

Chapter 2

Ground Insulation Measurement in AC IT Systems

Abstract In the chapter there is presented general information on physical nature of network-to-ground insulation. Sense of “insulation equivalent resistance” parameter is explained. A method of insulation resistances-to-ground of single phases and insulation equivalent resistance determination is presented for de-energized AC IT systems. Procedures of insulation equivalent resistance and total capacitance determination in live networks are described. Detailed description of few methods of single phases insulation parameters (i.e. resistances and capacitances) determination in both single- and three-phase systems is given. Several unconventional methods of insulation parameters measurement are presented. Attention is paid to ways of ground fault, ground leakage and possible electric shock currents analytical evaluation and practical measurement. Influence of insulation parameters on these currents levels is discussed. Ground fault current compensation problems are dealt with.

2.1 General Information

In AC IT systems phase voltages and ground fault currents depend on line-to-ground insulation parameters of single conductors, but are not influenced by wire-to-wire insulation. This conclusion can be easily explained for single-phase networks. Leakage current from phase wire to earth is of course equal to leakage current from earth to the neutral wire. Its value is given by formula (1.21), from which it follows that earth leakage current depends **only** on line-to-ground insulation parameters of single conductors.

2.1.1 Spatial Distribution of Insulation Resistance: Network's Insulation Equivalent Circuit

Most often AC IT systems are supplied from a transformer, sometimes they are fed by a generator. Modern AC IT supply systems are equipped with necessary measurement

devices (voltage, current, power, energy etc. meters), insulation monitor and sometimes fault locating system (see Figs. 1.1 and 1.2a, b). The most extensive component of a network are wires supplying power to all its parts. Insulation between conductors and also between any of them and ground has spatial distribution. Electrical parameters of network insulation are resistance and capacitance. Their values are important for network performance both in transient and steady-state conditions.

In order to simplify description of behaviour of spatially distributed physical systems it is convenient to transform them into a topology consisting of discrete elements. The lumped element model of electric circuit's insulation makes the simplifying assumption that its attributes (parameters)—resistance and capacitance—are concentrated into idealized elements i.e. resistors and capacitors connected to the network conductors.

According to the simplified network circuit diagram these elements are resistors R_a , R_b etc. and capacitors C_a , C_b etc. However practical usefulness of this representation comprising respective conductors is quite limited. Commonly applied insulation monitors measure insulation equivalent resistance which is a substitute resistance of all elements existing between galvanically connected points of this electric circuit and ground. Meaning (sense) of this electrical parameter can be explained with use of Thevenin's theorem. Equivalent network insulation-to-ground resistance is resistance between the point of possible fault and ground. It is calculated as a substitute resistance of all parallelly connected elements existing between this network and ground with all voltage sources being shorted and all current sources being eliminated. The purpose of this substitute parameter follows directly from Thevenin's theorem—its application simplifies ground fault current calculation. If insulation capacitance to ground can be neglected, this current magnitude is inversely proportional to sum of fault resistance at the place of the fault and the aforementioned substitute insulation resistance. Due to this dependence as well as convenience to perform measurement, insulation equivalent resistance parameter is much more often used than resistances of single conductors insulation to ground. For the same reasons network insulation equivalent (total) capacitance to ground is more useful parameter than capacitances of single conductors to ground.

2.2 Insulation Parameters Determination in Single-Phase Networks

2.2.1 De-energized Networks

2.2.1.1 Measurements with Megohmmeters

In de-energized single-phase AC IT systems insulation-to-ground equivalent resistance R_i can be easily measured with an megohmmeter. This parameter is defined similarly to insulation-to-ground equivalent impedance (see formula 1.19):

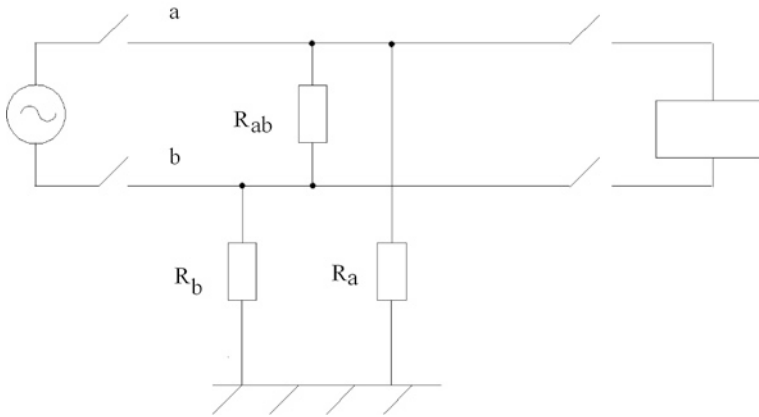


Fig. 2.1 Single phase AC IT network circuit diagram showing all insulation resistances. *Note* for insulation measurement all voltage sources and loads must be disconnected!

$$R_i = \frac{R_a \cdot R_b}{R_a + R_b} \quad (2.1)$$

Both conductors (phase “a” and neutral “b”) should be shorted together and insulation equivalent resistance measured between these wires and ground. If resistances of single wires insulation to ground are sought, more measurements should be executed (see Fig. 2.1).

This procedure comprises the following insulation resistance measurements between ground (g) and:

- (1) shorted “a” and “b”—readout $R_{ab-g} = R_i$,
- (2) “a” with grounded “b”—readout R_{a-bg} ,
- (3) “b” with grounded “a”—readout R_{b-ag} .

As result three equations are obtained with three unknown parameters R_a , R_b , R_{ab}

$$R_i = \frac{R_a \cdot R_b}{R_a + R_b}, R_{a-bg} = \frac{R_a \cdot R_{ab}}{R_a + R_{ab}}, R_{b-ag} = \frac{R_b \cdot R_{ab}}{R_b + R_{ab}} \quad (2.2)$$

The sought R_a , R_b values are given by the following formulas

$$R_a = \frac{2 \cdot R_i \cdot R_{a-bg} \cdot R_{b-ag}}{R_{a-bg} \cdot R_{b-ag} + R_i \cdot (R_{b-ag} - R_{a-bg})}, \quad (2.3)$$

$$R_b = \frac{2 \cdot R_i \cdot R_{a-bg} \cdot R_{b-ag}}{R_{a-bg} \cdot R_{b-ag} + R_i \cdot (R_{a-bg} - R_{b-ag})}$$

Similar approach can be adopted in three-phase AC IT systems, however more separate measurements with an megohmmeter are necessary as there are six unknown insulation parameters.

If insulation-to-ground capacitances of single conductors are sought, these quantities could be determined with an additional procedure using an AC auxiliary source replacing network's disconnected supply source(s). This method is presented in the next section as a procedure applied in live networks.

2.2.1.2 Indirect Methods of Insulation Parameters Determination

There are several so called “technical” methods of indirect determination of parameters of electrical elements or circuits **supplied by an auxiliary (test) voltage** source. These procedures are based on use of typical (multi)meters as voltmeters, ammeters or wattmeters. In fact none of them is specially addressed to measurement of electrical insulation parameters (resistance and capacitance). Nevertheless under some assumptions few procedures bring results with satisfactory accuracy. An example of a simple indirect method exploiting a voltmeter, an ammeter and an auxiliary resistor is presented in Fig. 2.2.

The measuring circuit fed by an auxiliary voltage source U includes a resistor $R_0 = 1/G_0$ connected in parallel to the tested two-terminal element (e.g. network-to-ground insulation) of unknown parameters $G_i = 1/R_i$, $B_i = 1/X_i$. This procedure consists of two steps.

These two steps are described by equations

$$I_1^2 = (G_i^2 + B_i^2) \cdot U^2 \quad (2.4)$$

$$I_2^2 = [(G_i + G_0)^2 + B_i^2] \cdot U^2 \quad (2.5)$$

from which formulas for G_i , B_i can be derived

$$G_i = -\frac{G_0}{2} + \frac{I_2^2 - I_1^2}{2 \cdot G_0 \cdot U^2} \quad (2.6)$$

$$B_i = \sqrt{\left(\frac{I_1}{U}\right)^2 - G_i^2} \quad (2.7)$$

This method requires constant RMS value U of auxiliary voltage and internal impedance of (micro)ammeter negligible in comparison to R_i , X_i and R_0 which is practically always true. In some cases these procedures may also be applied in live circuits in normal working conditions.

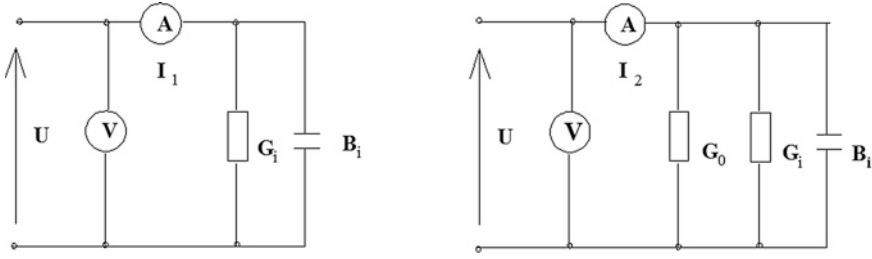


Fig. 2.2 Explanation of an indirect method with two steps

2.2.2 Live Networks

In live single-phase AC IT systems (Fig. 1.1) insulation equivalent resistance and capacitance can be calculated using measured conductor-to-ground RMS voltages of one of the wires a or b . Conductor-to-ground voltage of this wire (e.g. a) is measured in three states: (1) U_1 in normal working condition (2) U_2 with resistor $R_1 = 1/G_1$ connected between this conductor and ground, (3) U_3 with resistor $R_2 = 1/G_2$ connected instead of R_1 . These conditions are described by the following equations of (ground) leakage currents balances according to Kirchhoff's first law:

$$\underline{U}_1 \cdot (G_a + jB_a) = (E - \underline{U}_1) \cdot (G_b + jB_b) \quad (2.8)$$

$$\underline{U}_2 \cdot (G_a + G_1 + jB_a) = (E - \underline{U}_2) \cdot (G_b + jB_b) \quad (2.9)$$

$$\underline{U}_3 \cdot (G_a + G_2 + jB_a) = (E - \underline{U}_3) \cdot (G_b + jB_b) \quad (2.10)$$

By eliminating the source voltage E two equations containing two unknown parameters G_i , B_i , where $G_i = G_a + G_b$ and $B_i = B_a + B_b$, are obtained.

