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Overview of Methods of Insulation Parameters Determination in Live Unearthed Electrical Networks

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Abstract – In the publication there is presented an overview of existing methods of insulation-to-ground parameters determination in live electrical networks with isolated neutral point. These parameters are necessary for calculation of ground fault currents and overvoltages occurring in these systems. There are described few methods of determination of insulation admittance parameters (leakage conductance and capacitance) based on measurement of voltages and computational processing of obtained results. To execute the presented procedures it is necessary to measure network voltages (RMS values or phasors) in certain operational conditions, namely in healthy operation and/or during an intentional grounding of a selected phase through a special element. Chapter 1 of the paper deals with determination of insulation equivalent admittance parameters whereas chapter 2 explains how to get insulation admittance parameters for single phases. Majority of available methods were developed abroad but very few have been applied in practice. In the paper limitations and shortcomings of respective procedures are pointed out. A modified method for general case of these parameters asymmetry in 3-phase networks is proposed.

Keywords – distribution networks, isolated neutral point, insulation admittance, conductance, capacitance

Introduction

For correct and safe operation of three-phase both overhead and cable power (mainly MV distribution) networks with isolated (unearthed) neutral point it is necessary to know actual values of its insulation-to-ground parameters. Insulation-to-ground of each phase has got two characteristic parameters: leakage conductance (or its reciprocal magnitude - resistance) and capacitance. These two parameters influence levels of ground fault currents and overvoltages between respective phases and ground. That's why insulation of these lines should be monitored in order to detect any possible problems or risks of its deterioration. However in practice this task is carried out only in de-energized networks because there are no safe and accurate methods of this supervision in live networks. As a result insulation level of lines is monitored only by electrical ground fault protections which switch off the line immediately after the insulation-to-ground breakdown (or they signal the detected failure). This limitation demonstrates the necessity to develop required tools for continuous or at least periodical monitoring of insulation of electrical networks with isolated neutral point. In the paper there are described few methods of insulation parameters determination applied abroad with their shortcomings and limitations. Two other methods (C, F) are provided by author: the first is featured by its universal scope of application, the second one is a novel proposal for determination of insulation-to-ground parameters of all single phases with asymmetrical values.

1. Existing Methods of Insulation Equivalent Admittance Determination in Live Three-Phase Networks

There have been developed and tested abroad few methods of insulation equivalent admittance (complex value of aggregated conductances and capacitances $\underline{Y_i} = G_a + G_b + G_c + j\omega(C_a + C_b + C_c)$) determination in live three-phase networks with isolated neutral point. It should be remembered that insulation-to-ground equivalent admittance of the whole network is formed by parallel connection of leakage conductances and capacitances of all phases in all lines. This basic indicator of insulation condition is used for quick calculation of ground fault currents according to Thevenin theorem.

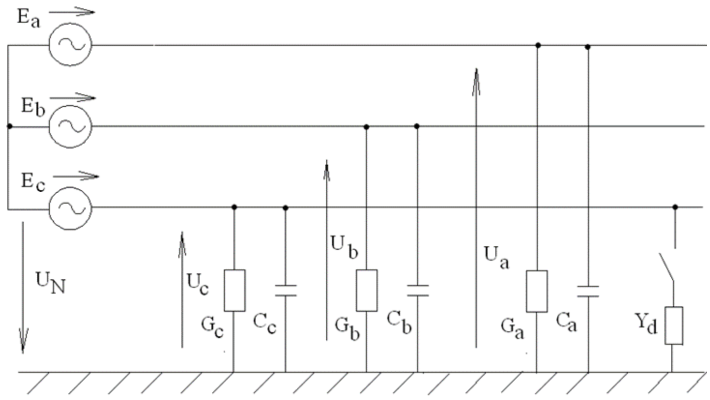

Fig.1 Circuit diagram of a three-phase AC IT system for measurement procedures. Designations: $\underline{E_a}$, $\underline{E_b}$, $\underline{E_c}$ - source phase voltages, $\underline{U_N}$ – network displacement voltage, $\underline{Y_d}$ – admittance of a grounding element, G_a , G_b , G_c – phase *a, b, c* insulation-to-ground conductances, C_a , C_b , C_c - phase *a, b, c* insulation-to-ground capacitances.

