Journal of Automation,
Electronics
and Electrical Engineering

# NOVEL PASSIVE METHODS OF PERIODICAL INSULATION RESISTANCE DETERMINATION IN AC/DC IT SYSTEMS

**Piotr OLSZOWIEC**

ul. Raczynskiego 17, 28-200 Staszów, Polska, olpio@o2.pl

DOI: https://doi.org/10.24136/jaeee.2023.003

**Abstract** – – In the publication there is presented current status of development of passive methods of periodical insulation resistance determination in AC/DC IT systems. Their importance is strengthened by the fact that these procedures can be executed both manually by operator and by microprocessor monitors. Two novel methods offer a new approach which might be used also in other measuring applications. For better understanding of the proposed solutions there is given mathematical description of presence of DC components in voltages at both sides of rectifier. For the existing method of "Three Readings of a Voltmeter" and for new alternative techniques there is given an evaluation of their accuracy of insulation resistance determination.

**Key words** – AC/DC IT systems, insulation, passive method, periodical measurement

## INTRODUCTION

Electrical unearthed networks (IT) are commonly applied in many industries for reliable and safe supply of important devices and systems. Network-to-ground insulation resistance is a decisive factor determining possible ground fault currents. Therefore its level greatly affects such dangers as electric shock of humans, fire and explosion threats as well as risks of electric devices malfunction. Knowledge of actual values of this insulation parameter is therefore an indispensable condition for normal operation of electrical unearthed single- and multiphase networks designated as AC IT. The same relates to AC unearthed circuits with rectifiers designated as AC/DC IT systems (also called "mixed" networks). The main insulation parameter is network-to-ground insulation equivalent resistance which is a substitute resistance of all parallel elements between galvanically linked parts of an electrical system and ground. According to Thevenin's theorem this parameter value determines level of ground fault currents in a given circuit. Network-to-ground insulation equivalent resistance can be measured both in de-energized and in live systems. For this purpose dedicated devices are used which provide periodical or continuous measurement result. Generally measurements may utilize two main operating principles. Passive approach [1], [2], [3] applicable exclusively for live systems (i.e. under voltage), is based on voltages and/or currents measurements with use of diode rectifiers or passive electrical elements only, first of all resistors. Insulation equivalent resistance value is obtained by means of calculations exploiting measurements results. A distinctive quality of these methods is possibility to perform them both manually by operator or mechanically by a digital measuring device. Active procedures [4], [5] are executed with help of an auxiliary supply source injecting test signal. In practice for AC/DC IT systems both active and passive methods are applied. Though generally active methods are more widespread, passive techniques offer some substantial advantages including lower cost, fast and accurate indication etc. Passive methods can be also used for occasional (in case of necessity) checking of other insulation monitors measurement results correctness. In the paper two novel passive procedures are proposed which offer prospects for further improvement of this technique.

## 1 DEVELOPMENT OF PASSIVE METHODS OF INSULATION RESISTANCE MEASUREMENT IN LIVE AC/DC IT SYSTEMS

Practically the only one passive method currently used for periodical insulation measurement in “mixed” networks is procedure of “Three Readings of a Voltmeter” which is widely applied mainly in DC circuits [6-8]. For AC IT circuits this method has been tested by EKRA [9]. For “mixed” networks no manufacturer has offered it so far. Therefore technical literature on this subject is quite modest and relatively outdated.