Substituting

$$\left(\frac{U_1}{U_2}\right)^2 = q_1 + 1 \quad \text{and} \quad \left(\frac{U_1}{U_3}\right)^2 = q_2 + 1 \quad (2.11)$$

these equations are as follows

$$\left(\left|\frac{G_i + G_1 + jB_i}{G_i + jB_i}\right|\right)^2 = q_1 + 1 \quad (2.12)$$

$$\left(\left|\frac{G_i + G_2 + jB_i}{G_i + jB_i}\right|\right)^2 = q_2 + 1 \quad (2.13)$$

From Eqs. (2.12) and (2.13) the following formulas are derived

$$R_i = \frac{1}{G_i} = 2 \cdot \frac{\frac{q_2}{R_1} - \frac{q_1}{R_2}}{\frac{q_1}{R_2^2} - \frac{q_2}{R_1^2}} \quad (2.14)$$

$$B_i = \sqrt{\frac{G_1^2}{q_1} + \frac{2 \cdot G_1}{q_1} \cdot G_i - G_i^2} \quad (2.15)$$

Modification of the method described above is possible. It consists in replacement of resistors R_1 and R_2 by capacitors $C_1 = B_1/\omega$ and $C_2 = B_2/\omega$. In this case insulation equivalent parameters are given by the following formulas (their derivation has been omitted as similar to the method described above):

$$B_i = \frac{1}{2} \cdot \frac{B_2^2 \cdot q_1 - B_1^2 \cdot q_2}{B_1 \cdot q_2 - B_2 \cdot q_1} \quad (2.16)$$

$$R_i = \frac{1}{G_i} = \frac{1}{\sqrt{\frac{B_2^2}{q_2} + \frac{2 \cdot B_2}{q_2} \cdot B_i - B_i^2}} \quad (2.17)$$

This approach may serve for calculation of not only insulation equivalent resistance and capacitance values, but also for determination of single conductors resistances R_a , R_b and capacitances C_a , C_b . The procedure requires connection of only one element between a selected conductor and ground, however knowledge of the source voltage E is necessary. According to formulas (1.3) given in Sect. 1.2, real x and imaginary y parts of vector \underline{U}_a complex magnitude can be calculated:

$$x = \operatorname{Re} \underline{U}_a = \frac{E^2 + U_a^2 - U_b^2}{2 \cdot E} \quad (2.18)$$

$$y = \operatorname{Im} \underline{U}_a = \sqrt{U_a^2 - x^2} \quad (2.19)$$

Thus

$$\underline{U}_a = x + j \cdot y \quad (2.20)$$

$$\underline{U}_b = E - x - j \cdot y \quad (2.21)$$

Similarly with conductor a grounded by resistor $R_1 = 1/G_1$ phase-to-ground voltages \underline{U}'_a , \underline{U}'_b are given as follows:

$$\underline{U}'_a = v + j \cdot w \quad (2.22)$$

$$\underline{U}'_b = E - v - j \cdot w \quad (2.23)$$

where

$$v = \frac{E^2 + U_a'^2 - U_b'^2}{2 \cdot E} \quad (2.24)$$

$$w = \sqrt{U_a'^2 - v^2} \quad (2.25)$$

Substituting these expressions to Eqs. (2.18), (2.19) the following is obtained:

$$(x + j \cdot y) \cdot (G_a + jB_a) = (E - x - j \cdot y) \cdot (G_b + jB_b) \quad (2.26)$$

$$(v + j \cdot w) \cdot (G_a + G_1 + jB_a) = (E - v - j \cdot w) \cdot (G_b + jB_b) \quad (2.27)$$

In each of (2.26) and (2.27) equations real and imaginary parts of both sides must be equal. By comparing these parts four Eqs. (2.28)–(2.31) are obtained. From these equations the unknown parameters G_a , G_b , B_a , B_b can be determined. The final formulas have been omitted—these can be easily derived by readers.

$$x \cdot G_a - y \cdot B_a = (E - x) \cdot G_b + y \cdot B_b \quad (2.28)$$

$$x \cdot B_a + y \cdot G_a = (E - x) \cdot B_b - y \cdot G_b \quad (2.29)$$

$$v \cdot (G_a + G_1) - w \cdot B_a = (E - v) \cdot G_b + w \cdot B_b \quad (2.30)$$

$$v \cdot B_a + w \cdot (G_a + G_1) = (E - v) \cdot B_b - w \cdot G_b \quad (2.31)$$

2.3 Insulation Parameters Determination in Live Three-Phase Networks

2.3.1 Insulation Equivalent Resistance and Capacitance Values Determination

In live three-phase IT AC systems (Fig. 1.2a, b) insulation equivalent resistance and capacitance values can be determined on the basis of measured RMS voltages of a selected phase a , b or c [1]. 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 . In these conditions zero-sequence component of phase voltages is as follows:

$$\underline{U_{01}} = \frac{\underline{E_a} \cdot \underline{Y_a} + \underline{E_b} \cdot \underline{Y_b} + \underline{E_c} \cdot \underline{Y_c}}{\underline{Y_a} + \underline{Y_b} + \underline{Y_c}} = \frac{\underline{E_a} \cdot \underline{Y_a} + \underline{E_b} \cdot \underline{Y_b} + \underline{E_c} \cdot \underline{Y_c}}{G_i + j \cdot B_i} \quad (2.32)$$

$$\underline{U_{02}} = \frac{\underline{E_a} \cdot \underline{Y_a} + \underline{E_b} \cdot \underline{Y_b} + \underline{E_c} \cdot (\underline{Y_c} + G_1)}{\underline{Y_a} + \underline{Y_b} + \underline{Y_c} + G_1} = \frac{\underline{E_a} \cdot \underline{Y_a} + \underline{E_b} \cdot \underline{Y_b} + \underline{E_c} \cdot \underline{Y_c} + \underline{E_c} \cdot G_1}{G_1 + G_i + j \cdot B_i} \quad (2.33)$$

$$\underline{U_{03}} = \frac{\underline{E_a} \cdot \underline{Y_a} + \underline{E_b} \cdot \underline{Y_b} + \underline{E_c} \cdot (\underline{Y_c} + G_2)}{\underline{Y_a} + \underline{Y_b} + \underline{Y_c} + G_2} = \frac{\underline{E_a} \cdot \underline{Y_a} + \underline{E_b} \cdot \underline{Y_b} + \underline{E_c} \cdot \underline{Y_c} + \underline{E_c} \cdot G_2}{G_2 + G_i + j \cdot B_i} \quad (2.34)$$

By substituting formulas (2.32), (2.33), (2.34) to (1.10), (1.11), (1.12), phase voltages of conductor c in these operating states are obtained:

$$\underline{U_{c1}} = \frac{-\underline{E_a} \cdot \underline{Y_a} - \underline{E_b} \cdot \underline{Y_b} + \underline{E_c} \cdot (\underline{Y_a} + \underline{Y_b})}{G_i + j \cdot B_i} \quad (2.35)$$

$$\underline{U_{c2}} = \frac{-\underline{E_a} \cdot \underline{Y_a} - \underline{E_b} \cdot \underline{Y_b} + \underline{E_c} \cdot (\underline{Y_a} + \underline{Y_b})}{G_1 + G_i + j \cdot B_i} \quad (2.36)$$

$$\underline{U_{c3}} = \frac{-\underline{E_a} \cdot \underline{Y_a} - \underline{E_b} \cdot \underline{Y_b} + \underline{E_c} \cdot (\underline{Y_a} + \underline{Y_b})}{G_2 + G_i + j \cdot B_i} \quad (2.37)$$

Dividing $\underline{U_{c1}}$ by $\underline{U_{c2}}$ and $\underline{U_{c1}}$ by $\underline{U_{c3}}$, there are obtained two equations containing two unknown parameters G_i , B_i where $G_i = \text{Re}(\underline{Y_a} + \underline{Y_b} + \underline{Y_c})$ and $B_i = \text{Im}(\underline{Y_a} + \underline{Y_b} + \underline{Y_c})$. Substituting

$$\left(\frac{U_{c1}}{U_{c2}} \right)^2 = q_1 + 1 \quad \text{and} \quad \left(\frac{U_{c1}}{U_{c3}} \right)^2 = q_2 + 1 \quad (2.38)$$

the aforementioned equations assume the following form

$$\left(\left| \frac{G_1 + G_i + j \cdot B_i}{G_i + jB_i} \right| \right)^2 = q_1 + 1 \quad (2.39)$$

$$\left(\left| \frac{G_2 + G_i + j \cdot B_i}{G_i + jB_i} \right| \right)^2 = q_2 + 1 \quad (2.40)$$

It should be noticed that Eqs. (2.39) and (2.40) are identical to (2.12) and (2.13). Therefore their solutions are also identical and are given by formulas (2.24) and (2.15).

