



APPLICATION OF MODIFIED PASSIVE INSULATION MONITORS FOR SELECTIVE EARTH FAULT LOCATION IN LIVE LOW VOLTAGE AC IT CIRCUITS

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Abstract – In the publication there are presented most popular passive methods of continuous insulation monitoring in live low voltage unearthed AC networks. There are given formulas for determination of insulation equivalent resistance for multi-phase networks sources with both symmetrical and asymmetrical voltages. Novel solution of elimination of the most popular measuring scheme's shortcomings is proposed. New methods of insulation resistance measurement and earth fault location based on supervision of test current flow imposed by modified diode rectifier scheme are presented.

Keywords – AC IT networks, diode rectifier, earth fault location, insulation resistance, mean value

INTRODUCTION

Electrical unearthed networks (IT) are commonly applied in many industries for reliable and safe supply of important devices and systems. Network-to-earth Insulation monitoring is indispensable for correct operation of electric systems. In the past in low voltage (LV) AC IT networks wide application has been found by insulation monitoring schemes based on diode rectifiers. This passive approach [1], [2], [3], [4], applicable exclusively for live systems (i.e. under voltage), is based on measurement of voltages produced by diode rectifiers. Insulation equivalent resistance value is obtained either by means of calculations exploiting voltages measurements results or by indication of voltmeters graduated in $k\Omega$. However in recent years, in spite of numerous advantages of that traditional (i.e. passive) technology, leading position was taken by active methods executed by isometers (insulation meters). These digital devices exploit superimposed voltage test signal produced by an auxiliary source (see Fig.1 and 2). Practically all technical literature on this subject is now devoted to new active methods [1]. Nevertheless it seems useful to remind traditional insulation monitors with rectifier circuits and review possible ways of their improvement. Main advantages of passive isometers with diode rectifiers are – as compared to more costly active technologies - first of all continuous, instantaneous operation as well as simpler construction, lack of an auxiliary test signal source and insensitivity to ground capacitances. This paper's purpose is

to remind most common passive measuring systems as well as to find ways to their improvement and broaden their scope of application.

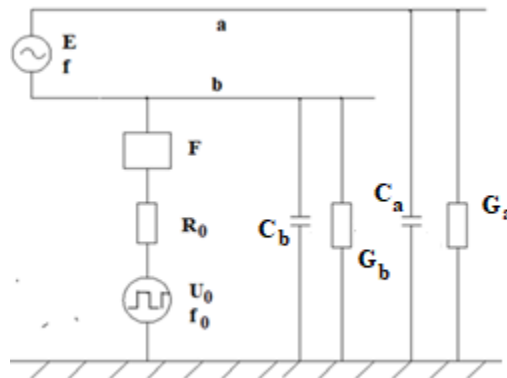


Fig. 1. Circuit diagram of a single phase AC IT network with active insulation monitoring system consisting of an auxiliary voltage $+U_0 / -U_0$ amplitude source of periodical rectangular pulses with variable polarity of f_0 frequency. F – band-pass filter for f_0 frequency, R_0 – measuring circuit's internal resistance. Other elements: E – network source voltage of f ($f \neq f_0$) frequency, G_a, G_b – insulation conductances, C_a, C_b – insulation capacitances.

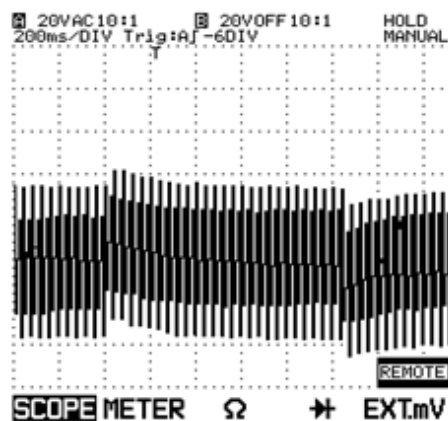


Fig. 2. Waveform of a model network phase voltage (rated parameters 60 V, 50 Hz) variation with a typical active isometer (Fig.1) in operation. An auxiliary rectangular voltage controlled by microprocessor is imposed on the monitored network. Frequency of voltage pulses with amplitude up to ± 50 V is adjusted to actual insulation resistance and capacitance levels. The isometer's operation produces phase-to-ground voltage oscillations.

