MEASUREMENT ACCURACY OF SHORT-CIRCUIT LOOP IMPEDANCE IN POWER SYSTEMS

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Abstract − This paper presents the problems relating to the measurement of power system loop impedance in present day low voltage networks particularly in presence of voltage disturbances. The paper discusses the main sources of loop impedance measurement errors such as: the difference in impedances arguments, transients in tested circuit and the distortion of the voltage waveform in the measurement point. The conditions how to minimize measurement inaccuracy are also given. Example of loop impedance measurement errors are presented in the form of graves for different parameters of the tested circuit.

Keywords: loop impedance, low voltage network, measurement accuracy.

1. INTRODUCTION

Measurements of the power system loop impedance in present day low voltage network are of great practical significance, especially to study short circuit behaviour of power system elements or to determine the quality factor of the supplying voltage waveform. The most important is the value of the loop impedance when testing the effectiveness of protective neutral earthing. The loop impedance, $Z = R + jX$ comprises of a series connected resistance R and inductive reactance X of the phase conductors from the point of fault back to the transformer, the transformer winding, cabling and earth neutral path to the position of fault.

The system loop impedance Z is normally obtained by measurement. Periodical measurement results may contain high negative error due to effect of voltage changes in testing point. An accurate impedance measurement is needed for reliable operation of the protective devices and consequently for safety of human and apparatus. Accuracy in measurement depends on the parameters of the tested circuit, the disturbances of the supplying system, and the measuring method and instrument used.

There are known publications [1,2,3,5,6,7] relating to this type of problem, however methods and measurement equipment available are only suitable for use, with satisfactory accuracy, in networks with sinusoidal voltage waveforms. It's been noticed lately that voltage curves at measurement point can be highly distorted. This has a deciding effect on the measurement result obtained using known methods and instruments. Using typical loop impedance measurement instruments in such cases, could lead to high value of measurement errors. As a result of this, electrical equipment could be exploited with unsatisfactory protection with the resultant danger of electrical shock.

The intent of this paper is to discuss and analize the impedance measurement methods and instruments use in present day low voltage network. In particular the classical sources of measurement errors will be described and also errors due to voltage distortion will be presented in the form of graves.

2. THEORETICAL PRINCIPLES OF LOOP IMPEDANCE MEASUREMENT

The principle of classical methods [3,4,5] for measurement the system loop impedance $Z = R + jX$ are based on determination of the two sinusoidal voltage values at the measurement point: first, the open circuit voltage E - when measurement load impedance of known value $Z_0 = R_0 + jX_0$ is switched OFF, and the second, the load voltage V- when the measurement load impedance Z_0 is switched ON between phase conductor L and protective conductor N.

The tested circuit can be represented by the circuit which consist of a series connected sinusoidal voltage source E and the loop impedance Z and instrument load impedance Z_0 as it is shown in Fig.1.

The measured loop impedance is given by the following definite vector relationship

$$\underline{Z}=\underline{Z}_0\frac{\underline{E}-\underline{V}}{\underline{V}}=\underline{Z}_0\left(\frac{\underline{E}}{\underline{V}}-1\right) \qquad (1)$$

Due to the technical difficulties involved in the application of equation (1), the following approximation is used to obtain measurement value

$$Z_M=Z_0\frac{E-V}{V}=Z_0\left(\frac{E}{V}-1\right) \qquad (2)$$

and the impedance measuring error is given by

$$\delta Z=\frac{Z_M-Z}{Z}$$

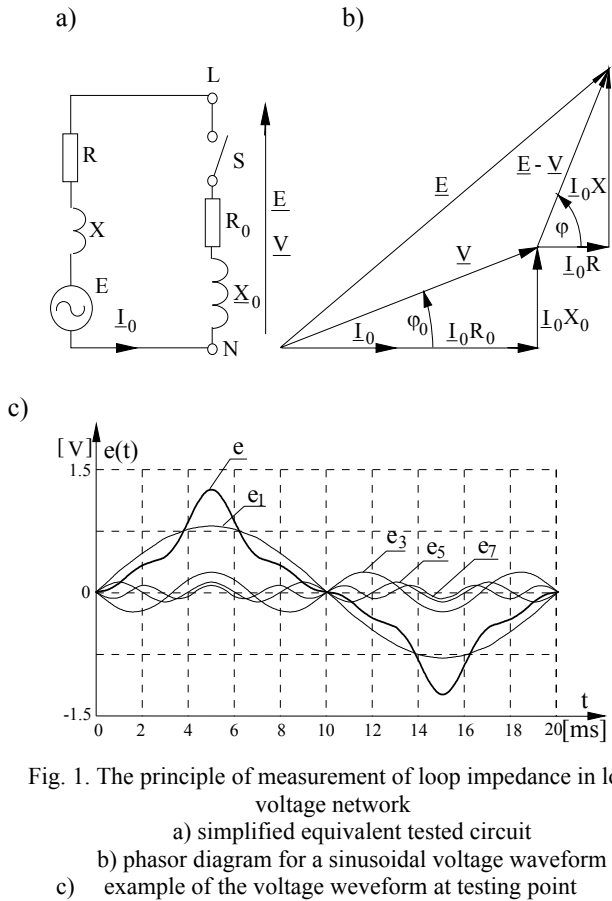a)   b)