For three-phase networks modification of the method described above is also possible. It consists in replacement of resistors R_1 and R_2 by capacitors $C_1 = B_1/\omega$ and $C_2 = B_2/\omega$. In this case insulation equivalent parameters are given by formulas (2.16) and (2.17).

This procedure can be also applied in AC IT systems with any number of phases. Its correctness for multi-phase networks may be proved in the following way. According to Thevenin's theorem voltages of phase c in the second and the third step are equal respectively to (mind that U_{c1} is a pre-fault value)

$$U_{c2} = \frac{U_{c1}}{\left| \frac{1}{G_i + jB_i} + \frac{1}{G_1} \right|} \cdot \frac{1}{G_1} = U_{c1} \cdot \frac{|G_i + jB_i|}{|G_i + G_1 + jB_i|} \quad (2.41)$$

$$U_{c3} = \frac{U_{c1}}{\left| \frac{1}{G_i + jB_i} + \frac{1}{G_2} \right|} \cdot \frac{1}{G_2} = U_{c1} \cdot \frac{|G_i + jB_i|}{|G_i + G_2 + jB_i|} \quad (2.42)$$

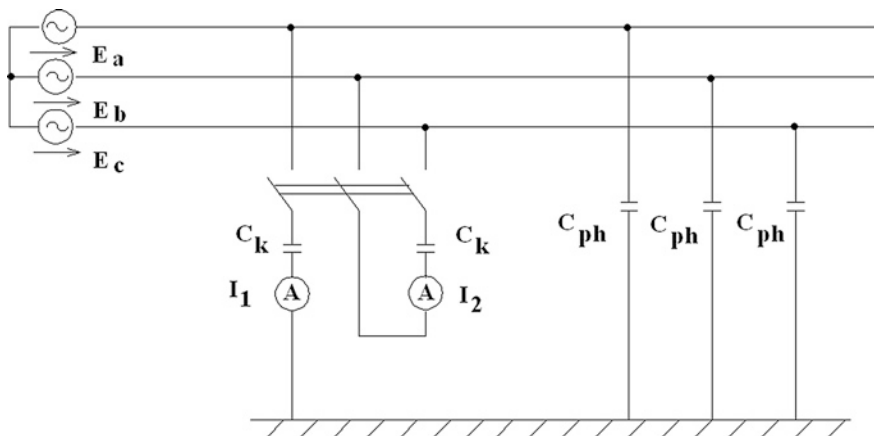


Fig. 2.3 Determination of symmetrical phase-to-ground capacitances C_{ph} in a three-phase AC IT network with negligible leakage conductances

From both equations given above, applying (2.38), formulas (2.39) and (2.40) are obtained.

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

$$\underline{I_{fa}} = \underline{U_{a1}} \cdot \underline{Y_i} = \underline{U_{a2}} \cdot (\underline{Y_i} + j \cdot \omega \cdot C) \quad (2.43)$$

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 Eq. (2.43) formula (2.44) for determination of insulation admittance parameters G_i and B_i is obtained:

$$\underline{Y_i} = G_i + j \cdot B_i = \frac{j \cdot \omega \cdot C \cdot \underline{U_{a2}}}{\underline{U_{a1}} - \underline{U_{a2}}} \quad (2.44)$$

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 E).

In case of symmetrical source voltages and symmetrical phase-to-ground capacitances C_{ph} (which however is not always true for low voltage networks) and negligible leakage conductances a simple procedure exists for determination of network-to-ground equivalent (total) capacitance [3]. After closing a switch

(Fig. 2.3) currents I_1 and I_2 flowing through two additional capacitors of equal value C_k are measured. Total network-to-ground capacitance is calculated as

$$3 \cdot C_{ph} = \frac{\sqrt{3} \cdot C_k \cdot I_1}{I_2 - \sqrt{3} \cdot I_1} \quad (2.45)$$

2.3.2 *Insulation Resistance and Capacitance Determination for Single Phases*

There are known several methods of single phases insulation parameters determination in live three-phase networks (in general in multi-phase networks). Each procedure consists of series of measurements and analytical processing of their results. These procedures are aimed at obtaining a necessary number of independent equations with unknown insulation parameters. In the most general case values of respective insulation parameters may be different. As these parameters are spatially distributed along the wires, it is impossible to measure (accurately) currents flowing through them. Therefore only voltages across these elements are accessible for measurement. For practical application only these methods are useful which provide safe operation of the system and persons performing measurements. In particular any applied procedure may cause neither interruptions of power supply, nor excessive changes of voltages and currents levels. Below there are presented three selected methods based on measurements and calculation; the first and the third procedures were proposed by the author.

2.3.2.1 *Method of an Additional Single-Phase Voltage Source*

This method employing an additional single-phase voltage source is explained in Fig. 2.4. It consists of measurements of phase voltages in the following operating conditions of the network:

- (1) normal network operation
- (2) intentional grounding of a selected phase (e.g. c) through an element with Y_d admittance
- (3) inclusion of an additional voltage source U_d of the network frequency in series into a selected phase (phase b in Fig. 2.4).

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

$$\underline{U}_{a1} \cdot \underline{Y}_a + \underline{U}_{b1} \cdot \underline{Y}_b + \underline{U}_{c1} \cdot \underline{Y}_c = 0 \quad (2.46a)$$

$$\underline{U}_{a2} \cdot \underline{Y}_a + \underline{U}_{b2} \cdot \underline{Y}_b + \underline{U}_{c2} \cdot \underline{Y}_c = -\underline{U}_{c2} \cdot \underline{Y}_d \quad (2.46b)$$

$$\underline{U}_{a3} \cdot \underline{Y}_a + \underline{U}_{b3} \cdot \underline{Y}_b + \underline{U}_{c3} \cdot \underline{Y}_c = 0 \quad (2.46c)$$

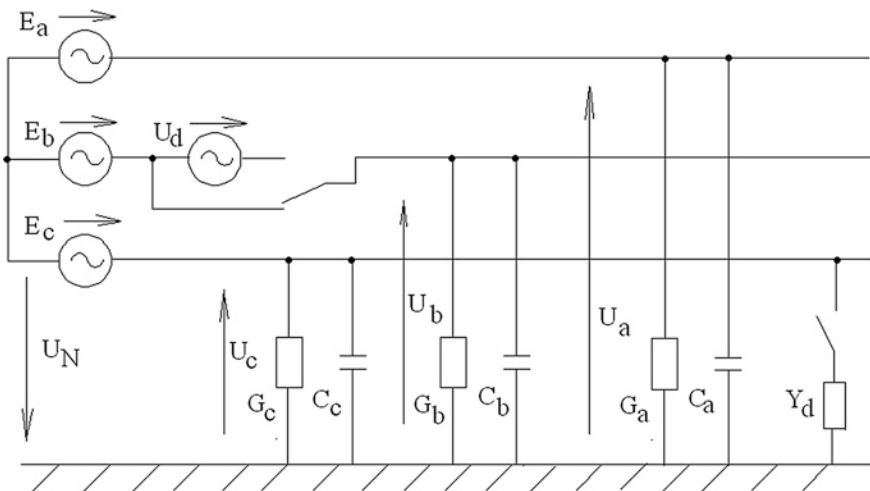


Fig. 2.4 Circuit diagram of a three-phase AC IT system for measurement procedure I. Designations: E —positive sequence symmetrical component of source voltages, U_d —additional voltage source, U_N —network displacement voltage, Y_d —admittance of grounding element, G_a , G_b , G_c —phase a , b , c insulation-to-ground conductances, C_a , C_b , C_c —phase a , b , c insulation-to-ground capacitances

Phase voltages and insulation admittances are complex values. To calculate three unknown admittances Y_a , Y_b , Y_c three leakage current balance equations written according to Kirchhoff's first law are necessary. To get an univocal result (i.e. set of three admittance complex values) system of these equations should have one solution. This requirement is met if determinant of the equations system (2.46a, 2.46b, 2.46c) is not equal to zero. Its value can be calculated with help of the following relationships between voltages of network sources:

$$\begin{aligned} \underline{U}_{a1} &= E - \underline{U}_{N1}, \underline{U}_{b1} = a^2 E - \underline{U}_{N1}, \underline{U}_{c1} = aE - \underline{U}_{N1} \\ \underline{U}_{a2} &= E - \underline{U}_{N2}, \underline{U}_{b2} = a^2 E - \underline{U}_{N2}, \underline{U}_{c2} = aE - \underline{U}_{N2} \\ \underline{U}_{a3} &= E - \underline{U}_{N3}, \underline{U}_{b3} = a^2 E + U_d - \underline{U}_{N3}, \underline{U}_{c3} = aE - \underline{U}_{N3} \end{aligned} \quad (2.47)$$

where for simplicity it was assumed that source voltages remain constant during measurements and contain only positive sequence symmetrical component, $a = e^{j120}$. Taking into account (2.47) determinant of the system of Eqs. (2.46a, 2.46b, 2.46c) is expressed by the following formula:

$$\det M = \begin{vmatrix} E - \underline{U}_{N1} & a^2 E - \underline{U}_{N1} & aE - \underline{U}_{N1} \\ E - \underline{U}_{N2} & a^2 E - \underline{U}_{N2} & aE - \underline{U}_{N2} \\ E - \underline{U}_{N3} & a^2 E + U_d - \underline{U}_{N3} & aE - \underline{U}_{N3} \end{vmatrix} \quad (2.48)$$

After performing calculation this determinant is equal to

$$\det M = (1 - a) \cdot E \cdot (\underline{U}_{N2} - \underline{U}_{N1}) \cdot U_d \quad (2.49)$$

This matrix M 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.