Below there are presented three selected procedures of insulation equivalent admittance determination. Two methods ([1], [2]) exploit measurement of zero sequence component of network phase voltages (equal to network displacement voltage U_N at Fig.1). The third method mentioned in [3] deserves special attention as it requires only two measurements of RMS values of a selected phase voltage.

Method A

This method [1] exploits measurement of network displacement voltage U_N (see Fig.1) when one of phase conductors is grounded through an additional element – in this case capacitor with susceptance B_d i.e. $Y_d=B_d$. The sought value of insulation equivalent admittance is given by formula.

$$\left|\underline{Y_i}\right| = B_d \cdot \left|\frac{\underline{E_c}}{\underline{U_N}}\right| \tag{1}$$

This formula can be derived from formula defining network displacement voltage $\underline{U_N}$ with the additional capacitor C_d connected between phase *c* and ground

$$\underline{U_N} = \frac{\underline{E_a}\cdot\left(G_a + j\omega C_a\right) + \underline{E_b}\cdot\left(G_b + j\omega C_b\right) + \underline{E_c}\cdot\left(G_c + j\omega C_c + jB_d\right)}{\underline{Y_i} + jB_d} \tag{2}$$

In case of symmetry of source phase voltages $\underline{E_a}$, $\underline{E_b}$, $\underline{E_c}$, conductances $G_a = G_b = G_c$ and capacitances $C_a = C_b = C_c$, equation (2) is reduced to the following one

$$\underline{U_N} = \frac{\underline{E_c}\cdot jB_d}{\underline{Y_i} + jB_d} \tag{3}$$

The next assumption necessary to obtain formula (1) from (3) is condition $B_d << \left|\underline{Y_i}\right|$. But if this requirement is met, $\underline{U_N}$ voltage level in comparison to source phase voltage value E_c will be very low and this leads to inaccurate measurement and calculation result. Only if all these listed simplifying conditions are met, formula (1) is true. Otherwise application of this formula will give result burdened with an error which might go outside permissible limits.

Method B

This method is executed in the same way as method A, however network displacement voltage $\underline{U_N}$ is used in different way. As in method A an additional element - lets use resistor with known conductance value G_1 – is connected between phase *a* and ground. If requirements of symmetry of source phase voltages $\underline{E_a}$, $\underline{E_b}$, $\underline{E_c}$, conductances $G_a = G_b = G_c$ and capacitances $C_a = C_b = C_c$ are met, complex value of $\underline{U_N}$ can be expressed as

$$\underline{U_N} = U_N \cdot (\cos\alpha + j\sin\alpha) = E_a \frac{G_1}{G_1 + (G_i + jB_i)} \tag{4}$$

where $G_i = G_a + G_b + G_c$ and $B_i = \omega(C_a + C_b + C_c)$, α is an angle between phasors $\underline{E_a}$ and $\underline{U_N}$, phase angle of phasor $\underline{E_a}$ is assumed 0.

To determine sought insulation parameters G_i and B_i , RMS value U_N and phase angle α of phasor $\underline{U_N}$ must be known – these two values are measured with for example scopemeter or oscilloscope.

From equation (4) parameters G_i and B_i are obtained as

$$G_i = \left(\frac{E_a}{U_N} \cos\alpha - 1 \right) G_1 \tag{5}$$

$$B_i = -\frac{E_a \cdot \sin\alpha}{U_N} G_1 \tag{6}$$

Method B has got similar drawbacks and limitations as method A. These are requirements of symmetry of source phase voltages $\underline{E_a}$, $\underline{E_b}$, $\underline{E_c}$, conductances $G_a = G_b = G_c$ and capacitances $C_a = C_b = C_c$. It is also required that G_1 be much smaller than G_i and B_i in order not to disturb operation of the network. However this requirement may cause difficulty to execute accurate measurement of phasor's $\underline{U_N}$ small value U_N and α .