1 TRADITIONAL PASSIVE SCHEMES

Below there are presented few most popular traditional passive schemes for measurement of network-to-ground insulation equivalent resistance in live LV AC IT networks.

Scheme A

Perhaps the oldest insulation monitoring scheme without an auxiliary test signal source is a system with full-wave diode bridge rectifier fed by the monitored network voltages (Fig.3). A separating transformer is supplied by a phase-to-phase voltage whereas its secondary winding is connected by rectifier and current limiting resistor R_0 between one of phase conductors and earth.

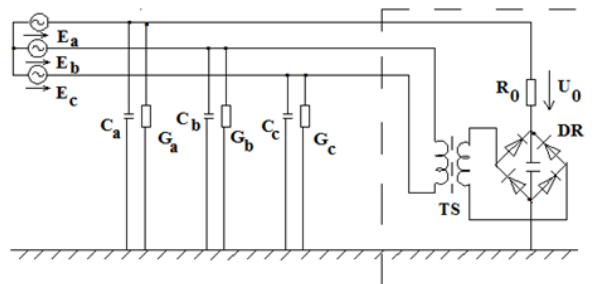


Fig. 3. Scheme A of insulation resistance measurement in a 3-phase network: TS – separating transformer, DR – full-wave bridge rectifier, R_0 – current limiting resistor, E_a , E_b , E_c – phase voltages of the source, C_a , C_b , C_c – phase-to-ground capacitances, G_a , G_b , G_c – phase insulation leakage conductances

Mean value U_{0-mean} of voltage across R_0 resistor

$$U_{0-mean} = \sqrt{2} \cdot E_{bc} \cdot \frac{R_0}{R_0 + R_i} \tag{1}$$

provides information on the sought parameter R_i (insulation equivalent resistance $1/R_i = G_a + G_b + G_c$). Its value is given by formula

$$R_i = R_0 \cdot \frac{\sqrt{2} \cdot E_{bc} - U_{0-mean}}{U_{0-mean}} \tag{2}$$

The measurement result does not depend on insulation capacitances because mean values of charging and discharging currents are zero. However R_i value depends on two voltages at a time (E_{bc} and U_0). Necessity to make two readouts simultaneously might be a shortcoming of this and other passive methods.

Scheme B

Measurement scheme B (Fig.4) also executes continuous insulation monitoring. Capacitor C is periodically charged by phases B and C through diode D. When the diode is blocked, the capacitor discharges through elements connected in series: current limiting resistor R_0 and parallel network

insulation leakage conductances G_a, G_b, G_c .

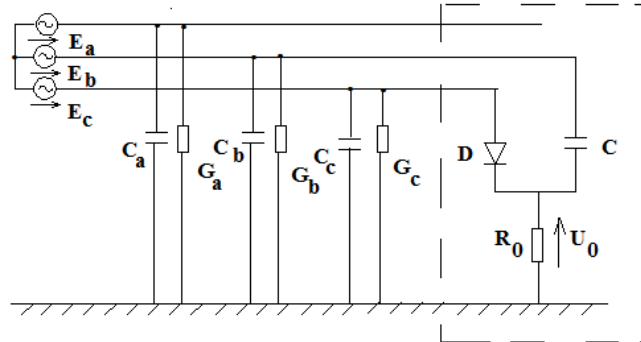


Fig. 4. Scheme B of continuous insulation equivalent resistance measurement in a 3-phase network: D – diode, C – capacitor, R_0 – current limiting resistor

The sought parameter R_i is obtained from formula

$$R_i = R_0 \cdot \frac{U_{C-mean} - U_{0-mean}}{U_{0-mean}} \quad (3)$$

where U_{C-mean} – mean value of voltage across the capacitor. Examples of voltages waveforms in this scheme are shown in Fig.5. There is presented periodical process of charging and discharging of the capacitor. For C and R_0 meeting condition $C \cdot R_0 \gg T$ (T – period of the network voltage), voltage across the capacitor is practically constant and equal to E_{bc} .