As it was assumed above, source voltages usually contain only positive component and its value is constant during the measurements. It can be proved however that for insulation parameters measurement it is necessary that phase voltages contain negative component in one step of the cycle and zero sequence component in another one.

Negative sequence component of phase voltages may appear as result of:

- (1) series connection of an additional voltage source into one phase
- (2) swapping of two source (network) phases.

Voltage zero sequence component may appear when:

- (1) an additional voltage source is connected in series with one or more phases (it may be both an active element and passive one e.g. a choke across which there is voltage drop due to load current)
- (2) one or more phases are grounded through an element with specially chosen admittance (intentional asymmetry of insulation admittances of single phases).

To get a solution different from zero, the second method of providing voltage zero sequence component must be applied because only for a network with one phase grounded, system of Eqs. (2.46a, 2.46b and 2.46c) is not homogeneous.

2.3.2.2 Method of Two Phases Swapping

In this method [2] steps 1 and 2 are identical as in method I, but in step 3 voltage negative sequence component is introduced by swapping of two phases e.g. a and b with a switch S as shown in Fig. 2.5.

Due to this change—over (swapping) positive component of source voltages is transformed into negative one. As a result the following system of equations is obtained:

$$\underline{U}_{a1} \cdot \underline{Y}_a + \underline{U}_{b1} \cdot \underline{Y}_b + \underline{U}_{c1} \cdot \underline{Y}_c = 0 \quad (2.50)$$

$$\underline{U}_{a2} \cdot \underline{Y}_a + \underline{U}_{b2} \cdot \underline{Y}_b + \underline{U}_{c2} \cdot \underline{Y}_c = -\underline{U}_{c2} \cdot \underline{Y}_d \quad (2.51)$$

$$\underline{U}_{a3} \cdot \underline{Y}_a + \underline{U}_{b3} \cdot \underline{Y}_b + \underline{U}_{c3} \cdot \underline{Y}_c = 0 \quad (2.52)$$

where

$$\begin{aligned} \underline{U}_{a1} &= E - \underline{U}_{N1}, \underline{U}_{b1} = a^2 E - \underline{U}_{N1}, \underline{U}_{c1} = aE - \underline{U}_{N1} \\ \underline{U}_{a2} &= E - \underline{U}_{N2}, \underline{U}_{b2} = a^2 E - \underline{U}_{N2}, \underline{U}_{c2} = aE - \underline{U}_{N2} \\ \underline{U}_{a3} &= E - \underline{U}_{N3}, \underline{U}_{b3} = E - \underline{U}_{N3}, \underline{U}_{c3} = aE - \underline{U}_{N3} \end{aligned} \quad (2.53)$$

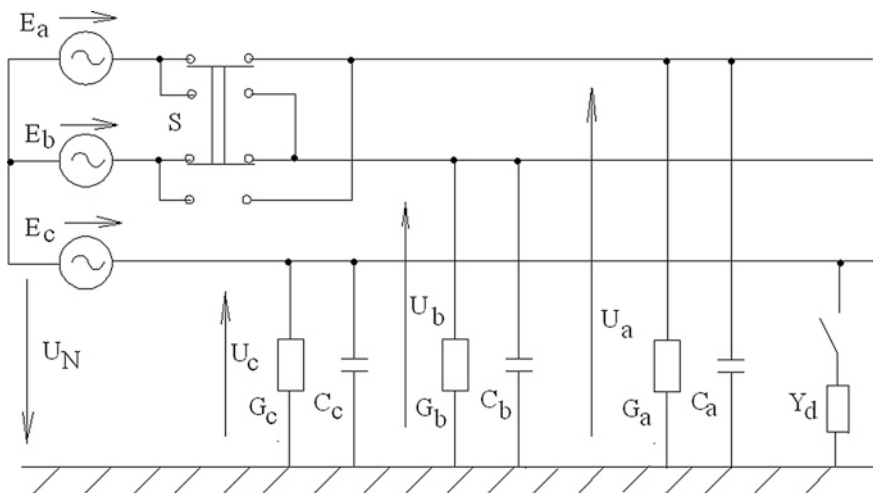


Fig. 2.5 Illustration of phase swapping method

Determinant of this system of equations is given by the following formula:

$$\det M = \begin{vmatrix} E - \underline{U}_{N1} & a^2 E - \underline{U}_{N1} & a E - \underline{U}_{N1} \\ E - \underline{U}_{N2} & a^2 E - \underline{U}_{N2} & a E - \underline{U}_{N2} \\ a^2 E - \underline{U}_{N3} & E - \underline{U}_{N3} & a E - \underline{U}_{N3} \end{vmatrix} \quad (2.54)$$

After performing calculation it is equal to

$$\det M = 3 \cdot (1 - a) \cdot E^2 \cdot (\underline{U}_{N2} - \underline{U}_{N1}) \quad (2.55)$$

As in the previous method voltages \underline{U}_{N1} and \underline{U}_{N2} are again different complex quantities. Unfortunately this method requires to switch off network supply twice to swap phases. It should be noted that both methods (I and II) can be applied only if network insulation parameters and source voltages are constant during the whole measuring cycle. The next requirement is knowledge of complex values of phase voltages in each step. These complex quantities can be determined using formulas (1.9)–(1.12).

However instead of a troublesome execution of an additional voltage source inclusion (method I) or practically impermissible phase swapping (method II) another measurement procedure can be suggested. Step 3 of method I or II is modified to utilize an auxiliary voltage source with a different frequency. It is connected between one of phases and ground. This idea of an auxiliary voltage source with a different frequency application has been also successfully implemented for continuous insulation monitoring.

2.3.2.3 Application of an Auxiliary AC Voltage Source with a Different Frequency

This method also consists of three separate steps. The first (normal operation of a network) and the second (artificial grounding of a line phase) are identical to steps 1 and 2 described above.

Measurements executed in these two steps are usually sufficient in most applications if single phase-to-ground capacitances are approximately equal i.e. $C_a = C_b = C_c = C_{ph}$. In this case four equations with four unknown parameters G_a, G_b, G_c, C_{ph} are obtained.

In the third step of the proposed procedure an auxiliary AC voltage source with RMS value U_{aux} of a different frequency $f_{aux} \neq f$ is connected between ground and a selected phase e.g. a . The equivalent scheme of the network in step 3 is shown in Fig. 2.6.

The auxiliary AC voltage source is connected in series with a band-pass filter F for f_{aux} frequency. To get two independent equations at this step it is necessary to measure not only RMS values of U_{aux} voltage and I_{aux} current but also phase shift φ between them. In this way three equations with complex coefficients and six unknown insulation parameters $G_a, G_b, G_c, C_a, C_b, C_c$ are obtained:

$$\begin{aligned} \underline{U_{a1}} \cdot (G_a + j \cdot 2\pi \cdot f \cdot C_a) + \underline{U_{b1}} \cdot (G_b + j \cdot 2\pi \cdot f \cdot C_b) \\ + \underline{U_{c1}} \cdot (G_c + j \cdot 2\pi \cdot f \cdot C_c) = 0 \end{aligned} \quad (2.56a)$$

$$\begin{aligned} \underline{U_{a2}} \cdot (G_a + j \cdot 2\pi \cdot f \cdot C_a) + \underline{U_{b2}} \cdot (G_b + j \cdot 2\pi \cdot f \cdot C_b) \\ + \underline{U_{c2}} \cdot (G_c + j \cdot 2\pi \cdot f \cdot C_c) = -\underline{U_{a2}} \cdot \underline{Y_d} \end{aligned} \quad (2.56b)$$

$$|\underline{U_{aux}}| \cdot [(G_a + G_b + G_c) + j \cdot 2\pi \cdot f_{aux} \cdot (C_a + C_b + C_c)] = |\underline{I_{aux}}| \cdot e^{j\varphi} \quad (2.56c)$$

It should be noted that by measuring U_{aux} , I_{aux} , φ in step 3, insulation equivalent conductance and capacitance values can be calculated without need of steps 1 and 2 execution. Of course at this step a DC auxiliary source cannot be applied as it would produce only one equation without possibility to measure capacitance.

