MODERN CALCULUS ASPECTS FOR ISOLATED NEUTRAL ELECTRICAL SYSTEMS

Silvia-Maria DIGĂ, Denisa RUŞINARU, Cristian BRATU

University of Craiova, Faculty of Electrical Engineering, Energy Department, Decebal Bld, 105, 200440- Craiova, Romania, Tel/Fax: +4.0251.435781, sdiga@elth.ucv.ro, drusinaru@elth.ucv.ro, cbratu@ elth.ucv.ro

Abstract – **There is well known the importance of the system earthing, different policies affecting the system behavior, e.g. the maximum level of earth-fault currents and permanent overvoltages. In this paper the authors introduce considerations of the isolated neutral systems and present a calculus algorithm and additional Visual Basic-development software for this type of neutral earthing practice.**

Keywords: *neutral earthing, isolated neutral systems, earth-fault current, neutral voltage displacement, unfaulted phase overvoltage.*

1. INTRODUCTION

In the case of the normal symmetrical operation of the transmission and distribution networks, there is no matter if the transformer neutral is isolated or directly earthed.

The neutral earthing arrangement has a great importance in the case of an accidental earth-fault. So that, for the systems directly earthed, the accidental earth-fault leads to a single-phase short-circuit current. On the other hand, an accidental earth-fault determines increasing of the unfaulted phase voltages. Consequently, the neutral earthing arrangements lead in certain conditions to overcurrents or overvoltages.

In general, three methods of earthing the neutral points of electrical systems are employed:

1. isolate the neutral entirely;
2. earth the neutral via a suppression coil ;
3. solidly earth the neutral point (direct earthing).

According to the IEC norms (for insulation coordination) the particularities associated to each neutral earthing arrangement are defined as following:

- Isolated neutral network = network whose neutral has no link specially made to the earth;
- Network earthed via a suppression coil = network having the neutral point linked to the earth via a coil; its inductance can be adjusted to closely match the network phase-earth capacitances, depending on the system configuration, so that the resultant earth-fault current is small.
- Directly earthed network = network whose neutral point is directly linked to the earth (or via an low- value impedance, which reduces the transient oscillations and allows the flowing of a current big enough for protection selectivity).

The system earthing can be also evaluated based on the value of the earth-fault currents expressed by the ratio between the line-to-earth fault current $I_{sc}^{(1)}$ and the 3-phase short-circuit current $I_{sc}^{(3)}$:

$\frac{I_{sc}^{(1)}}{I_{sc}^{(3)}} \leq 0,25$ for networks with low earth-fault currents;

$\frac{I_{sc}^{(1)}}{I_{sc}^{(3)}} \in (0,25;1)$ for networks with high earth-fault currents;

$\frac{I_{sc}^{(1)}}{I_{sc}^{(3)}} > 1$ for networks with very high earth-fault currents.

The earthing arrangements of the generators' neutral is solved according to the generators configurations:

- generators integrated with MV/HV transformers;
- generators with busbars at the generation voltage;
- generators supplying directed the networks to consumers.

The main objective of the generator neutral point earthing is achieving of a satisfactory protection in case of an earth-fault, meaning:

- earth-fault current limitation;
- eventual overvoltages limitation.

The most usual method is that of earthing via a resistance able to limit the earth-fault current to those values considered safe for the integrity of the generator stator coil, but allowing simultaneously the selective operation of the protection system by using ordinary installation.

2. ISOLATED NEUTRAL SYSTEMS

The isolated neutral networks are MV networks with earth-fault currents within 10 A. In this case, there should be outlined the followings:

a) The normal operation of an isolated neutral network is indicated in references, as well as the phasor diagram corresponding to an operation with symmetrical load [1].

In the case of a phase-to-earth fault [2]:
- line-to-line voltage and the load currents are not affected;
- the unfaulted phase voltages rises of $\sqrt{3}$ times;
- the faulted phase voltage become 0 (the arc resistance was assumed R = 0).