c)

Fig. 1. The principle of measurement of loop impedance in low
voltage network
a) simplified equivalent tested circuit
b) phasor diagram for a sinusoidal voltage waveform
c)   example of the voltage weveform at testing point

In practice, the values measured and eventually converted are usually maximum values of both voltages E_m and V_m or their rms values E_{rms} and V_{rms}. It is universally assumed that, the source voltage is a sinusoidal waveform with an amplitude of $E_m = \sqrt{2}\, E_1$. The load voltage V, presumed to be sinusoidal, has an amplitude of $V_m = \sqrt{2}\, V_1$. The set of assumptions presented above relate to whole groups of loop impedance measurement techniques. The difference between specific impedance meter is based on the conversion method applied to the voltages to obtain a measurement result.

3. MEASUREMENT ACCURACY

All meters and methods in use presently for measuring loop impedance [2,3,4,6] show remarkable differences in metrological properties. The fundamental characteristic parameter of any method or meter is the measurement error. Negative errors are the most dangerous when testing the effectiveness of protective neutral earthing, i.e. in the case where the measured value of loop impedance is less than the actual value. This leads to the situation where machinery with ineffective protection is exploited, which can be the cause of electrical shock. The accuracy demanded by the regulations is not high; for example from [1] the permissible error margin is as high as 30%. Such mild requirements are the result of the fact that the measurement is affected by many factors which lead to inaccuracies. Some of the causes

of inaccuracies are due to the method itself (simplification of the equivalent tested circuit, approximations applied in the measuring techniques of the meters), as well as inaccuracies in the construction of the instrument.

One of the more significant and obvious causes of error is changes and fluctuations in network voltage induced by changes in the working load of the studied system. An effective elimination of this problem is achieved by reducing the time between the determination of both values of voltage [6]. Another way of reducing the effect of voltage fluctuations is to increase the value of measurement current. The measurement current must however be much smaller than the operational current the nearest protection device. Initial network loads are also another cause of inaccuracies in loop impedance measurement.

The most important sources of loop impedance measurement errors will be described and will be presented in the form of graves.

3.1. The phase difference error

In practical situation it is difficult to measure the geometrical difference of the voltage vectors $\underline{E}$ and $\underline{V}$ at the testing point. Therefore the most impedance meters are based on arithmetical relation between voltage magnitudes E and V, so the measurement value of loop impedance Z_M is given by (2). Since the geometrical difference $(\underline{E} - \underline{V})$ is greater than the arithmetical difference (E - V), (as shown in Fig.1b and Fig.2b), so we must expect negative error $\delta Z_{\varphi d}$ due to phase difference arguments $(\varphi - \varphi_0)$ between loop impedance angel $\varphi - $ (Arg Z) and measurement load impedance angel $\varphi_0 - $ (Arg Z_0).
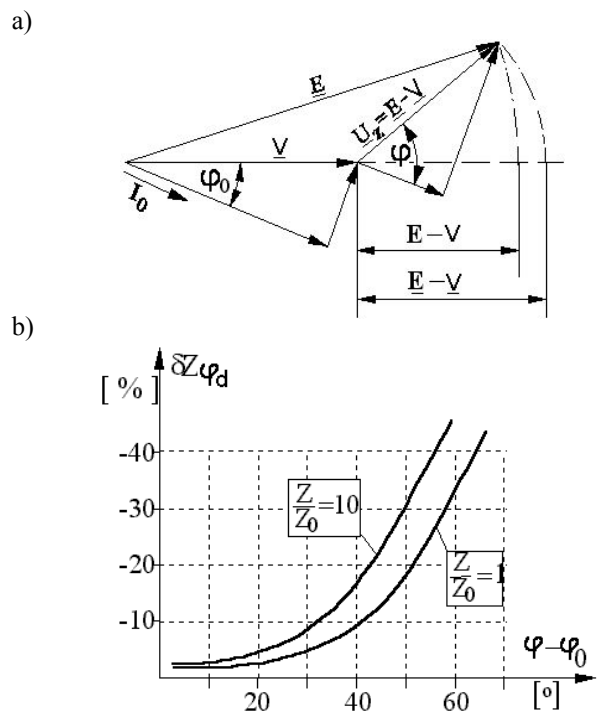
a)

b)