To avoid problems with accurate measurement of small values as well as when symmetry of source voltages, insulation ground conductances or capacitances is not fulfilled, another method of insulation equivalent admittance determination was proposed. As it was only mentioned in [3] its more detailed description is presented below.

Method C

In live three-phase IT AC systems insulation equivalent resistance and capacitance values can be determined on the basis of measured RMS voltages of a selected phase. Phase-to-ground voltage of this conductor (e.g. *c*) is measured in three states: (1) in normal working (healthy) condition, (2) with resistor $R_1 = 1/G_1$ connected between this conductor and ground, 3) with resistor $R_2 = 1/G_2$ connected instead of R_1. According to Thevenin's theorem RMS values of phase *c* voltages in the second and the third state are equal respectively to (U_{c1} is phase *c* voltage RMS value in state 1)

$$U_{c2} = \frac{U_{c1}}{\left| \frac{1}{G_i + jB_i} + \frac{1}{G_1} \right|} \cdot \frac{1}{G_1} = U_{c1} \cdot \frac{|G_i + jB_i|}{|G_1 + G_i + jB_i|} \tag{7}$$

$$U_{c3} = \frac{U_{c1}}{\left| \frac{1}{G_i + jB_i} + \frac{1}{G_2} \right|} \cdot \frac{1}{G_2} = U_{c1} \cdot \frac{|G_i + jB_i|}{|G_2 + G_i + jB_i|} \tag{8}$$

Dividing U_{c2} by U_{c1} and U_{c3} by U_{c1} , there are obtained two equations containing two unknown parameters G_i, B_i . Substituting

$$\left(\frac{U_{c1}}{U_{c2}}\right)^2 = q_1 + 1 \quad \text{and} \quad \left(\frac{U_{c1}}{U_{c3}}\right)^2 = q_2 + 1 \tag{9}$$

the aforementioned equations (7) and (8) assume the following form

$$\left(\left|\frac{G_1 + G_i + j \cdot B_i}{G_i + jB_i}\right|\right)^2 = q_1 + 1 \tag{10}$$

$$\left(\left|\frac{G_2 + G_i + j \cdot B_i}{G_i + jB_i}\right|\right)^2 = q_2 + 1 \tag{11}$$

From equations (10), (11) the following formulas are derived

$$R_i = \frac{1}{G_i} = 2 \cdot \frac{\frac{q_2}{R_1} - \frac{q_1}{R_2}}{\frac{q_1}{R_2^2} - \frac{q_2}{R_1^2}} \tag{12}$$

$$B_i = \sqrt{\frac{G_1^2}{q_1} + \frac{2 \cdot G_1}{q_1} \cdot G_i - G_i^2} \tag{13}$$

It is possible to replace in this method resistors R_1 and R_2 by capacitors C_1 and C_2. In this case insulation equivalent parameters are given by formulas given in [7]. There must be underlined the main features of the presented procedure. One quality is that troublesome measurement of phase angle (in method B) is replaced by measurements of RMS values. This method is universal as no requirements are put to symmetry of source phase voltages as well as to symmetry of insulation phase conductances and capacitances. Neither number of phases plays any role.

Method D

Another universal method of insulation equivalent resistance and capacitance values determination can be applied in multi-phase (not necessarily 3-phase) AC IT systems [4]. In this network a selected phase e.g. *a* voltage phasor is measured in two operating states: (1) in normal working (healthy) condition, (2) with an additional element, for example capacitor *C,* connected between the selected phase and ground. In both these conditions dead (it means fault resistance equal to zero) ground-fault in phase *a* current value I_{fa} is of course the same. According to Thevenin's theorem it is equal to

$$\underline{I}_{fa} = \underline{U}_{a1} \cdot \underline{Y}_i = \underline{U}_{a2} \cdot (\underline{Y}_i + j \cdot \omega \cdot C) \tag{14}$$

where $\underline{U}_{a1}$ and $\underline{U}_{a2}$ are complex values of phase *a* voltage measured in these two operating states, $\underline{Y_i}$ =G_i+jB_i is network insulation equivalent admittance. From equation (14) formula (15) for determination of insulation equivalent admittance parameters G_i and B_i is obtained:

$$\underline{Y_i} = G_i + j \cdot B_i = \frac{j \cdot \omega \cdot C \cdot \underline{U_{a2}}}{\underline{U_{a1}} - \underline{U_{a2}}} \tag{15}$$