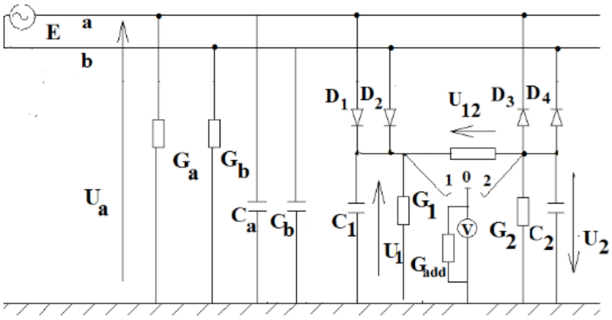

**Fig. 1. AC/DC IT single-phase system diagram with insulation resistance determination by “Three Readings of a Voltmeter” procedure where: e=e(t) – source voltage, $u_a = u_a(t)$ – conductor a – to-ground voltage, $u_1 = u_1(t)$, $u_2 = u_2(t)$ – positive, negative pole-to-ground voltages, $u_{12} = u_{12}(t)$ – rectifier output voltage, $G_a$, $G_b$ - AC side insulation leakage conductances, $G_1$, $G_2$ - DC side insulation leakage conductances, $G_{add}$ – additional resistor conductance, $C_a$, $C_b$ - AC side insulation-to-ground capacitances, $C_1$, $C_2$ - DC side insulation-to-ground capacitances, $D_1$ ... $D_4$ - diodes of rectifier.**

In AC/DC IT networks this procedure is executed at DC side of rectifier (Fig.1). With help of a voltmeter with infinite internal resistance and parallely connected additional resistor $R_{add}$ mean values of voltages of both poles (+) $U_1$ and (-) $U_2$ as well as rectified output voltage $U_{12}$ are measured. The sought value of the entire (i.e. galvanically connected sides AC and DC) “mixed” network’s insulation equivalent resistance $R_i$ is given by the formula

$$R_i = R_{add} \cdot \frac{U_{12} - U_1 - U_2}{U_1 + U_2} \tag{1}$$

where $R_i = \dfrac{1}{G_a + G_b + G_1 + G_2}$

Formula (1) is identical to the formula applied for DC circuits. This technique has been used for over century for manual checking (for three decades also by digital insulation monitors) of insulation resistance level in DC circuits. However in distinction from DC circuits so far it has not been implemented in automatic insulation monitors in AC/DC IT systems. In view of the fact that the method of "Three Readings of a Voltmeter" is the only one considered suitable for passive periodical insulation measurement in all types of systems (DC, AC, AC/DC), it is worth to analyze possible alternative ways of executing this task.

As it is commonly known, conductor-to-ground voltages at AC side may contain a DC component of substantial value [10]. This fact introduces certain obstacles (or difficulties) for possible methods of insulation-to-ground resistance determination. One of examples is use of an auxiliary DC voltage source e.g. in megohmmeters in live AC/DC IT systems. In this case the above mentioned DC component is added to or deducted from that auxiliary DC voltage introducing an error of measurement. That is why only measurement procedures insensitive to this disturbing factor may be applied in "mixed" networks. However presence of this component may be also advantageous: one of passive methods proposed by the author utilizes this characteristic property of "mixed" networks. Another novel method presented below is based on measurement of mean values of DC side voltages. To explain both new techniques it is necessary to describe more closely characteristic properties of AC/DC IT networks, namely presence of DC components in network-to-ground voltages at both sides of rectifier.

## 2 DERIVATION OF USEFUL FORMULAS

For determination of mean value of phase voltages at both AC and DC sides of a diode rectifier, a single phase AC/DC IT system will be used solely to simplify calculations. However this simplification (i.e. reduction of number of AC side phases) does not influence usefulness of the derived formulas and scope of their application. Therefore for further analysis an equivalent circuit diagram of a single phase AC/DC IT system shown in Fig.2 is used.

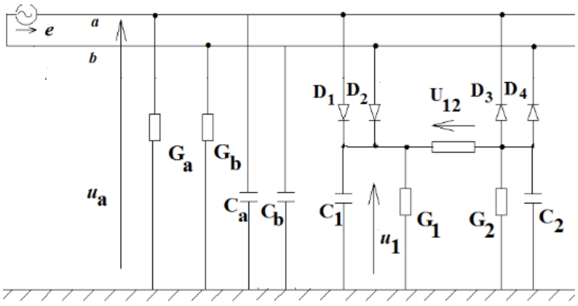

**Fig.2 An equivalent circuit diagram of a single - phase AC/DC IT system – designations as at Fig.1**

Let network source voltage be $e(t) = E_m \cdot \sin \frac{2\pi}{T} t$ . In successive two semiperiods of rectifier operation the following equations of leakage currents (flowing from network to ground) balance (I Kirchhoff's law) are valid:

0<t<T/2 – D1 and D4 conduct:

$$(G_a + G_1) \cdot u_a + (C_a + C_1)\frac{du_a}{dt} + (G_b + G_2) \cdot (u_a - e) + (C_b + C_2)\frac{d(u_a - e)}{dt} = 0 \qquad (2)$$

T/2<t<T – D2 and D3 conduct:

$$\begin{aligned}&(G_b + G_1) \cdot (u_a - e) + (C_b + C_1)\frac{d(u_a - e)}{dt} + \\ &(G_a + G_2) \cdot u_a + (C_a + C_2)\frac{du_a}{dt} = 0\end{aligned} \qquad (3)$$

From equations (2) and (3) mean value of $u_a$ voltage is calculated as

$$U_{a-mean} = \frac{1}{T} \cdot \left[ \begin{aligned}&\int_0^{T/2} e \cdot \frac{G_b + G_2}{G_a + G_b + G_1 + G_2} dt + \\ &+ \int_{T/2}^{T} e \cdot \frac{G_b + G_1}{G_a + G_b + G_1 + G_2} dt\end{aligned} \right] \qquad (4)$$

Of course, integrals of voltages e and ua over the whole period T are equal to zero as both functions are periodical. Therefore capacitive currents do not influence balance of leakage currents. Taking into account that

$$U_{12-mean} = \frac{2}{T} \cdot \int_0^{T/2} e dt$$

the sought formula is obtained as

$$U_{a-mean} = \frac{U_{12-mean}}{2} \cdot \frac{G_2 - G_1}{G_a + G_b + G_1 + G_2} \tag{5}$$

Mean value of single pole-to-ground voltages at DC side of the rectifier is calculated below in similar way with help of the same equivalent circuit diagram (Fig.2). For simplicity of calculations capacitances of the network-to-ground insulation have been neglected as they don’t influence mean values of the network-to-ground voltages at both sides of the rectifier. In successive two semiperiods of rectifier operation the following equations of leakage currents balance are valid:

$0<t<T/2$ – $D_1$ and $D_4$ conduct:

$$(G_a + G_1) \cdot u_1 + (G_b + G_2) \cdot (u_1 - e) = 0 \tag{6}$$

$T/2<t<T$ – $D_2$ and $D_3$ conduct:

$$(G_b + G_1) \cdot u_1 + (G_a + G_2) \cdot (e + u_1) = 0 \tag{7}$$

From equations (6) and (7) mean value of $u_1$ voltage is calculated as

$$U_{1-mean} = \frac{1}{T} \cdot \left[ \int_0^{T/2} e \cdot \frac{G_b + G_2}{G_a + G_b + G_1 + G_2} dt - \int_{T/2}^{T} e \cdot \frac{G_a + G_2}{G_a + G_b + G_1 + G_2} dt \right] \tag{8}$$

Taking into account that $\int_0^{T/2} edt = -\int_{T/2}^{T} edt$ the sought formula for mean value of $u_1$ voltage is obtained as

$$U_{1-mean} = \frac{U_{12-mean}}{2} \cdot \frac{G_a + G_b + 2 \cdot G_2}{G_a + G_b + G_1 + G_2} \tag{9}$$

Formula for mean value of $u_2$ voltage is

$$U_{2-mean} = U_{12-mean} - U_{1-mean} = \frac{U_{12-mean}}{2} \cdot \frac{G_a + G_b + 2 \cdot G_1}{G_a + G_b + G_1 + G_2} \tag{10}$$