In order to avoid a troublesome determination of phase shift φ , step 3 can be modified to comprise two steps 3 and 4 with measurement of I_{aux} current driven by the same auxiliary voltage source U_{aux} in identical conditions as in steps 1 and 2. As result four equations with six unknown insulation parameters are obtained. However it should be reminded that each of Eqs. (2.57) and (2.58) consists of two separate equations for real and imaginary parts.

$$\begin{aligned} \underline{U_{a1}} \cdot (G_a + j \cdot 2\pi \cdot f \cdot C_a) + \underline{U_{b1}} \cdot (G_b + j \cdot 2\pi \cdot f \cdot C_b) \\ + \underline{U_{c1}} \cdot (G_c + j \cdot 2\pi \cdot f \cdot C_c) = 0 \end{aligned} \quad (2.57)$$

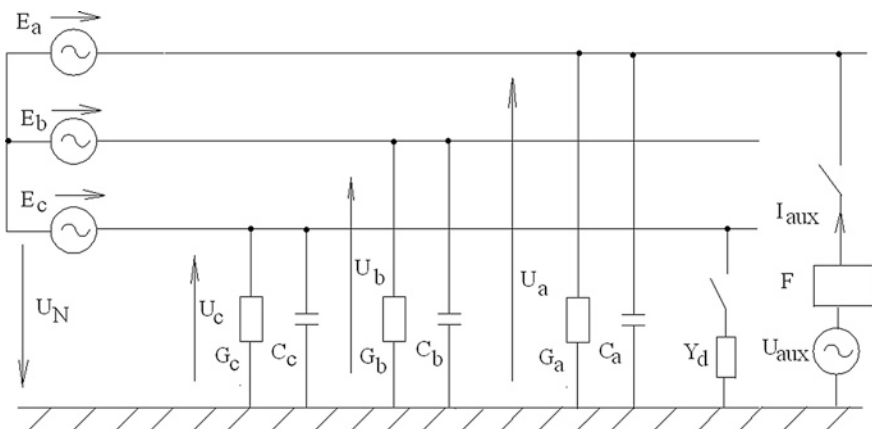


Fig. 2.6 Circuit diagram of a three-phase AC IT network for method III. Symbols I_{aux} —measuring current with frequency f_{aux} imposed by the auxiliary source, F —band-pass filter. The remaining symbols are as in Fig. 2.4

$$\begin{aligned} \underline{U_{a2}} \cdot (G_a + j \cdot 2\pi \cdot f \cdot C_a) + \underline{U_{b2}} \cdot (G_b + j \cdot 2\pi \cdot f \cdot C_b) \\ + \underline{U_{c2}} \cdot (G_c + j \cdot 2\pi \cdot f \cdot C_c) = -\underline{U_{a2}} \cdot \underline{Y_d} \end{aligned} \quad (2.58)$$

$$|\underline{U_{aux1}}| \cdot |[(G_a + G_b + G_c) + j \cdot 2\pi \cdot f_{aux} \cdot (C_a + C_b + C_c)]| = |\underline{I_{aux1}}| \quad (2.59)$$

$$|\underline{U_{aux2}}| \cdot |[(G_a + G_b + G_c) + j \cdot 2\pi \cdot f_{aux} \cdot (C_a + C_b + C_c) + \underline{Y_d}]| = |\underline{I_{aux2}}| \quad (2.60)$$

Steps 3 and 4 alone allow to determine insulation equivalent parameters $G_i = G_a + G_b + G_c$ and $C_i = C_a + C_b + C_c$ from Eqs. (2.59) and (2.60). In this case there is no need to execute steps 1 and 2.

2.4 Unconventional Measurement Methods

2.4.1 Periodical Measurement of Insulation Parameters

With help of Thevenin's theorem few other methods of insulation equivalent resistance and capacitance determination in live AC IT networks can be proposed. In distinction from methods described in Sect. 2.3 these procedures do not require performance of any calculations.

2.4.1.1 Insulation Resistance Measurement with Megohmmeters

For insulation resistance determination in de-energized circuits some dedicated measuring instruments are applied—these include both traditional hand-driven and modern digital megohmmeters. According to manufacturer's recommendation they are designed for use in circuits with no voltage. However their application is also possible in live systems under condition that the instrument is connected to terminals with no potential difference between them. If voltage superimposed by the network source on the measuring device terminals, e.g. ohmmeter, is equal to zero, then current flowing through the instrument measuring system will depend only on the device own (internal) source. If this network-to-ground voltage is not equal to zero, insulation equivalent resistance measurement is also possible. However voltage between network terminal and ground cannot be too high as it would force an impermissibly high current to flow through the instrument. Of course current driven by the tested network does not influence the instrument indication due to this device's different frequency (in this case DC). It should be noted that the above described application of megohmmeter may pose a threat of sensitive devices (e.g. semiconductor elements) damage or risk of misoperation of apparatuses installed in the tested circuit. For this reason insulation testing with megohmmeter in live auxiliary (control) circuits is not applied.

2.4.1.2 Measurement with Variable Elements

An unconventional method of AC IT single and multiple-phase networks insulation parameters determination was developed and tested by the author. It is based on application of variable (adjusted) resistors and capacitors. This approach makes it possible to set actual values of insulation equivalent resistance and capacitance on the above mentioned test elements. The idea of insulation resistance determination shown in Fig. 2.7a can be explained with Thevenin's theorem. The measurement result is independent from network-to-ground capacitance level due to use of DC test current.

The procedure is performed as follows. First with released switch S , output voltage U of rectifier is read out at with DC voltmeter. A variable test resistor r should be set to maximum resistance. Then S is pressed and resistance r gradually decreased while supervising growth of voltmeter indication to U' . When the measured DC voltage increases to half of its initial value (i.e. $U' = 0.5U$) the switch should be released. Resistance set at the resistor r is equal to insulation equivalent resistance R_i . This conclusion directly follows from the equivalent circuit for DC test voltage source seen from the terminals of resistor r (Fig. 2.7b). In this circuit with $r = R_i$ DC voltage U' is equal to half of rectifier output voltage U . Equivalent insulation resistance can be read at the resistor r scale or this resistor value can be measured with an ohmmeter.

In similar way insulation equivalent capacitance of AC IT network can be determined (Fig. 2.8a). In this case an auxiliary voltage source is not necessary but

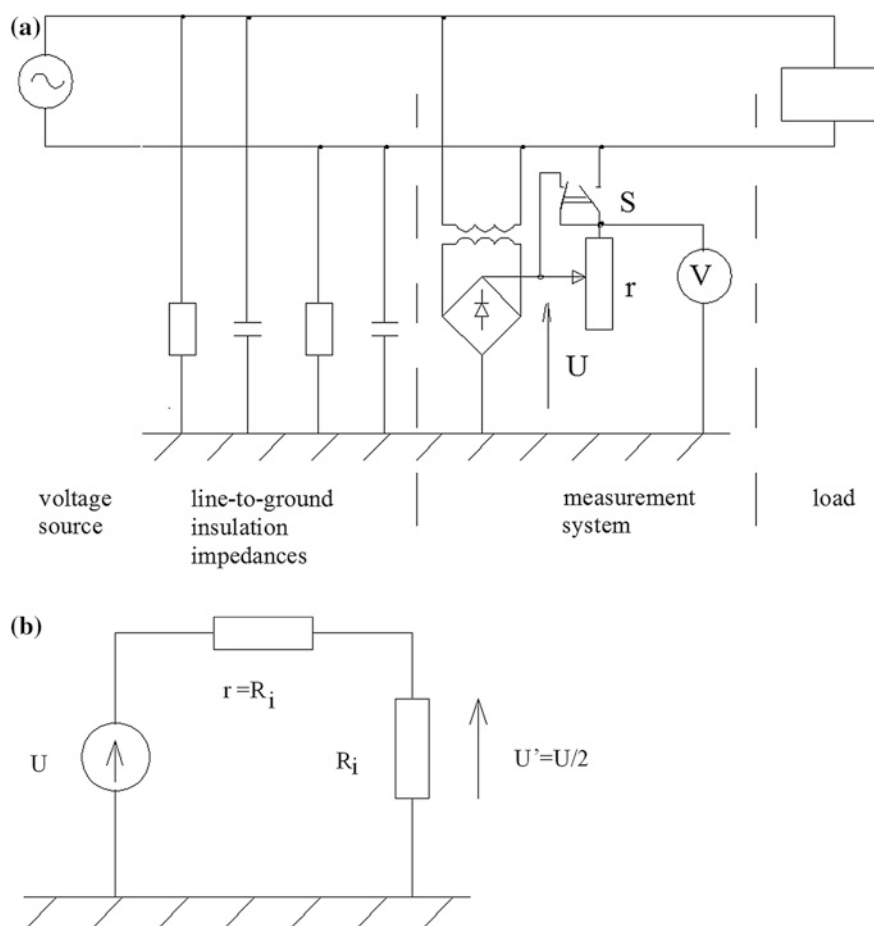


Fig. 2.7 **a** System of insulation equivalent resistance determination for a single phase AC IT network with use of a variable test resistor—designations in the text. **b** An equivalent circuit diagram of the tested network

a resistor r set to R_i in the procedure described above is used. A variable capacitor, set to the minimal value smaller than the network-to-ground capacitance C_i , is connected parallelly with resistor r . First with released switch S voltage U at the AC voltmeter is read out. Then switch S should be pressed and capacitance C gradually increased. As this capacitance grows, voltmeter indication drops from U to U'' . When the measured AC voltage decreases to half of its initial value (i.e. $U'' = 0.5U$) the switch should be released. Capacitance set at the capacitor C is equal to insulation equivalent capacitance C_i . This conclusion directly follows from the equivalent circuit seen from the terminals of resistor r and capacitor C (Fig. 2.8b). It is obvious that with $r = R_i$ and $C = C_i$ conductor-to-ground AC