Since the capacitance currents are not longer symmetrical, the resultant system capacitance current is not equal to zero, closing through the earth-fault arc. The phase-earth current is:

$$\underline{I}_p = \underline{I}_c = 3jU_f \omega C_p \text{ [A]} \qquad (1)$$

In the case of instability of the earth-fault arc, there can arise maximum overvoltages within (3,2-3,5)U_f.
The analytical expression of the phase voltages (phase C is the faulted one) when a single-phase short-circuit affected the system, are determined for two cases:
- Arc resistance $R \neq 0$;
- $R_1 = R_2 = R_0 = 0$ and the arc resistance R = 0 (where R with 1, 2, 0 indices means the positive, negative and zero sequence components in the network equivalent configurations).

b) Because of the electrical arc pulsation in the fault point of an earthed phase (phase C) there resulting trasitory overvoltages on the unfaulted phases, but also on the faulted phase. The unfaulted phase overvoltage ΔU_f is given by the equation (2) [1]:

$$\Delta U_f = U_{s\max} = \left[U_f + V_n\right] k_1 (1-d) \qquad (2)$$

where k_1 is the complement of the coupling coefficient and is determined by equation (3):

$$k_1 = \frac{C_p}{C_p + C_m} \qquad (3)$$

where C_p is the earth capacitance of one phase [F];
C_m – line-to-line capacitance [F];
V_n – neutral displacement voltage, calculated according to the equation (4) [1]:

$$V_n = a \cdot U_f \cdot \frac{1 + \frac{2}{3} k_1 (1-d)}{1 - \frac{2}{3} k_1 \cdot a(1-d)} \qquad (4)$$

where a = 0,9 is the reduction factor;
$e^{-\alpha t} = 1 - d$ - attenuation; it is given by the network losses and has the maximum value of:

- 0,96 for cable networks;
- 0,7-0,75 for overhead lines.

The faulted phase overvoltage reaches the maximum value of *2,2*U_f.

c) In the case of asymmetrical short-circuits (phase-to-earth or line-to-line-to-earth), there can arise overvoltages on the unfaulted phases due to the resonance between the circuits of positive, negative and zero sequence reactance [3], [4].

d) Prolonged overvoltages arisen in the isolated neutral systems in the moment of an earth-fault are determined by the resonance phenomena in the equivalent circuit composed by the positive sequence circuit in serial with the negative and zero sequence ones.
The value of the positive sequence voltage in the fault point is determined according to the equation (5), expressed in per units of the rated voltages [1]:

$$U^2 = \frac{1 + \sqrt{1 - k_1^2 \sin^2 2\delta}}{2k_1^2 \cdot \cos^2 \delta} \qquad (5)$$

with:

$$k_1 = 1 - \frac{q}{Q} \qquad (6)$$

where:
$q = \frac{1}{x_0}$ is capacitive power in the zero sequence configuration for $U_n=1$;
$Q = \frac{1}{x_1}$ - the reactive power of the passive sequence, looked from the fault point when the voltage $U_n = 1$ is applied;
δ - angle between electromotive voltage and the voltage in fault point.

By analyzing the equation (5) the following conclusions can be extracted:
- The value of the prolonged overvoltage increases while the reactive power consumption decreases.
- Increase of the source's power leads to the reducing of the prolonged overvoltages, since the Q decreases.
- The network extending results in overvoltages increasing, since q become bigger and k_1 smaller.
- The overvoltages are as bigger as the network rated is bigger.

The value of prolonged overvoltages is within (2-3,5) U_f.

e) During the switching-on operation of those transformers with isolated neutral, in the neutral point switching and temporary overvoltages arise. The temporary overvoltages arise in case of asymmetrical short-circuits (phase-to-earth), as well as for phases asynchronous switching-on. The amplitude of these overvoltages is lower than *Uf*.

3. STUDY CASE

The following input data are considered:
- line of 35 kV, length L=30 km;
- component of an isolated neutral system;
- phase C earthed;
- line material characteristics: OL-Al-120 mm^2;
- horizontal disposal of the phases $d_{12}=d_{23}=d_{31}$=4320 mm;
- line operates without ground-wire.