It must be noted that formulas (5), (9 ) and (10) are also true for any AC/DC IT system with unlimited number of phases and both symmetrical and asymmetrical source voltages. All formulas derived above can be used for numerous tasks of AC/DC IT systems analysis. Below there is shown one example: possibly a shortest derivation of the formula (1) with help of formulas (9) and (10). When positive pole of rectifier is grounded by means of an additional resistor *Radd=1/*Gadd , mean value of its u1 voltage is given as

$$U_{1-mean} = \frac{U_{12-mean}}{2} \cdot \frac{G_a + G_b + 2 \cdot G_2}{G_a + G_b + G_1 + G_2 + G_{add}} \tag{11}$$

When negative pole of rectifier is grounded by means of the same resistor, mean value of its $u_2$ voltage is

$$U_{2-mean} = \frac{U_{12-mean}}{2} \cdot \frac{G_a + G_b + 2 \cdot G_1}{G_a + G_b + G_1 + G_2 + G_{add}} \tag{12}$$

Substituting both expressions (11) and (12) into (1), an identity is obtained. In the next chapter it is demonstrated how all these derived formulas (5), (9), (10) can prove useful to find novel methods of insulation resistance determination.

## 3 NOVEL METHODS OF PERIODICAL DETERMINATION OF AC/DC IT NETWORKS INSULATION PARAMETERS

### Method I

Formula (5) describing phase voltages mean value can be used for a novel method of periodical determination of the whole AC/DC IT network insulation equivalent resistance $R_i=1/G_i$. The proposed procedure (developed by the author) consists of two steps. AC side conductor-to-ground voltage mean value is measured in two states: (1) $U_{ph-mean1}$ in normal working condition, (2) $U_{ph-mean2}$ with an additional resistor $R_{add}=1/G_{add}$ connected between any conductor at AC side and ground. In these two states AC phase-to-ground voltages mean values are measured by voltmeter with infinite internal resistance:

$$U_{ph-mean1} = \frac{U_{12-mean}}{2} \cdot \frac{G_1 - G_2}{G_i} \tag{13}$$

$$U_{ph-mean2} = \frac{U_{12-mean}}{2} \cdot \frac{G_1 - G_2}{G_i + G_{add}} \tag{14}$$

From both equations (13) and (14) the sought parameter $G_i=G_a+G_b+G_c+G_1+G_2$ is calculated as

$$G_i = G_{add} \cdot \frac{U_{ph-mean2}}{U_{ph-mean1} - U_{ph-mean2}} \tag{15}$$

Thus

$$R_i = R_{add} \cdot \frac{U_{ph-mean1} - U_{ph-mean2}}{U_{ph-mean2}} \tag{16}$$

If AC side-to-ground voltage has zero mean value (due to $G_1$=$G_2$), then one of $G_1$ or $G_2$ conductances should be changed by grounding artificially any selected pole through a test conductance $G_T$. Then both steps of the procedure described above are executed, after which the test conductance $G_t$ should be removed. The sought parameter $G_i$ is given as

$$G_i = G_{add} \cdot \frac{U_{ph-mean2}}{U_{ph-mean1} - U_{ph-mean2}} - G_T \tag{17}$$

**Method II**

In similar way another new method of periodical determination of AC/DC IT network insulation equivalent resistance can be developed. Lets select for measurements positive pole of rectifier. In this case the proposed procedure is based on formula (11) for mean value of this pole-to-ground voltage. Its mean voltage is measured in two states: (1) $U_{1-mean0}$ in normal working condition, (2) $U_{1-mean1}$ with an additional resistor $R_{add}=1/G_{add}$ connected between this (positive) pole and ground. In these two states these voltages are respectively:

$$U_{1-mean0} = \frac{U_{12-mean}}{2} \cdot \frac{G_a + G_b + 2 \cdot G_2}{G_a + G_b + G_1 + G_2} \tag{18}$$

$$U_{1-mean1} = \frac{U_{12-mean}}{2} \cdot \frac{G_a + G_b + 2 \cdot G_2}{G_a + G_b + G_1 + G_2 + G_{add}} \tag{19}$$

From both equations (18) and (19) the sought parameter $G_i$=$G_a$+$G_b$+$G_1$+$G_2$ is calculated as

$$G_i = G_{add} \cdot \frac{U_{1-mean1}}{U_{1-mean0} - U_{1-mean1}} \tag{20}$$

Thus

$$R_i = R_{add} \cdot \frac{U_{1-mean0} - U_{1-mean1}}{U_{1-mean1}} \tag{21}$$

It is worth to note a distinctive property of "mixed" networks. With help of formulas (18) and (19) it is easy to show that mean value of phase voltage (13) is equal to half of difference of mean values of rectifier poles voltages. In other words DC component of AC side voltages corresponds to asymmetry of DC voltages of both rectifier poles.