Fig. 2. Example of measurement phase difference error $dZ_{\varphi d}$
a) the phasor diagram of voltages
b) the curves of phase difference error

Inaccuracy arising from substitution of the vectors ($\underline{E},\underline{V},\underline{Z_0}$) by their moduli ($E,V,Z_0$) is, in light of the VDE regulations [1] acceptable, as long as the studied system is characterized by a difference of the impedance arguments no larger than 15° [$(\varphi - \varphi_0) < 15^{\circ}$], where: $\varphi = arctg\ X/R$, $\varphi_0 = arctn\ X_0/R_0$, and the impedance ratio $S = Z/Z_0$. In the case, when ($\varphi = \varphi_0$) we have: $E - V = \underline{E} – \underline{V}$ and the measurement error $\delta Z_{\varphi d} = 0$.

Figure 2. shows the curves of error $\delta Z_{\varphi d} = f(S, \varphi)$ as a result of calculation based on (4). To reduce the error $\delta Z_{\varphi d}$ to permissible value the instrument should have the measurement load impedance of constant magnitude Z_0 and be capable to vary phase angle φ_0.

The phase difference error has a systematic characteristic and its value is given by

$$\delta Z_{\varphi d} = \frac{Z_M - Z}{Z} = \frac{1}{S}\left(\sqrt{1+S^2+2S\cos(\varphi-\varphi_0)}-1\right)-1 \quad (4)$$

In order to approach the true value of the unknown loop impedance Z we must minimize the phase difference error by making the impedances phase angle φ equal to φ_0.

3.2. Error due to transients

The transient state occurs as a result of switching ON or OFF the measurement load impedance Z_0 for a short time. Electrical transient in voltage (as is shown in Fig.3) appears for a finite time after switching ON impedance Z_0. When the open circuit voltage E_{Mm} or load voltage V_{Mm} are measured during the transient interval, we must expect the transient measuring error δZ_t due to reactance and resistance in tested circuit. The transient error has been discussed in some details for a different model of tested circuit, in previous works [4].

In simple RL circuit the instantaneous load voltage v(t) is given by

$$v(t) = \frac{Z_0}{Z} \cdot \sqrt{2} \cdot E \cdot (\sin(\omega t + \psi_S - \varphi_C + \varphi_0) -$$
$$- \sin(\psi_S - \varphi_C) \cdot \exp(-\frac{t}{T})) \quad (5)$$

$$\delta Z_{t1} = \frac{V_{ms}\left(E_m - V_{m1}\right)}{V_{m1}\left(E_m - V_{ms}\right)} - 1 \quad (6)$$

The earth loop impedance meters which use resistive load and half-cycle high value testing current may contribute large negative error due of transients. In some cases this error may exceed a permissible value 30%. The error due to transient in voltage will not appear ($\delta Z_t = 0$) when:
− switching angle ψ_s is equal to angle of the tested circuit

$$\varphi_C = arctg\ \frac{X + X_0}{R + R_0}, (\psi_S = \varphi_C),$$

− arguments of loop impedance φ and load impedance φ_0 are equal ($\varphi = \varphi_0$).