It should be emphasized that for application of this method it is necessary to measure phase angles of voltages $\underline{U_{a1}}$ and $\underline{U_{a2}}$ (in relation to any reference phasor e.g. source voltage $\underline{E_a}$). Though this requirement may cause some difficulty in execution, this method is – similarly to method C - very universal with practically no limitations.

2. Methods of Insulation Admittance of Single Phases Determination in Live Three-Phase Networks

Problem of insulation admittance of single phases determination in general case (i.e. with asymmetrical values of G_a, G_b, G_c and/or C_a, C_b, C_c) is much more difficult than for symmetry of phase insulation conductances or capacitances. Few methods for this purpose have been developed so far but only one has found application. This is method E described below which has got however a substantial limitation – requirement of symmetry of phase insulation capacitances. Two other methods F and G have not been used so far due to significant interference with network operation.

Method E

This procedure [5] is used for determination of insulation parameters of single phases G_a, G_b, G_c and C= C_a = C_b = C_c . Symmetry of source phase voltages $\underline{E_a}$, $\underline{E_b}$, $\underline{E_c}$ is also required. In order to find these four unknown parameters G_a, G_b, G_c and C there are necessary four equations which are obtained in two operating states of the network: (1) in normal working (healthy) condition, (2) with resistor R_d=$1/G_d$ connected between a selected phase conductor e.g. phase *a* and ground. In each of these working conditions all phase voltages RMS values U_a, U_b, U_c are measured to calculate real and imaginary parts of complex displacement voltage phasors $\underline{U_{1N}} = U_{1N1} + jU_{1N2}$ in state 1 and $\underline{U_{2N}} = U_{2N1} + jU_{2N2}$ in state 2. Phase angle of source phase "a" voltage phasor $\underline{E_a}$ is assumed 0. As described in [5] $\underline{U_{1N}}$ phasor components are given by formulas

$$U_{1N1} = \frac{-2U_{1a}^2 + U_{1b}^2 + U_{1c}^2}{6 \cdot E_a} \text{ and } U_{1N2} = \frac{U_{1b}^2 - U_{1c}^2}{2\sqrt{3} \cdot E_a} \tag{16}$$

whereas for phasor $\underline{U_{2N}}$ similar formulas are valid

$$U_{2N1} = \frac{-2U_{2a}^2 + U_{2b}^2 + U_{2c}^2}{6 \cdot E_a} \text{ and } U_{2N2} = \frac{U_{2b}^2 - U_{2c}^2}{2\sqrt{3} \cdot E_a} \tag{17}$$

Insulation-to-ground equivalent admittance is

$$\underline{Y_i} = G_i + jB_i = G_a + G_b + G_c + j \cdot 3\omega C = \frac{G_d \cdot \left(E_a - \underline{U_{2N}}\right)}{\underline{U_{2N}} - \underline{U_{1N}}} \tag{18}$$

The sought insulation phase conductances are given by formulas

$$G_a = \frac{G_i + 2G_1}{3},\ G_b = \frac{G_i - G_1 - G_2}{3},\ G_c = \frac{G_i - G_1 + G_2}{3} \tag{19}$$

where

$$G_1 = \frac{G_i \cdot U_{1N1} - B_i \cdot U_{1N2}}{E_a} \text{ and } G_2 = \frac{\left(G_i \cdot U_{1N2} + B_i \cdot U_{1N1}\right) \cdot \sqrt{3}}{E_a} \tag{20}$$

Method F

This method employing an additional single-phase voltage source is explained in Fig.2 [6]. It consists of measurements of phase voltages phasors in the following operating states of the network: 1) normal network operation, 2) intentional grounding of a selected phase (e.g. *c*) through an element with $\underline{Y_d}$ admittance, 3) inclusion of an additional voltage source $\underline{U_d}$ of the network frequency in series into a selected phase (for example phase "*b*" in Fig.2).