Both methods are new solutions providing alternative ways of passive periodical determination of insulation equivalent resistance in AC/DC IT systems. As compared to traditional procedure of "Three Readings of a Voltmeter", methods I and II consist of smaller number of measurements, namely 2 instead of 3. An additional resistor is connected only once. Network voltages i.e. AC source voltages in method I and rectifier output voltage in method II, need not to be known, however they cannot change during measurements.

## 4 POSSIBLE ERRORS OF METHODS OF INSULATION RESISTANCE PERIODICAL DETERMINATION IN AC/DC IT SYSTEMS

Evaluation of possible errors of respective measurement methods enables to assess their usefulness for determination of insulation resistance in live AC/DC IT networks. Below maximum possible errors of two selected methods were determined.

For the "Three Readings of a Voltmeter" method (formula (1)) maximum error of $R_i$ determination can be expressed as

$$\begin{aligned}\Delta R_i &= \left[\left|\frac{\delta R_i}{\delta U_{12}}\right| + \left|\frac{\delta R_i}{\delta U_1}\right| + \left|\frac{\delta R_i}{\delta U_2}\right|\right]\cdot \Delta U = \\ &= \frac{2\cdot U_{12} + U_1 + U_2}{\left(U_1 + U_2\right)^2}\cdot R_{add}\cdot \Delta U\end{aligned} \tag{22}$$

where $\Delta U$ is an error of $U_1$, $U_2$ and $U_{12}$ voltages measurement with a voltmeter of $R_{add}$ substitute resistance. It was assumed that $R_{add}$ is an accurately known value and therefore there is no need to take into account an error of this resistance determination. For comparison in case of, for instance, method II (formula (21)) maximum error of $R_i$ determination does not exceed

$$\begin{aligned}\Delta R_i &= \left[\left|\frac{\delta R_i}{\delta U_{1-mean0}}\right| + \left|\frac{\delta R_i}{\delta U_{1-mean1}}\right|\right]\cdot \Delta U = \\ &= \left[\frac{1}{U_{1-mean1}} + \frac{U_{1-mean0}}{\left(U_{1-mean1}\right)^2}\right]\cdot R_{add}\cdot \Delta U = \\ &= \frac{U_{1-mean0} + U_{1-mean1}}{\left(U_{1-mean1}\right)^2}\cdot R_{add}\cdot \Delta U\end{aligned} \tag{23}$$

In Table 1 there are given few selected results of maximum errors evaluation of insulation equivalent resistance in "mixed" network by these two methods. All insulation resistances are in kohms, all voltages mean values in Volts. Rectifier output mean voltage is $U_{12}$ =230 V. Additional resistor value is $R_{add}$=100 kohm. For typical digital multimeter within range 0…1000 VDC voltage measurement maximum error is $\Delta U$=1 V. Relative {%] and absolute [kohm] errors of given by formulas (22) and (23) are given in columns 7 and 10 respectively.

From calculation results contained in the table few conclusions can be drawn:

1) Accuracy of insulation resistance determination is strongly influenced by selection of additional resistor value. The smallest error is obtained when $R_{add}$ is of the same order as $R_i$ .
2) Both compared methods display similar accuracy.
3) Accuracy achieved by traditional and novel periodical insulation resistance determination methods does not substantially differ from accuracy of sophisticated active methods of insulation continuous measurement.