The following data will be determined:
- earth-fault current;

- maximum neutral voltage;
- unfaulted phase overvoltage.

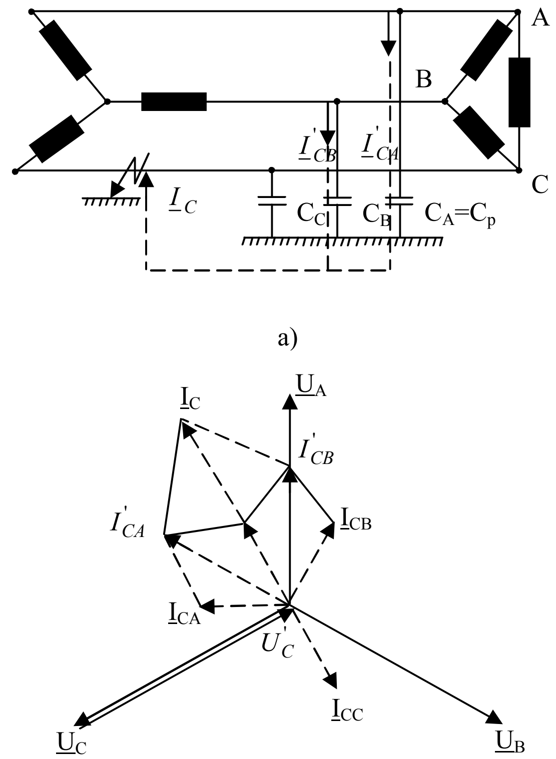

Figure 1: Isolated neutral networks in faulted operation (phase C earthed): a) network configuration; b) phasor diagram.

$$\begin{aligned} \underline{I}'_{CB} &= \underline{I}_{CB} - \underline{I}_{CC} \\ \underline{I}'_{CA} &= \underline{I}_{CA} - \underline{I}_{CC} \\ \underline{I}_C &= \underline{I}'_{CB} + \underline{I}'_{CA} \end{aligned} \qquad (7)$$

where I_{CB}, I_{CA}, I_{CC} are the capacitance currents for the normal operation with symmetrical loads.

It is noted that the line-to-line voltages ($\underline{U}_{AB}, \underline{U}_{BC}, \underline{U}_{CA}$) and load currents ($\underline{I}_{SA}, \underline{I}_{SB}, \underline{I}_{SC}$) are not affected.

The unfaulted phases voltages are $\underline{U}_A$ and $\underline{U}_B$, while on the faulted phase $\underline{U}_C = 0$.

Also, the electrical arc resistance is considered zero R=0.

The earth capacitance current is determined based on the equation (1), resulting:

$$\underline{I}_p = \underline{I}_c = 3j\omega C_p \cdot L \cdot U_f = 3j \cdot 2 \cdot \pi \cdot f \cdot C_p \cdot L \cdot U_f =$$

$$= 3j \cdot 2 \cdot \pi \cdot 50 \cdot 0{,}005512 \cdot 10^{-6} \cdot 30 \cdot \frac{35 \cdot 10^3}{\sqrt{3}} = 3{,}15\ A$$

where U_f[V] is the phase voltage;

C_p *[F]* – earth specific capacitance of one phase;

$$C_p = C_A = C_B = C_C = (0{,}6....0{,}7) \cdot C_s = 0{,}65 \cdot 0{,}00848 \cdot 10^{-6}$$
$$= 0{,}005512 \cdot 10^{-6}\ \text{F/km}$$

C_s-service line specific capacitance, according to the equation:

$$C_s = \frac{2\pi\varepsilon_0}{\ln\frac{d_m}{r_0}} = \frac{2\pi \cdot 8{,}84 \cdot 10^{-6}}{\ln\frac{4320}{6{,}2}} = 0{,}00848 \cdot 10^{-6}\ \text{F/km}$$

where d_m is the medium geometric distance between the phases determined with equation:

$$d_m = \sqrt[3]{d_{12} \cdot d_{23} \cdot d_{31}} = \sqrt[3]{4320 \cdot 4320 \cdot 4320} = 4320\ mm$$

