_d	R_i	X_i	R_o	X_o	Connection	Z_g
	[kV]	[MW]	[%]	[%]	[%]	[%]	[%]	[%]	-	[Ω]
TS Budva	110	85	1,707	6,217	1,658	5,493	1,608	7,523	Yg	0

Transformers:	Transformers data															
	U_{np}	p.c.	Z_{gp}	U_{ns}	s.c.	Z_{gs}	U_{nt}	t.c.	Z_{gt}	S_{n12}	S_{n13}	Z_{12d}	Z_{12o}	Z_{13d}	Z_{13o}	Z_{23d}	Z_{23o}
	[kV]	-	[Ω]	[kV]	-	[Ω]	[kV]	-	[Ω]	[MVA]	[MVA]	[%]	[%]	[%]	[%]	[%]	[%]
TS 110/35 kV	110	Yg	0	35	Yg	70	10,5	D	-	20	6,5	0,58+ j·10,38	0,58+ j·10,38	0,56+ j·5,79	0,56+ j·5,79	0,59+ j·1,83	0,59+ j·1,83
TS 35/10 kV Tivat: T1	35	Yg	40	10,5	D	-	-	-	-	8	-	0,52+ j·6,92	0,52+ j·6,92	-	-	-	-
TS 35/10 kV Tivat: T2	35	Yg	40	10,5	D	-	-	-	-	4	-	0,32+ j·5,82	0,32+ j·5,82	-	-	-	-
TS 35/10 kV Racica: T1	35	Y	-	10,5	D	-	-	-	-	4	-	0,35+ j·5,91	0,35+ j·5,91	-	-	-	-
TS 35/10 kV Racica: T2	35	Y	-	10,5	D	-	-	-	-	1,6	-	0,30+ j·5,72	0,30+ j·5,72	-	-	-	-

Lines:	Lines data							
	U_n	R_{d1}	X_{d1}	R_{o1}	X_{o1}	X_{cd1}	X_{co1}	length
	[kV]	[Ω/km]	[Ω/km]	[Ω/km]	[Ω/km]	[Ω/km]	[Ω/km]	[km]
OHL Budva-Tiv.	110	0,1922	0,41687	0,4102	1,28	$3{,}7094\cdot10^5$	$6{,}2659\cdot10^5$	16,6
Cable 35kV	35	0,2	0,095	0,8	0,920	$5{,}2361\cdot10^4$	$1{,}1363\cdot10^5$	3,75
OHLTivat-Kot.	35	0,224	0,109	0,870	1,030	$7{,}1428\cdot10^4$	$1{,}1764\cdot10^5$	3,985

where abbreviations means:

U_{np} – transformer's primary winding rated voltage,
U_{ns} – transformer's secondary winding rated voltage,
U_{nt} – transformer's tertiary winding rated voltage,
p.c. – primary winding connection,
s.c. – secondary winding connection,
t.c. – tertiary winding connection,
Z_{gp} – grounding impedance in neutral point of transformer's primary winding,
Z_{gs} – grounding impedance in neutral point of transformer's secondary winding,
Z_{gt} – grounding impedance in neutral point of transformer's tertiary winding,
OHL – overhead line,
TS – transformer substation.

Output data of the program (temporary overvoltage's factors for the cases of single earth fault and two phases to earth fault in the nodes of the observed distribution system) are given in Table 2.

TABLE 2 – FACTORS OF TEMPORARY OVERVOLTAGES

	Node No./Rated Voltage						
	2	**3**	**4**	**5**	**6**	**7**	**8**
Disturbance	110kV	110kV	35kV	35kV	10kV	35kV	10kV
Single earth fault	1,0405	1,1240	1,7723	1,7634	1,5801	1,7365	1,6823
Two phase to earth fault	1,0363	1,1378	1,4796	1,4765	1,3980	1,4695	1,4586

ANALYSIS OF THE OBTAINED RESULTS

By using analysis of the results given in Table 2, it can be noticed:

- In all nodes of the 110kV network (nodes no. 2 and 3.), which is, according to the data in Table 1, solidly earthed system, earth fault factors are less (up to 25%) than value 1.4 that is estimated as highest value for the solidly earthed networks.
- In the 110kV network, the values of the temporary overvoltage's factors in the cases of single earth fault and two phases to earth fault in the same nodes are very close (difference is about 6%).

- In the nodes of the 35kV network (nodes no. 4, 5, 7), which is according to the data in Table 1, compensated system, earth fault factor for the case of single earth fault is higher than value 1.73, that is estimated as highest value for the isolated neutral and impedance earthed power networks. This is because of effect of higher values of the cable's capacitance and observed configuration of the system, which directly influence on the values of direct and zero sequence impedance $\underline{Z}_{\alpha}$ and $\underline{Z}_{o}$.
- In the 35kV and 10kV network the values of the temporary overvoltage's factors for the case of single earth fault are higher than the same factors in the case of two phases to earth fault in the same nodes (difference is about 20%).

CONCLUSION

Determination of maximum continuous operating voltage and rated voltage of the surge arrester are one of the most significant phases during the process of surge arrester selection. The values of these surge arrester characteristics directly depend on maximum values of temporary overvoltages that can appear on the location of the surge arrester in the power system.

According to existing practice [1] only temporary overvoltages in the case of single earth fault are taken into account. Also, values of the temporary overvoltages factor during this fault (earth fault factor) are estimated on the value of 1.4 in solidly earthed power networks, and on the value of 1.73 in isolated neutral and impedance earthed power networks.

In the power systems, the series of other disturbances that cause temporary overvoltages can appear. Some of these disturbances are: two phase to earth fault, one or two-phase conductors break, resonance, simultaneous appearance of more disturbances etc. In the node(s) of the disturbances temporary overvoltage's factors can have higher values comparing with earth fault factors in that node(s).

In the paper, computer program for calculation of the exact value of temporary overvoltage's factors (for the cases of single earth fault and two phase to earth fault) in the complex power system, which can take into consideration a number of real systems operating conditions and influences, is written, described and analyzed. Program is written in MATLAB graphical user interface. This makes possible graphical input of the system graph elements, which represents the most simplified program interface. Input data of the program are lumped parameters of the system elements (generators, transformers, lines and customers) in sequence systems (direct, inverse and zero system), as well as their three-phase connections. On that way, application of the program enables enough accurate calculation of the temporary overvoltage's factors for the observed disturbances in the differently earthed networks. This is particularly very important for impedance-earthed network in which value of these factors cannot be properly estimated.

Application of the program is illustrated with calculation of the temporary overvoltage's factors on example of part of power system of Montenegro (distribution system of town Tivat). The input data considering parameters of the elements are taken from accessible record in National Electric Power Industry of Montenegro.
Analysis of obtained results show that, values of earth fault factors are significantly lower than value of 1.4 in solidly earthed networks, which is estimated as highest value for this type of networks. However, in the impedance-earthed networks in observed example, values of earth fault factors, for the case of single earth fault in several nodes, can be higher than value of 1.73, which is estimated as highest value for the isolated neutral and impedance earthed power networks. This is consequence of network configuration, as well as element's parameters, which directly has influence on the value of equivalent impedance of direct and zero component systems. Also, it can be noticed that temporary overvoltage's factor for the case of single earth fault has higher values than value of temporary overvoltage's factor for the case of two-phase to earth fault in the same nodes in the isolated neutral and impedance earthed power networks, while these values are very close in the solidly earthed networks.

Further improvement of the program should include possibilities for calculation of temporary overvoltage factors for the cases of other disturbances in the system that causes appearance of temporary overvoltages, as well as improvement of program interface.

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