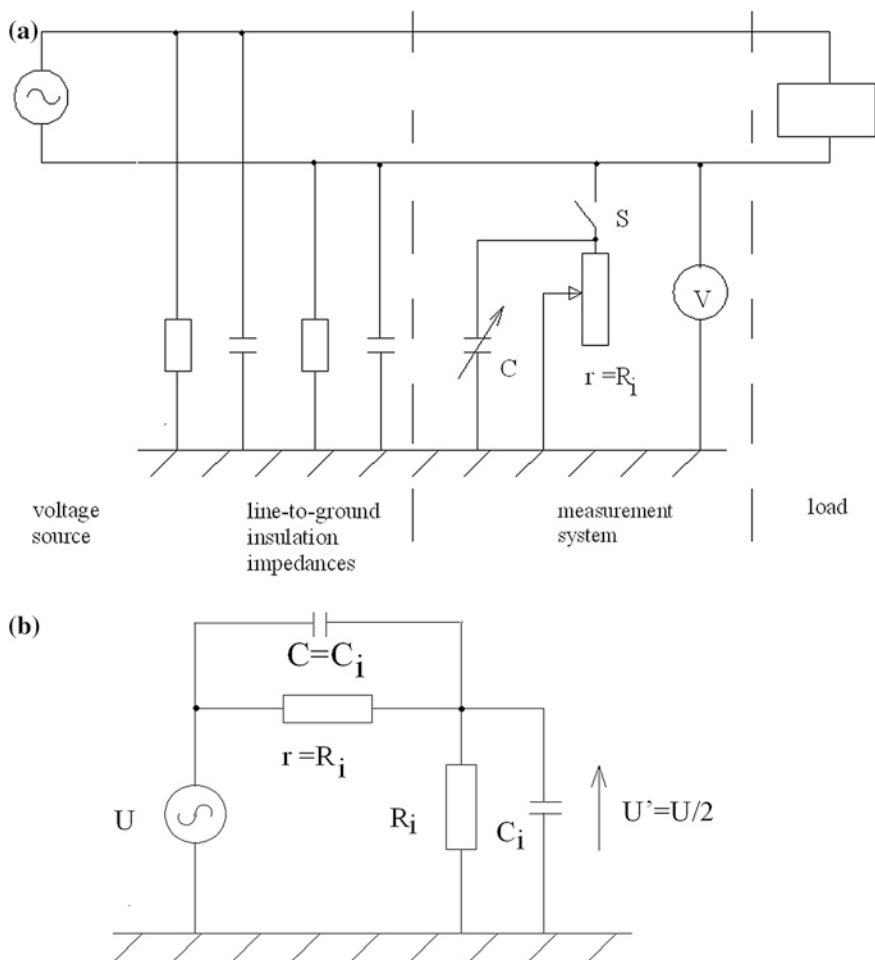


Fig. 2.8 **a** System of insulation equivalent capacitance determination for a single phase AC IT network with use of a variable capacitor—designations in the text. **b** An equivalent circuit diagram of the tested network

voltage U'' is equal to half of AC voltage U without connected elements r and C . Equivalent insulation capacitance can be read out at the capacitor C scale or this element value can be measured with a meter.

2.4.2 Devices and Systems for Ground Fault, Earth Leakage and Shock Currents Measurement

Variable elements set to insulation equivalent resistance or capacitance as described in Sect. 2.4.1 can be used for measurement of ground fault current in AC IT systems.

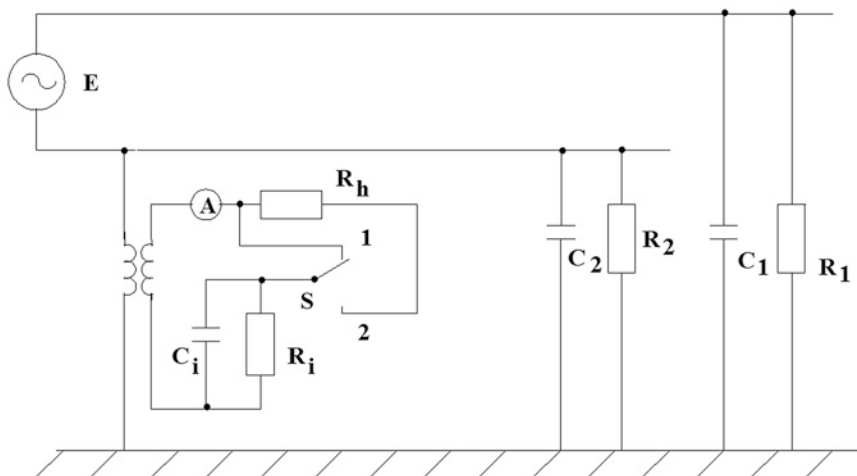


Fig. 2.9 Isolated test circuit for evaluation of ground fault and shock current in AC IT networks

The measurement is executed in an auxiliary test circuit isolated from ground. It is supplied from another source or from a transformer connected to the tested network as shown in Fig. 2.9. Supply voltage level of the test circuit should be equal to conductor-to-ground voltage of a selected wire and should not be influenced by execution of the test. In the test circuit there are used parallelly connected elements representing insulation equivalent parameters: resistor $r = R_i$ and capacitor $C = C_i$. A selection switch S is connected in series with these elements to choose either ground fault current (position 1) or shock current (position 2) measurement. In the latter option resistor R_h is used to represent human body internal resistance.

Using elements r and C possible ground fault and shock currents can be measured also in the live AC IT network. This method of measurement is based on Thevenin's theorem. Both parallelly connected elements r and C should be connected with an ammeter between selected wire and ground (Fig. 2.10). The readout value of current is equal to half of the dead ground fault current of this conductor. In order to measure a possible electric shock current, resistor with double resistance of human body should be connected in series with insulation equivalent model consisting of r and C . In this case an ammeter indication is equal to half of an electric shock current flowing through a body of a man touching this conductor.

In 2-wire AC IT live systems the above mentioned currents can be determined also by execution of an artificial dead ground fault of a selected phase e.g. a , of course only with sufficiently high level of insulation equivalent impedance. Voltage of the second conductor b should be measured without (U_{b1}) and with (U_{b2}) conductor a grounded by an ammeter. An earth fault current of conductor a is equal to the ammeter readout I , whereas total earth leakage current from conductor b in normal operating conditions I_{lb} is given by formula

$$I_{lb} = \frac{U_{b1}}{U_{b2}} \cdot I \quad (2.61)$$

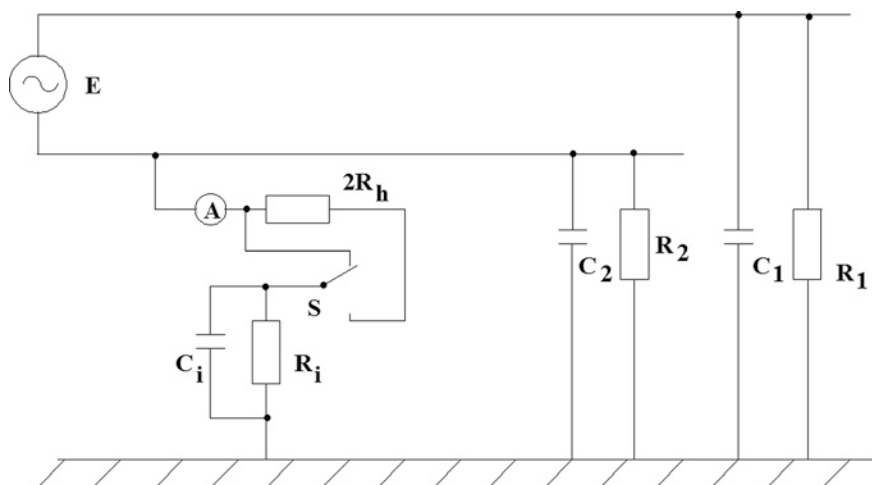


Fig. 2.10 Test circuit for evaluation of ground fault and shock current in live AC IT networks

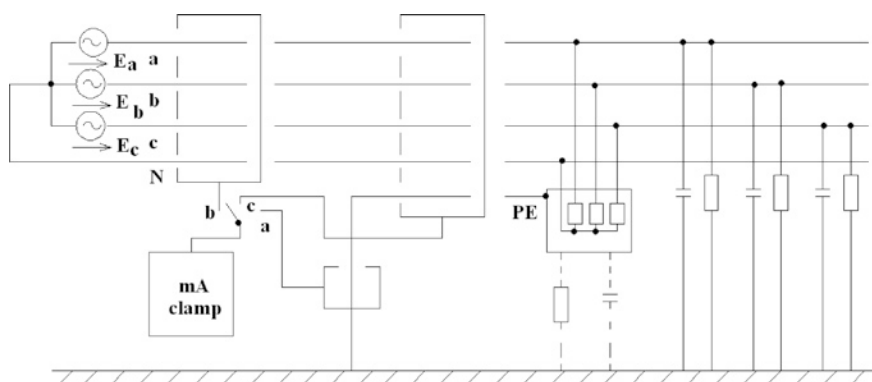


Fig. 2.11 Various methods of ground leakage current measurement

Residual (ground leakage) currents can be measured in live AC IT systems with use of clamp-on ammeters. There are several methods of ground leakage current determination (Fig. 2.11). When grounding conductor of a device with a conducting housing is embraced with clamp-on meter (a) only ground leakage current flowing through this wire is measured. When phase and neutral conductors are embraced (b) total ground leakage current flowing from the network is measured. If all conductors (phase, neutral and earthing) are included (c), clamp-on meter measures the leakage current flowing exclusively through ground and not in the mentioned wires. Of course application of clamp-on ammeter does not enable to discriminate resistive (i.e. flowing through insulation leakage resistances) and capacitive (i.e. flowing through insulation capacitances to ground) components of the measured ground leakage current.