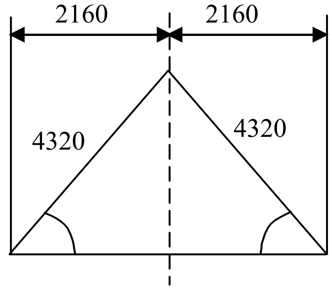

Figure 2: Explicative to the calculus of the medium geometric distance

r_0 – external radius of the line conductor determined with equation:

$$r_0 = \frac{d_c}{2} = \frac{12{,}36}{2} \cong 6{,}2\ \text{mm}$$

d_c – line conductor diameter determined with equation:

$$\frac{\pi d_c^{\,2}}{4} = s \quad \Rightarrow \mathrm{d_c} = \sqrt{\frac{4 \cdot \mathrm{s}}{\pi}} = \sqrt{\frac{4 \cdot 120}{\pi}} = 12{,}36\ mm$$

The neutral maximum voltage or the neutral displacement voltage is determined based on the equation (4), as following:

$$\begin{aligned} V_n &= a \cdot U_f \frac{1 + \frac{2}{3} k_1 (1 - d)}{1 - \frac{2}{3} k_1 \cdot a(1 - d)} = \\ &0{,}9 \cdot U_f \frac{1 + \frac{2}{3} \cdot 0{,}85 \cdot 0{,}75}{1 - \frac{2}{3} \cdot 0{,}85 \cdot 0{,}9 \cdot 0{,}75} = \\ &= 2{,}07 \cdot U_f = 2.07 \frac{35 \cdot 10^3}{\sqrt{3}} = \\ &= 41{,}83\ \text{kV} \end{aligned} \qquad (8)$$

with:

a=0,9 – reduction factor;

k_1 – complement of the coupling coefficient, determined based on the equation (3), as following:

$$k_1 = \frac{C_p}{C_p + C_m} =$$
$$= \frac{0{,}005512 \cdot 10^{-6}}{0{,}005512 \cdot 10^{-6} + 0{,}0009752 \cdot 10^{-6}} \cong$$
$$\cong 0{,}85$$

C_m – mutual specific capacitance between phases determined with equation:

$C_m = (0{,}10...0{,}13) \cdot C_s = 0{,}115 \cdot 0{,}00848 \cdot 10^{-6} =$
$0{,}0009752 \cdot 10^{-6}$ F/km

1-*d* is the oscillation damping, due to the network losses, with value 0,7...0,75 for overhead lines.
The overvoltages of the unfaulted phases can be determined for two calculus versions:

Version I
According to the equation (8):

$$U_{s\max} = U_f + V_n = U_f + 2{,}07 \cdot U_f =$$
$$3{,}07 \cdot U_f = 3{,}07 \cdot \frac{35}{\sqrt{3}}$$
$$\cong 62{,}04 \text{ kV}$$

Version II

According to the Fig. 3 and Table 1, there results:

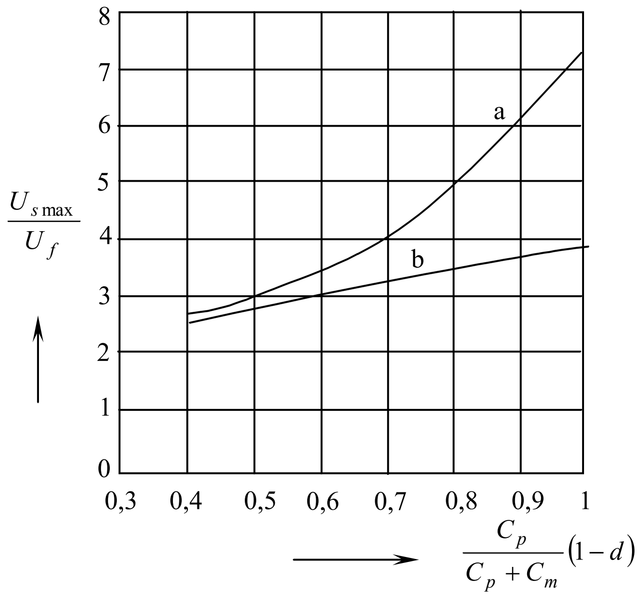

Figure 3. Variation of the ratio between unfaulted phases overvoltage and the phase voltage: a) according to W. Petersen; b) according to N.N. Beliakov [1]