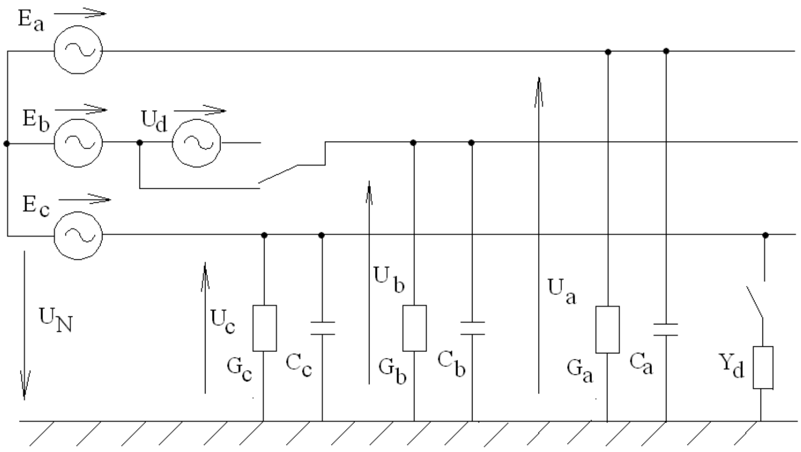

Fig.2 Circuit diagram of a three-phase AC IT system for measurement procedure F. Designations: E_a , E_b , E_c – source phase voltages, U_d - additional voltage source, U_N – network displacement voltage, Y_d – admittance of grounding element, G_a , G_b , G_c – insulation-to-ground conductances, C_a , C_b , C_c - insulation-to-ground capacitances.

Network operating conditions relating to steps 1, 2, 3 are described by the following system of equations expressing balance of earth-leakage currents according to Kirchhoff's 1st law:

$$\underline{U_{a1}} \cdot \underline{Y_a} + \underline{U_{b1}} \cdot \underline{Y_b} + \underline{U_{c1}} \cdot \underline{Y_c} = 0 \quad (21)$$

$$\underline{U_{a2}} \cdot \underline{Y_a} + \underline{U_{b2}} \cdot \underline{Y_b} + \underline{U_{c2}} \cdot \underline{Y_c} = -\underline{U_{c2}} \cdot \underline{Y_d} \quad (22)$$

$$\underline{U_{a3}} \cdot \underline{Y_a} + \underline{U_{b3}} \cdot \underline{Y_b} + \underline{U_{c3}} \cdot \underline{Y_c} = 0 \quad (23)$$

Phase voltages and insulation admittances are complex values. To calculate three unknown admittances $\underline{Y_a}$, $\underline{Y_b}$, $\underline{Y_c}$ (6 real values in total) three leakage current balance equations are necessary. To get an univocal result (i.e. strictly one set of three admittance complex values) system of these equations should have one solution. This requirement is met if determinant of the equations system (21), (22), (23) is not equal to zero. Its value can be calculated with help of the following relationships between voltages of network sources:

$$\underline{U_{a1}} = E - \underline{U_{N1}},\ \underline{U_{b1}} = a^2E - \underline{U_{N1}},\ \underline{U_{c1}} = aE - \underline{U_{N1}},\ a=ej120^o \quad (24)$$

$$\underline{U_{a2}} = E - \underline{U_{N2}},\ \underline{U_{b2}} = a^2E - \underline{U_{N2}},\ \underline{U_{c2}} = aE - \underline{U_{N2}} \quad (25)$$

$$\underline{U_{a3}} = E - \underline{U_{N3}},\ \underline{U_{b3}} = a^2E + U_d - \underline{U_{N3}},\ \underline{U_{c3}} = aE - \underline{U_{N3}} \quad (26)$$