2.5 Influence of Insulation Parameters on Possible Ground Fault, Electric Shock and Ground Leakage Currents Levels

2.5.1 Assessment of Ground Fault and Ground Leakage Currents

In AC IT systems earth leakage currents flow both through places with deteriorated insulation level and through network-to-ground capacitances. Earth leakage current level is an indicator of insulation condition i.e. insulation resistance and capacitance levels. Earth leakage currents flow leads to heat losses in its path and possible risks of electric shock, fire, explosion and corrosion. Insulation leakage resistances may be distributed at random (non-uniformly) along the network conductors. In a single-phase system total earth leakage current (including resistive and capacitive components) from one conductor I_l is of course equal to total earth leakage current from the other conductor. This conclusion directly follows from the 1st Kirchhoff 's law. This steady-state value is equal to

$$\underline{I_l} = \frac{E}{\underline{Z_a} + \underline{Z_b}} \quad (2.62)$$

For assessment of fire risk only RMS value of earth leakage current's resistive component is important. It should be noted that resistive components of leakage currents from conductors a and b in a single-phase network are not always equal. RMS value of resistive component I_{lres} of leakage current from any wire e.g. a in that network always meets the following conditions

$$I_{lres} = \frac{U_a}{R_a} \leq \frac{E}{R_a} \leq \frac{E}{R_i} \quad (2.63)$$

It might be of practical interest to determine highest possible leakage currents from any conductor in a single-phase network with known levels of insulation equivalent conductance G_i and total susceptance B_i . It is obvious that the highest leakage current resistive component $I_{lres \max}$ is smaller than $E \cdot G_i$. For negligible B_i values it assumes maximum when insulation conductance is divided equally between both conductors i.e. $I_{lres \max} = E \cdot \frac{G_i}{4}$.

Magnitude I_{fa} of a possible dead ground fault current fulfills conditions

$$\frac{U_{apref}}{R_i} \leq I_{fa} = \frac{U_{apref}}{|Z_i|} \leq \frac{E}{|Z_i|} = E \cdot \sqrt{\frac{1}{R_i^2} + B_i^2} \quad (2.64)$$

where U_{apref} is prefault value of phase a voltage.

In three-phase AC IT systems with $B_i = 0$, resistive component of leakage current from phases b , c assumes its maximum for the following insulation parameters $G_b = G_c = G_i/2$, $G_a = 0$. This highest value is calculated with formula

$$I_{lres \max} = \frac{E \cdot \sqrt{3}}{4} \cdot G_i.$$

Magnitude I_{fa} of a dead ground fault current in three-phase networks can be assessed in similar way

$$\frac{U_{apref}}{R_i} \leq I_{fa} = \frac{U_{apref}}{|Z_i|} \leq \frac{\sqrt{3} \cdot E}{|Z_i|} = \sqrt{3} \cdot E \cdot \sqrt{\frac{1}{R_i^2} + B_i^2} \quad (2.65)$$

where E is network nominal phase voltage. Geometric sum of phasors of earth leakage currents from all conductors (phases and neutral) is also equal to zero. Generally each of these currents contains both resistive and capacitive component. These components are determined in relation to line-to-ground voltage of a given conductor. For fire risk assessment knowledge of the highest value of leakage current's resistive component I_{lres} can be very useful. This maximum value in any phase of three-phase system fulfills the following inequalities

$$I_{lres \max} \leq \frac{U_{phase \max}}{R_i} \leq \frac{\sqrt{3} \cdot E}{R_i} \quad (2.66)$$

A more difficult task is determination of leakage current in any part of network e.g. in an outgoing line (feeder). In this case leakage current is equal to geometric sum of currents flowing in all conductors of this line. Analytic determination of this value requires knowledge of admittances of these conductors-to-ground insulation including all galvanically connected elements of this line. However in practice this requirement is not fulfilled because insulation resistance (or impedance) measurement is performed for the entire network. Therefore for single lines or parts of a network it is more convenient to measure than to calculate leakage currents.

2.5.2 Assessment of Power Losses in Insulation

For evaluation of fire hazards in unearthed networks it is also useful to know high-est possible heat losses produced (dissipated) in its insulation by leakage currents. In single-phase systems total active power losses in network-to-ground insulation can be assessed by formula (2.67) and in three-phase systems by formula (2.68):

$$P = \frac{U_a^2}{R_a} + \frac{U_b^2}{R_b} < \frac{U_a^2 + U_b^2}{R_i} \leq \frac{E^2}{R_i} \quad (2.67)$$

$$P = \frac{U_a^2}{R_a} + \frac{U_b^2}{R_b} + \frac{U_c^2}{R_c} < (\sqrt{3} \cdot E)^2 \cdot \left(\frac{1}{R_a} + \frac{1}{R_b} + \frac{1}{R_c} \right) = \frac{3 \cdot E^2}{R_i} \quad (2.68)$$

where R_i is network insulation equivalent resistance, E —source phase voltage.

It can be easily checked that in AC IT systems total active power loss in network-to-ground insulation may vary from zero to its maximum possible levels given by both formulas.

It can be also shown that when insulation susceptance can be neglected, total active power losses attain their highest possible level for equal insulation resistances of all network phases.

2.5.3 Electric Shock Hazard Assessment

An important issue for ensuring safe working conditions for persons is determination of maximum possible leakage and shock currents in electric devices. Grounding is an additional safety measure applied in AC IT systems to limit dangerous touch voltages on conducting parts not belonging to electric circuits. In case of a device insulation deterioration leakage current may flow to ground. Maximum value of this current flowing through the enclosure grounding wire can be assessed if network insulation parameters are known. An example of these abnormal conditions in single-phase networks is discussed below. Figure 2.12 shows a single-phase network circuit diagram with grounded conducting enclosure where x and y are resistances of insulation between conductors a , b and the enclosure, R_g is grounding resistance.

If insulation equivalent resistance R_i is known e.g. from insulation monitor indication, maximum possible touch voltage between the enclosure and ground can be determined. To simplify calculations the enclosure-to-ground capacitances were neglected as much smaller than capacitances of the network. It can be shown that the highest possible current in the grounding wire of the enclosure will be for $R_a = y = \infty$ and $B_a = 0$ (or $R_b = x = \infty$ and $B_b = 0$). For these values network insulation equivalent resistance R_i is

$$R_i = \frac{1}{\frac{1}{R_b} + \frac{1}{x + R_g}} \quad (2.69)$$

whereas the highest possible RMS voltage U_g between the enclosure and ground equals to

$$\begin{aligned} U_{g \max} &= E \cdot \left| \frac{\frac{1}{R_g + x}}{\frac{1}{R_g + x} + \frac{1}{jB_b + \frac{1}{R_b}}} \right| \cdot \frac{R_g}{R_g + x} \\ &= E \cdot R_g \cdot \frac{\left| \frac{1}{R_b} + jB_b \right|}{\left| 1 + (R_g + x) \cdot \left(\frac{1}{R_b} + jB_b \right) \right|} = R_g \cdot I_{g \max} \end{aligned} \quad (2.70)$$

From (2.70) maximum grounding resistance R_g can be derived, for which voltage between the enclosure and ground does not exceed permissible limit value. It can be shown that condition (2.70) does not impose any substantial limit on the range of permissible resistances of protective groundings in AC IT systems. Much lower grounding resistance is required to limit touch voltages on conducting enclosures in case of a double ground fault of both conductors a and b (one wire grounded outside the device, the other one connected to its enclosure). The current of this

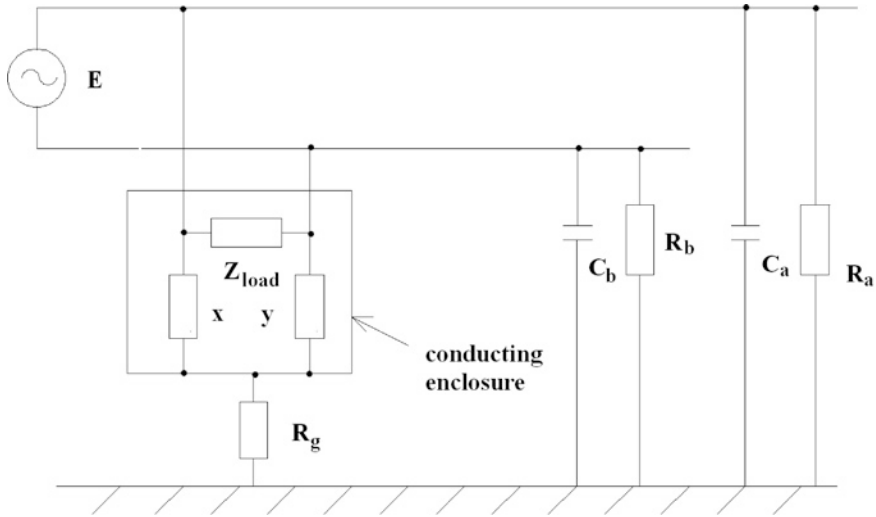


Fig. 2.12 Circuit diagram of a single-phase network with grounded conducting enclosure

double fault must be high enough to ensure adequately fast reaction of overcurrent protections installed in this circuit.

It is also important to know the highest possible voltage between ground and the enclosure in case of its grounding conductor interruption. Assuming in (2.70) $B_b = B_i$ and $R_g = \infty$ the discussed parameter U_g attains its maximum possible value E . Thus in case of insulation deterioration (but not an earthfault!) in the most unfavourable condition (i.e. $R_a = \infty$, $B_a = 0$, $R_g = \infty$) even the total source voltage E may be present on the conducting enclosure.

2.6 Ground Fault Current Compensation

Ground fault current levels in AC IT systems can be reduced by forcing an inductive current flow with help of an additional, parallel inductive element. This idea is explained in Fig. 2.13a, b for a three-phase network with symmetrical voltage source and any possible, in general case nonsymmetrical, ground insulation admittances. Two ways of compensating reactor connection are considered.