By linear interpolation $\frac{U_{s\max}}{U_f}$ is determined corresponding to $k_1 \cdot (1-d) = 0{,}85 \cdot 0{,}75 = 0{,}6375$, according to the equation (9):

$$x = x_1 + \frac{(y - y_1)\cdot(x_2 - x_1)}{y_2 - y_1} \quad (9)$$

$k_1 \cdot (1-d) = \frac{C_p}{C_p + C_m}(1-d)$	$\frac{U_{s\max}}{U_f}$
0,3	-
0,4	2,67
0,5	3
0,6	3,5
0,7	4,17
0,8	4,83
0,9	6
0,10	7,5

Table 1: Variation of the ratio between the unfaulted phases overvoltage and the phase voltage, as a function of $\frac{C_p}{C_p + C_m} \cdot (1-d)$ according to W. Petersen

	$k_1(1\text{-}d)$	$\frac{U_{s\max}}{U_f}$	
y_1=	0,6	3,5	= x_1
y_2=	0,7	4,17	= x_2

Table 2: Explanation linked to the overvoltages determination by linear interpolation

Since

$$\frac{U_{s\max}}{U_f} = 3{,}5 + 0{,}25 = 3{,}75 \quad (10)$$

there results:

$$U_{s\max} = 3{,}75\, U_f = 75{,}77 \ kV \quad (10')$$

There should be mentioned that the calculus was performed according to the W. Petersen equations. These ones give covering values, superior to those developed by N.N. Beliakov or even corresponding to the real cases.

4. ALGORITHM AND SOFTWARE DEVELOPED IN VISUAL BASIC ENVIRONMENT FOR STUDY CASE

This software is an application developed in Visual Basic environment. It is designated to the electrical values calculus requested by the fast solving of the neutral earthing arrangements problems.
Visual Basic owns a large visual components library (lists, calendars, menus, etc.), with graphical and functional characteristics already implemented. Using this instrument type, the software designer can introduce and use self-developed components.

Visual Basic is an object-oriented programming language, having already implemented a class list with general utilisation.
According to the mathematical model, the authors developed a program for the calculus of different electrical values. Any user can administrate the input data.
For launching of calculus application, the *Start* button is pressed for displaying the *Start* menu. The cursor is moved after on the *Programs* (All Programs). In displayed sub-menu *Analiza linii electrice* is appealed and after that, *Linii electrice*. The interfaces 1, 2 and 3 are activated.