The effect of transient states can be eliminated by an appropriate construction of the measurement instrument. It is often based on the principle that both voltages are measured with the appropriate time lag in relation to the commutations of the measuring load.
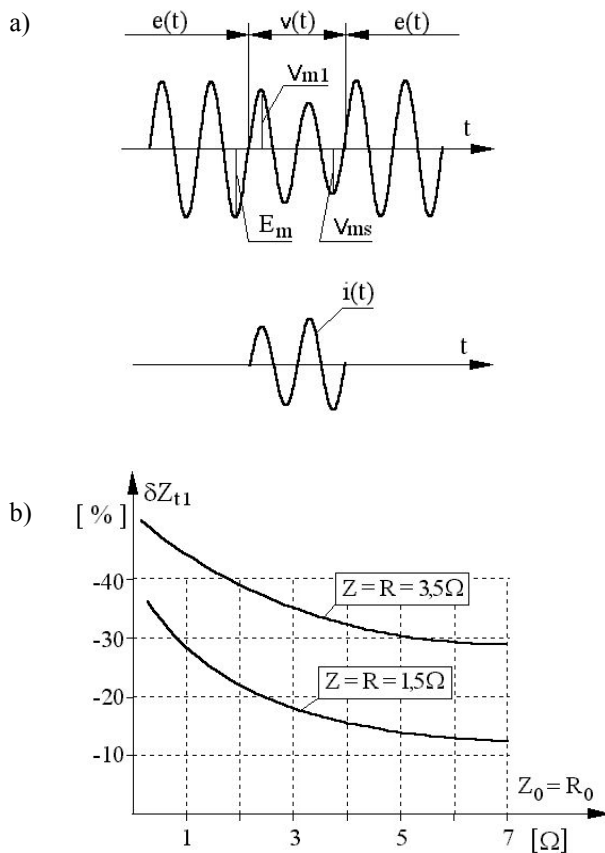

Fig. 3. Example of transient error
a) the instantaneous voltages and current waveform at testing point
b) the curves of transient error δZ_{t1}

3.3. Errors due to distortion of the voltage waveform

To date, all regulations relating to the measurement of loop impedance have not taken into consideration the question of the effect of voltage waveform distortion on the measurement error. This state of affairs may be due to the lack of research into this problem.

In networks with distorted voltage waveforms, all loads, including those creating disturbances, are covered by protective neutral earthing. The impedance measurements results are liable to contain a negative error of δZ due to the effects of supply voltage distortion.

From the point of view of their sensitivity to supply voltage changes in particular distortion of the voltage waveform, the known classical methods can be divided into two groups, which are characterised by different properties.

The first group includes impedance measuring techniques where the measurement result Z_{rms} is obtained on the base of rms values of measured voltages E_{rms} and V_{rms}. These include the so-called "drop voltage methods", which have been in use for some time now.

The second group consists of a number of widely used specialised meters containing thyristor switches which help achieve short duration high value test currents. The measurement impedance results Z_m are based on the memorised maximum values of measured voltages: E_m and U_m. These instruments are scaled by their producers for sinusoidal waveforms.

The author performed investigation [5] of the effects of harmonics on the accuracy of loop impedance measurement for a linear model of tested circuit represented bay equivalent circuit shown in Fig.1a. The investigation and calculation were conducted for a whole range of parameters of tested circuit. The instantaneous open circuit voltage e(t) at testing point is describe as

$$e(t) = \sqrt{2}[E_1 \sin(\omega t + \alpha_1) + E_3 \sin(3\omega t + \alpha_3) + \\ + E_5 \sin(5\omega t + \alpha_5) + E_7 \sin(7\omega t + \alpha_7)] \tag{7}$$

The measured values of impedances Z_{rms} and Z_m as well as measurement errors δZ_{rms} and δZ_m were determined on the basis of the rms values E_{rms} and V_{rms} as well as maximum values Em and V_m.

Knowing the actual value of the loop impedance Z the errors δZ_{rms} and δZ_m are given by relationships

$$\delta Z_m = \left[\frac{Z_m - Z}{Z}\right] = \left[\frac{Z_0\left(\frac{E_m}{U_m}-1\right)}{Z} - 1\right]$$

$$\delta Z_{rms} = \left[\frac{Z_{rms} - Z}{Z}\right] = \left[\frac{Z_0\left(\frac{E_{rms}}{V_{rms}} - 1\right)}{Z} - 1\right] \tag{8}$$

where rms voltages are:

$$E_{rms} = \sqrt{E_1^2 + E_3^2 + E_5^2 + E_7^2}$$

$$V_{rms} = \sqrt{V_1^2 + V_3^2 + V_5^2 + V_7^2} \tag{9}$$

Determination of the rms and maximum values of the distorted voltage waveform as well as measuring errors δZ_{rms} and δZ_m given by above mathematical expression were performed with the help of the computer program MATHCAD.