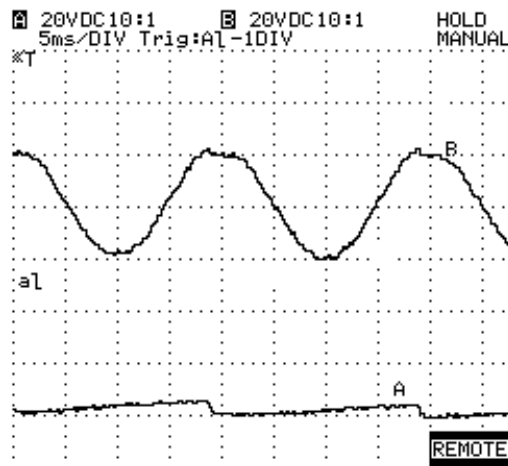


Fig. 5. Waveforms of voltages in scheme B in a 3-phase network (example): A – voltage U_0 , B – phase-to-phase voltage E_{bc} .

Scheme C

Three-phase rectifier with star connected diodes is considered the most popular passive insulation monitoring systems (Fig.6) [3].

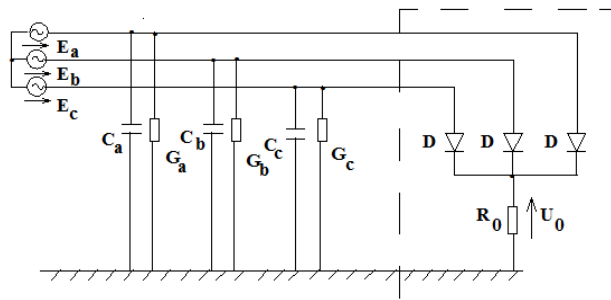


Fig. 6. Scheme C of insulation resistance measurement in a 3-phase network: D – diodes of rectifier, R₀- current limiting resistor

In this scheme diode with the highest potential of anode is conducting. Switchover from one diode to the next one takes place immediately when their phase voltages become equal. For symmetrical source phase voltages E_a, E_b, E_c with rms E value, mean value of $u_0(t)$ voltage is given by formula [3]

$$U_{0-mean} = R_0 \cdot \frac{E \cdot \frac{3\sqrt{3}\sqrt{2}}{2\pi}}{R_i + R_0} \tag{4}$$

from which R_i is obtained

$$R_i = R_0 \cdot \frac{\frac{\sqrt{2} \cdot E_{bc} - U_{0-mean}}{\pi}}{U_{0-mean}} \tag{5}$$

Derivation of formula (6) determining mean value of U_0 voltage across R_0 resistor in a network with asymmetrical source voltages $\underline{E}_a, \underline{E}_b, \underline{E}_c$ (Fig.5) is contained in [5,6]. In case of 3-phase network asymmetrical voltages sought result is

$$R_i = \left(\frac{\sqrt{2} \cdot (E_{ab} + E_{bc} + E_{ca})}{2\pi \cdot U_{0-mean}} - 1 \right) \cdot R_0 \tag{6}$$

Elimination of shortcomings of schemes A, B, C. Main shortcoming of methods A, B, C (except of lack of self- monitoring) is dependence of calculated parameter R_i simultaneously on the network source phase-to-phase voltage and on U_0 voltage. These voltages are of course proportional but when using formulas (2), (3) and (5) their current values must be known. This is not a problem for a digital insulation monitor which processes input voltages $e(t)$ and $u_0(t)$ on-line. However if measurements are executed by a man and source voltages vary with time, simultaneous readings of all voltmeters must be made which generally is not possible. Scale of U_0

voltmeter (if used) can be graduated in kΩ only if network source voltages are known and do not change. In scheme C significant difficulty can be caused by possible asymmetry of the source voltages e_a, e_b, e_c . In order to accurately determine R_i parameter from formula (6), all three phase-to-phase voltages must be simultaneously measured. The latter obstacle can be overcome by a simple modification proposed by the author. In a three-phase rectifier with star connected diodes only two diodes can be used [7] (Fig.7).