For simplicity it was assumed that source voltages remain constant during measurements and contain only positive sequence symmetrical component *E*. Taking into account relationships given above, determinant of the system of equations (21), (22), (23) is

$$\det M = \begin{vmatrix} E - \underline{U_{N1}} & a^2E - \underline{U_{N1}} & aE - \underline{U_{N1}} \\ E - \underline{U_{N2}} & a^2E - \underline{U_{N2}} & aE - \underline{U_{N2}} \\ E - \underline{U_{N3}} & a^2E + \underline{U_d} - \underline{U_{N3}} & aE - \underline{U_{N3}} \end{vmatrix} \quad (27)$$

After performing calculation this determinant is equal to

$$\det M = (1-a) \cdot E \cdot (\underline{U_{N2}} - \underline{U_{N1}}) \cdot \underline{U_d} \quad (28)$$

This determinant value is obviously different from zero because displacement voltages in steps 1 and 2 are not equal due to additional grounding element's admittance in step 2.

Method G

In this method [4] steps 1 and 2 are identical as in method F, but in step 3 there is executed swapping of two phases (switchover) e.g. *a* and *b* with a switch *S* as shown in Fig.3.

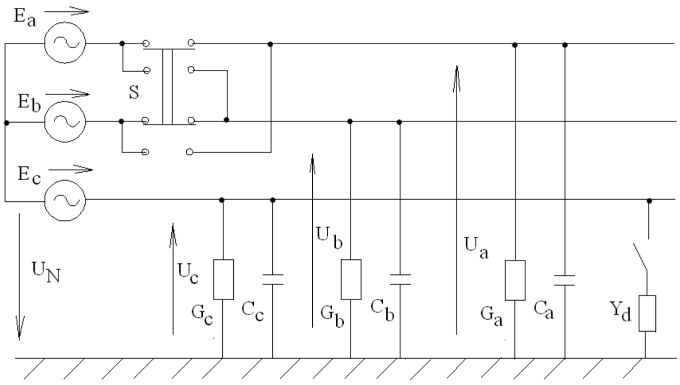

Fig.3 Illustration of phase swapping method. Designations as in Fig.2, S – switch (circuit breaker or on-load disconnector)

For this procedure the following system of equations is valid:

$$\underline{U}_{a1} \cdot \underline{Y}_a + \underline{U}_{b1} \cdot \underline{Y}_b + \underline{U}_{c1} \cdot \underline{Y}_c = 0 \quad (29)$$

$$\underline{U}_{a2} \cdot \underline{Y}_a + \underline{U}_{b2} \cdot \underline{Y}_b + \underline{U}_{c2} \cdot \underline{Y}_c = -\underline{U}_{c2} \cdot \underline{Y}_d \quad (30)$$

$$\underline{U}_{a3} \cdot \underline{Y}_a + \underline{U}_{b3} \cdot \underline{Y}_b + \underline{U}_{c3} \cdot \underline{Y}_c = 0 \quad (31)$$

Determinant of this system of equations is:

$$\det M = \begin{vmatrix} E - \underline{U}_{N1} & a^2 E - \underline{U}_{N1} & aE - \underline{U}_{N1} \\ E - \underline{U}_{N2} & a^2 E - \underline{U}_{N2} & aE - \underline{U}_{N2} \\ a^2 E - \underline{U}_{N3} & E - \underline{U}_{N3} & aE - \underline{U}_{N3} \end{vmatrix} \quad (32)$$

After performing calculation it is equal to

$$\det M = 3 \cdot (1 - a) \cdot E^2 \cdot (\underline{U}_{N2} - \underline{U}_{N1}) \quad (33)$$

Similarly to method F this determinant is also different from zero, thus this method provides an univocal solution.

Unfortunately this method requires to switch off network's supply twice to swap phases. It should be underscored that all presented methods from A to G can be applied only if network insulation parameters and source voltages are constant during the whole measuring cycle. However instead of a troublesome execution of an additional voltage source inclusion (method F) or practically impermissible phase swapping (method G) another measurement procedure can be suggested for determination of 6 insulation asymmetrical parameters. Step 3 of method F or G should be modified to utilize an auxiliary voltage source with a different frequency. It is connected between one of phases and ground as described in [7], [8].

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