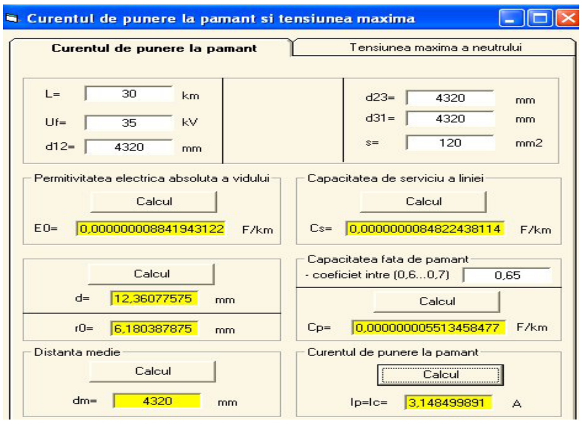

Figure 4: Interface no. 1

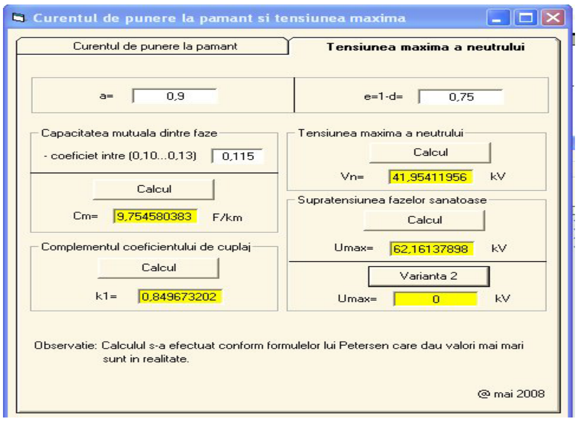

Figure 5: Interface no.2

In the white boxes the initial data of the problem are introduced in usual units. The program converts them subsequently in fundamental values in order to be appealed in the calculus. Introducing the data from up toward down, and from left to the right makes possible the data processing.
In the yellow boxes the values calculated by the software are displayed by successively pushing of the *calcul* buttons.
This software means a new approach to identify the influence that the modification of some parameters has for a network and consequently, the finding of some solution to mitigate their destructive effects.

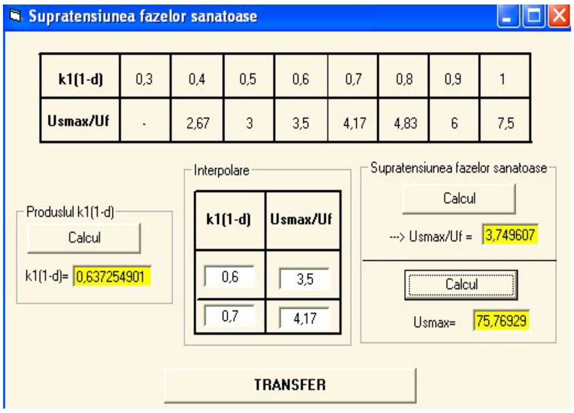

Figure 6: Interface no. 3

5. CONCLUSIONS

In the transmission and distribution networks almost 70÷80% of the faults are caused by the temporary single-phase earth-faults.
If these faults are not removed just on time, there can appear even permanent phase-to-phase or 3-phase short-circuits.
The effects of a phase-to-earth fault are of thermical type associated to the arc at the earth-fault place or isolation solicitation leading to its faster aging and breaking.
In the case of an accidental phase-to-earth fault, the neutral earthing arrangement has a great importance. If the neutral is directly earthed, then the accidental phase-to-earth fault leads to a single-phase short-circuit current. If the neutral is isolated, then the accidental phase-to-earth fault leads to increasing of the unfaulted phase voltages.
Therefore the neutral earthing arrangement determines in certain circumstances some overcurrents or overvoltages whose values should be known exactly.
The Authors are focused on the development of a software library with a wide applicability to the usual network configurations. Their researches will be consequently extended to the other neutral arrangements, following comparisons from the main features point of view: electrical arc, transient or steady-state overvoltages, telecommunication lines influence, etc.

References

[1] Mircea, I., *Instalații şi echipamente electrice. Ghid teoretic şi practic.* Editura Didactică şi Pedagogică, Bucureşti, 2002.

[2] *** *Normativ pentru construcția liniilor aeriene de energie electrică cu tensiuni peste 1000 V*, NTE 003/04/00.

[3] Digă, S. M., Velea, F., Ruşinaru, D., Bratu, C., *Modern aspects regarding the efficiency's improving of earthing installation of the substations' apparatus,* REGIONAL ENERGY FORUM, FOREN 2008, Section no: 3 Electricity Transportation and Distribution Grids, Neptun, 15-19 iunie 2008, No. code: S3-26.

[4] Dina, A., Iobăgel, A.M., Guzun, D.B., Dăescu, I., *Limitation of disturbances transmitted from power distribution grids to low voltage grids according to the distribution grid neutral earthing mode,* REGIONAL ENERGY FORUM, FOREN 2008, Section no: 3 Electricity Transportation and Distribution Grids, Neptun, 15-19 iunie 2008.