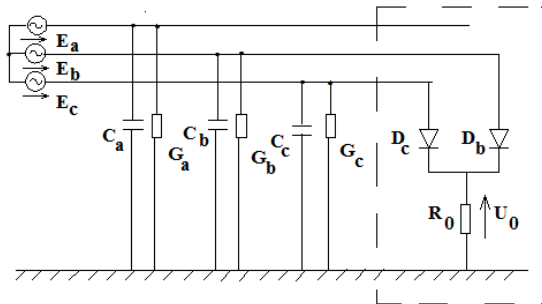


Fig. 7. Modified scheme C of insulation resistance measurement with two diodes in a 3-phase network

As shown in [7] formula for R_i is as follows

$$R_i = \frac{1}{G_i} = R_0 \cdot \frac{\sqrt{2} \cdot E_{bc} - U_{0-mean}}{\pi U_{0-mean}} \quad (7)$$

In this method the result depends on voltage E_{bc} of two selected phases. Therefore neither any possible asymmetry of source voltages phasors $\underline{E}_a, \underline{E}_b, \underline{E}_c$, nor number of network's phases play any role.

2 NEW PROSPECTS FOR INSULATION MEASUREMENT AND EARTH FAULT LOCATION

All presented schemes of passive insulation monitoring with diode rectifiers have been used so far practically only for insulation level measurement and sometimes for deterioration alarming. For these tasks scheme B and a modified two-diode scheme C seem to be most suitable of all. For implementation of measuring function it is necessary only to connect a DC overvoltage relay in parallel with R_0 resistor (Fig.8). For the setting U_{0-set} this relay would detect insulation resistance drop below the threshold equal to

$$R_{i-set} = R_0 \cdot \frac{\sqrt{2} E_{bc} - U_{0-set}}{\pi U_{0-set}} \quad (8)$$

However a certain drawback of this simplest solution is dependence of the alarm threshold on network voltage (E) variation for a fixed relay setting U_{0-set} . One way to avoid this problem is application of stabilized voltage source. There is also another one remedy that has not been used so far. Calculation of R_i resistance can be performed also by executing division of mean values of

two voltages. It should be noticed that the same rectified test current i_0 superimposed by the diode rectifier flows through series connected resistances R_0 and R_i . To take advantage of this fact it is necessary to measure mean value of any phase conductor-to-ground voltage U_{ph} . As i_0 current's mean value equals

$$I_{0-mean} = \frac{U_{0-mean}}{R_0} = \frac{U_{ph-mean}}{R_i} \quad (9)$$

the sought R_i value is

$$R_i = R_0 \frac{U_{ph-mean}}{U_{0-mean}} \quad (10)$$

Thus according to formula (10) scheme C can be implemented with a digital isometer performing division of voltages $U_{ph-mean}$ and U_{0-mean} supplied to its inputs. As both these voltages are proportional for fixed resistances R_i and R_0 , their ratio does not change with variation of phase-to-phase voltage feeding the rectifier.

The second advantage of all presented schemes is possibility for implementation of earth fault location in AC IT networks. Fast and reliable earth fault location is very important to fully exploit the main quality of unearthed circuits i.e. capability to continue operation of the network after the first insulation-to-ground breakdown. However to avoid consequences of possible second insulation failure it is necessary to find and eliminate this fault as quickly as possible. With passive insulation monitoring technology earth fault locating function has practically not been used so far for two reasons. Earlier there were no measuring devices capable of accurate measurement of small DC currents superimposed on high AC currents. Later on, when such portable DC clamp meters were developed, new technologies of active earth fault location became widespread. Now these new dedicated systems of earth fault location in both DC and AC unearthed networks totally dominate at the market. However taking advantage of an opportunity offered by schemes A, B, C should not be neglected thanks to their simplicity and low cost. Earth faults can be located by measuring DC test current superimposed by diode rectifiers with help of DC residual current electronic transformer. This procedure is illustrated in Fig.8. Insulation monitor fulfills there role not only of insulation equivalent resistance continuous measurement but also task of earth fault location in any conductor "x" where the superimposed DC residual test current is measured by an electronic current transformer. To perform the latter task for a selected feeder line the monitor is fed with signal of measured DC test current I_x .