**Table 1**

| $R_a$ $R_b=\infty$ | $R_1$ | $R_2$ | $R_i$ | $U_1$ in 3-volt.method | $U_2$ in 3-volt.method | $R_i$ [%]/kohm error (22) | $U_{1mean0}$ in method II | $U_{1mean1}$ in method II | $R_i$ [%] / kohm error (23) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 10 | 10 | ∞ | 5 | 54.8 | 164 | 28/1.4 | 57.5 | 54.8 | 74/3.7 |
| 100 | 100 | ∞ | 50 | 38.3 | 115 | 2.6/1.3 | 57.5 | 38.3 | 6.5/3.25 |
| 100 | ∞ | 100 | 50 | 115 | 38.3 | 2.6/1.3 | 172.5 | 115 | 2.2/1.1 |
| 100 | ∞ | ∞ | 100 | 57.5 | 57.5 | 4.3/4.3 | 115 | 57.5 | 5.2/5.2 |
| 1000 | ∞ | 100 | 91 | 115 | 5.5 | 4.3/4.0 | 219.5 | 115 | 2.7/2.5 |

## 5 SUMMARY

The publication presents current situation of implementation of periodical measurements of insulation resistance in AC/DC IT systems. These procedures can be executed both manually and by digital monitors. Therefore they are an important technique of insulation monitoring, especially that they can replace – if need be - other procedures of this purpose, including widespread active methods of continuous operation. Two novel methods offer a new approach which might be used also in other measuring applications. For better explanation of the proposed solutions there is presented derivation of formulas describing presence of DC components in voltages at both sides of rectifier. Description of new alternative methods is followed by evaluation of maximum errors of insulation resistance determination. Neither derivation of these fundamental formulas nor evaluation of maximum errors of any existing procedures have been presented in available technical literature.

## NOWE METODY PASYWNE OKRESOWEGO WYZNACZANIA REZYSTANCJI IZOLACJI W UKŁADACH AC/DC IT

W artykule przedstawiono aktualny stan rozwoju pasywnych metod okresowego wyznaczania rezystancji izolacji doziemnej w układach AC/DC IT. Podano dwa nowe sposoby realizacji tego zadania. Dla pełnego zrozumienia nowych rozwiązań pokazano matematyczne uzasadnienie zależności określających składowe DC w napięciach doziemnych obu stron prostownika diodowego. Dla istniejącej metody oraz jednej z proponowanych procedur oszacowano maksymalne możliwe błędy analitycznego wyznaczania wartości zastępczej rezystancji izolacji całego układu AC/DC IT.

**Słowa kluczowe**: układy AC/DC IT, izolacja, metoda pasywna, pomiar okresowy

## BIBLIOGRAPHY

[1] P.Olszowiec „Insulation Measurement and Supervision in Live AC and DC Unearthed Systems”, Springer-Verlag Berlin, 2nd edition 2014

[2] P.Olszowiec “Kontrola izolacji w obwodach prądu stałego” COSiW Warszawa 2011

[3] Tsapenko E.F. “Kontrol izolacji w sietiach do 1000 V” [Insulation monitoring in networks up to 1000 V]. Moscow, Energia, 1972 (in Russian).

[4] Hofheinz W.: “Protective Measures with Insulation Monitoring”, VDE Verlag, 1998.

[5] https://www.bender.de/en/products/insulation-monitoring/isometer-irdh275/ (of the day 2023.08.01)

[6] PN-76/E-83005 “Baterie akumulatorowe kwasowe stacyjne o napięciu do 220 V – Ogólne wymagania I badania”

[7] https://www.spie-energotest.pl/wyroby/kontrola-doziemie%C5%84-dctest2.html (of the day 2023.08.01)

[8] Ciszewski R., Fulczyk K. „Projektowanie obwodów pomocniczych urządzeń elektroenergetycznych elektrowni i stacji”, WNT Warszawa 1969

[9] https://ekra.ru/product/nku-kru/ob-kont-sop-iz/ekra-ski/ (of the day 2023.08.01)

[10] Ivanov E.: „Kak pravilno izmeriat’ soprotivlenie izolacii ?”, Novosti Elektrotechniki 2/2002 (in Russian).