In the first case (Fig. 2.13a) reactors were connected between single phases and ground. Capacitors were included in series to reactors to eliminate galvanic connection to ground; this may be necessary to ensure network-to-ground insulation monitoring with DC test signal. With an equivalent inductive admittance B_L of the reactor-capacitor circuit, ground fault current through fault resistance r in phase a (see formula 1.14) is

$$\underline{I_{fa}} = \frac{\underline{U_a}}{r} = \frac{E}{r} \cdot \frac{(1 - a^2) \cdot (\underline{Y_b} - jB_L) + (1 - a) \cdot (\underline{Y_c} - jB_L)}{\left(\frac{1}{r} + \underline{Y_a}\right) + \underline{Y_b} + \underline{Y_c} - 3 \cdot jB_L} \quad (2.71)$$

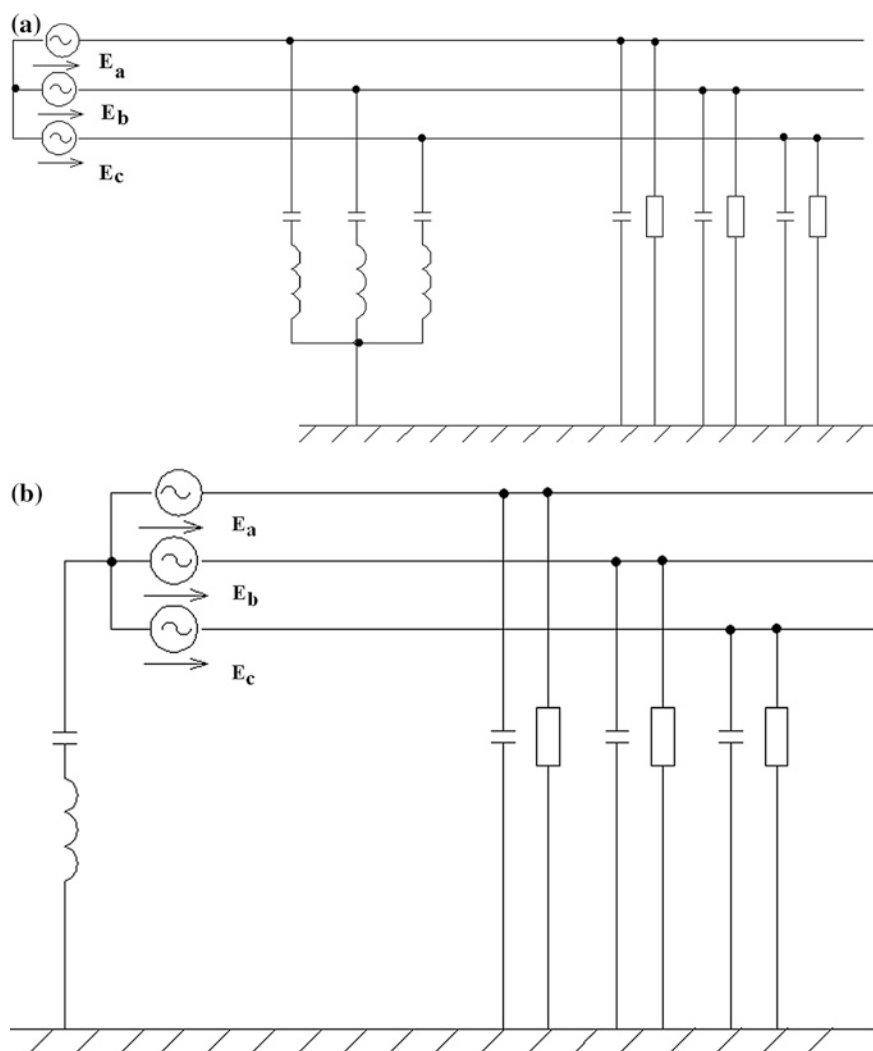


Fig. 2.13 **a** Connection of compensating reactors between single phases and ground. **b** Compensating reactor connection between neutral point and ground

In case of symmetry of single phases-to-ground capacitances and complete compensation in each phase i.e. $B_L = B_a = B_b = B_c$ ground fault current depends only on the single phases-to-ground insulation conductances and fault resistance r . Under these conditions this current assumes minimal value for equal insulation conductances of single phases. If these conductances are not identical, the ground fault current is lowest for incomplete compensation of ground capacitances by reactors.

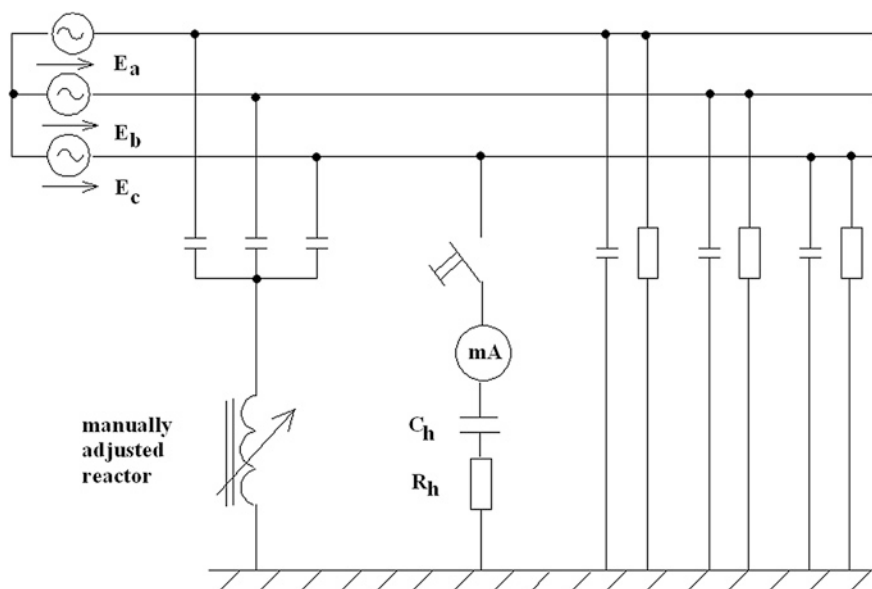


Fig. 2.14 An example of a simple compensation system of electric shock current in three-phase AC IT system

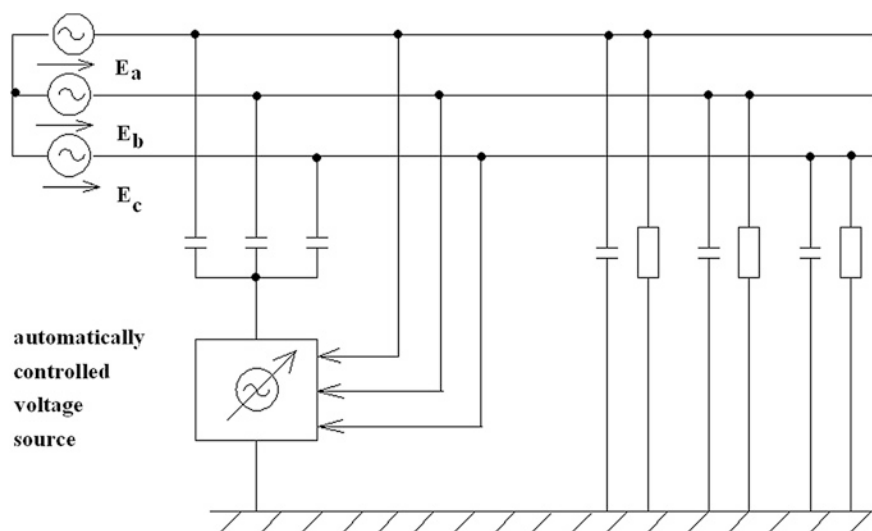


Fig. 2.15 System of continuous compensation of capacitive and resistive components of ground fault current with a controlled voltage source

If a reactor with admittance B_L is connected between the network neutral point and ground as shown in Fig. 2.13b, ground fault current I_{fa} is given by formula

$$\underline{I_{fa}} = \frac{\underline{U_a}}{r} = \frac{E}{r} \cdot \frac{(1 - a^2) \cdot \underline{Y_b} + (1 - a) \cdot \underline{Y_c} - jB_L}{\left(\frac{1}{r} + \underline{Y_a}\right) + \underline{Y_b} + \underline{Y_c} - jB_L} \quad (2.72)$$

For symmetrical insulation admittances (i.e. symmetry of both conductances and capacitances) this current assumes zero value with complete compensation i.e. $\frac{B_L}{3} = B_a = B_b = B_c$. Similarly to the previous method, for nonsymmetrical insulation admittances the lowest ground fault current is obtained with incomplete (i.e. $B_L \neq B_a + B_b + B_c$) compensation by the reactor.

For limiting fire and electric shock hazards in AC IT systems various methods of ground fault current compensation have been applied. An example of these technologies is capacitive current compensation system designed for 3-phase networks operated among others at ships [4]. A simplified circuit diagram of this concept is shown in Fig. 2.14.

Ground fault or shock current's capacitive component is compensated here by a reactor connected between an artificial neutral point and ground. Its reactance is manually adjusted during test grounding of respective phases (in the drawing this procedure is shown only for phase c as an example) via an element modelling human body impedance $R_h - C_h$. During periodical testing the reactor reactance should be set to such value at which the lowest current in the human body model is obtained. To ensure optimal compensation of shock current's capacitive component, network-to-ground capacitances should be kept symmetrical—this is achieved with help of an additional set of manually adjusted capacitors (not shown in the figure). The task of complete ground fault or shock current's capacitive component compensation can be implemented also with use of additional voltage source connected between the network artificial neutral point and ground (Fig. 2.15). This voltage source, automatically controlled by the grounded phase detector, drives an inductive current to compensate the capacitive component of ground fault current. In this system continuous compensation of the resistive component of a possible ground fault current can also be executed.

This system makes it possible to achieve practically complete ground fault current compensation after approximately 20 ms.

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