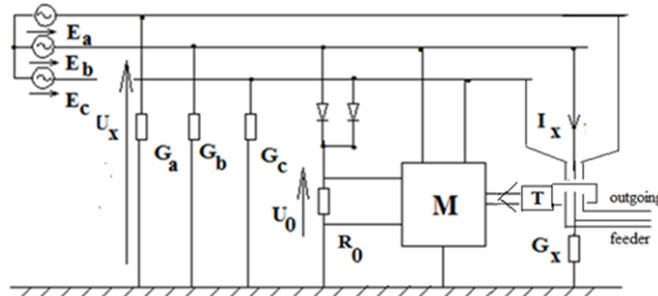


Fig. 8. Application of a scheme of insulation resistance continuous measurement in a 3-phase network executing also earth fault location: *M* – insulation monitor and earth fault locator, *T*– DC current transformer feeding signal of test current to the monitor, *G_x* - insulation leakage conductance at the earth fault place of the outgoing feeder line phase B, *I_x* - test current flowing through *G_x* to earth

The scheme shown at Fig.8 can therefore be used for determination of both the whole network insulation equivalent resistance R_i and that of single feeders like R_x . As mean value of voltages of all conductors against earth in AC network is the same, mean values of leakage currents from these conductors to earth are proportional to their insulation-to-ground conductances. To monitor insulation of a 3-phase feeder line, DC current transformer should be installed around conductors of all phases as shown at Fig.8. Microprocessor device *M* determines equivalent insulation resistance of the entire network from (7) and insulation resistance of a single conductor „x” from the following formula

$$R_x = \frac{1}{G_x} = \frac{U_{x-mean}}{I_{x-mean}} \quad (11)$$

When the above value is lower than the set threshold, for example 1 kΩ, the monitor issues an alarm and displays number of the faulted outgoing feeder.

Another way to implement earth fault location is to replace DC residual current transformer by DC current clamp meter. In this case jaws of the DC clamp meter are also closed around all conductors of monitored AC line. Indication of clamp meter is read by staff and used for comparison to other measurements. Modern DC current clamp meters and DC residual current transformers (examples presented at Fig.8) can measure very accurately currents even smaller than 1 mA DC.



Fig. 9. Examples of modern electronic DC residual current transformer (left) and digital DC residual current clamp (right)

With use of these two presented measuring devices some other (than that one shown at Fig.8) reliable and selective systems of insulation monitoring and earth fault detection can be easily fulfilled. For these schemes no insulation monitor is necessary. At Fig.10 there is explained how to manually detect possible earth fault by using readouts of a portable DC current clamp meter at some selected points of a faulty conductor. If the clamp meter indicates different DC test currents at point 1 and 2, this means that there is a leakage current flowing (escaping) through the earth fault located between these points. In this way we obtain a simple manual method of reliable earth fault location based on comparison principle. Difference of measured DC test currents $I_x = I_1 - I_2$ is earth fault (leakage to earth) current I_x . Additionally measured mean value of U_x phase voltage may be used to evaluate earth fault resistance in the located place according to formula (10).

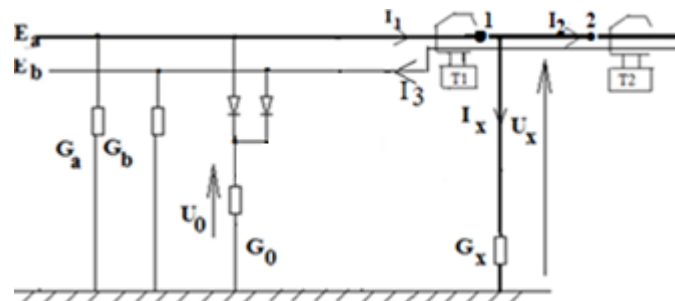


Fig. 10. Illustration of manual method of earth fault location at point "x" with help of two consecutive readouts of DC test current with DC current clamp meter at points 1 and 2

3 SUMMARY

This publication presents an overview of traditional passive schemes of continuous measurements of insulation resistance in live low voltage AC IT circuits. Thanks to their numerous advantages these methods can be still an important technique of insulation monitoring and can successfully compete with other procedures of this purpose, including widespread active methods. In the paper there is presented a modified measuring scheme based on two-diode rectifier. A practical principle of insulation resistance determination with use of phase voltage mean value

and DC test current is presented. This procedure is based on division of two above mentioned DC magnitudes and is performed continuously by digital insulation monitors. There is also proposed to apply DC test current superimposed by any of described monitoring schemes for earth fault location in AC IT networks. Two examples of selective earth fault location are given: one requires application of digital insulation monitors and the second one is executed manually with use of modern portable DC residual current sensors (clamp meters).

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