As an example Fig. 4 shows the graphs relationships of the short-circuit loop impedance measurement errors δZ_{rms} and δZ_m as a function of loop impedance argument φ for the meters used in different measuring points in the network with two types of voltage waveforms. These graphs were plotted for loop impedance meters with one value of load impedance $Z_0 = 10\Omega$ and one value of its argument $\varphi_0 = 45°$.
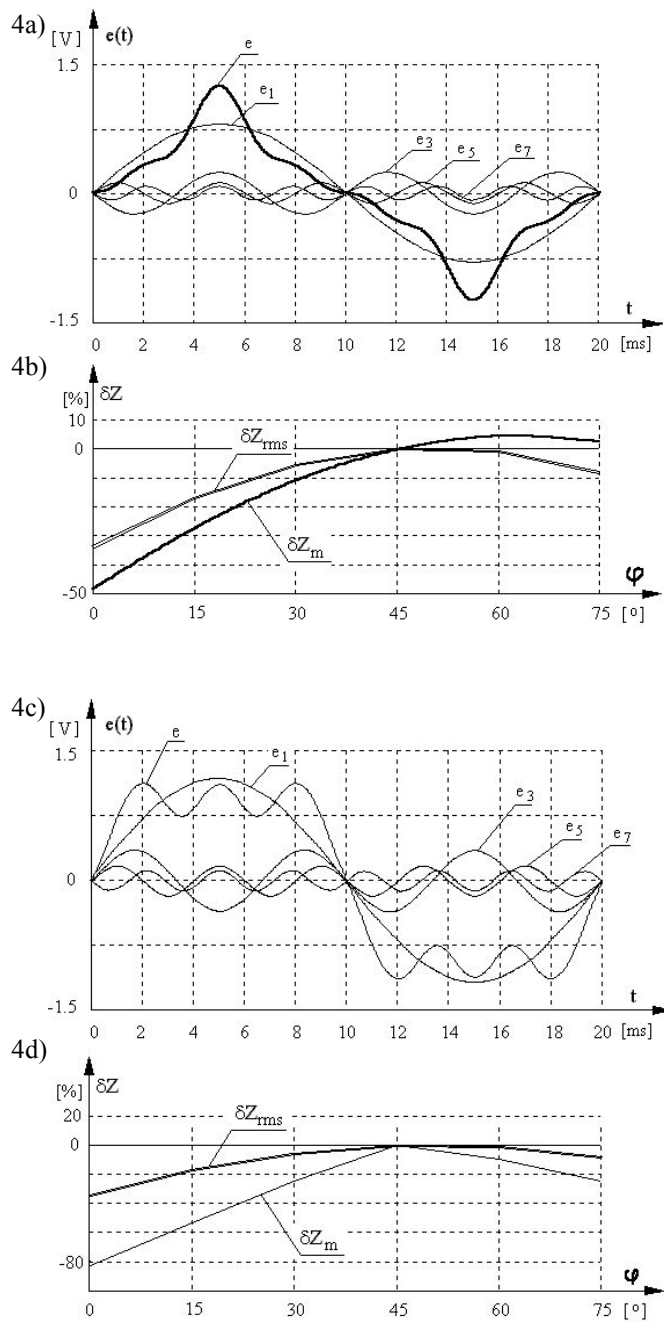
Fig. 4. Impedance measurement errors for two type of voltage waveforms at testing point for a given parameters of the tested circuit: Z= 1Ω, Z_0 = 10Ω, φ_0 = 45

4a) sharp voltage waveform:

$$e(t) = \sqrt{2}[E_1 \sin\omega t + 0,2\sin(3\omega t + 180°) + \\ + 0,15\sin(5\omega t + 0°) + 0,1\sin(7\omega t + 180°)]$$

4b) graphs of errors δZ_{rms} = f(φ) and δZ_m = f(φ)

4c) flat voltage waveform:

$$e(t) = \sqrt{2}[E_1 \sin\omega t + 0,2\sin(3\omega t + 0°) + \\ + 0,15\sin(5\omega t + 0°) + 0,1\sin(7\omega t + 180°)]$$

4d) graphs of errors δZ_{rms} = f(φ) and δZ_m = f(φ)

As it is seen in Fig 4b and 4d, the impedance measurement error may reach value of 80%, which is far above the permissible value. The error has zero value only in the case of equality of both arguments ($\varphi = \varphi_0$) the result of the fact that the measurement is affected by many factors which lead to inaccuracies. Some of the causes of inaccuracies are due to the method itself (simplification of the equivalent tested circuit, approximations applied in the measuring techniques of the meters), as well as inaccuracies in the construction of the instrument.

One of the more significant and obvious causes of error is changes and fluctuations in network voltage induced by changes in the working load of the studied system. An effective elimination of this problem is achieved by reducing the time between the determination of both values of voltage [4]. Another way of reducing the effect of voltage fluctuations is to increase the value of measurement current. The measurement current must however be much smaller than the operational current the nearest protection device.

4. CONCLUSIONS

The measuring accuracy of the modern loop impedance meters applied in present day power systems is significantly affected by changes in voltage at the testing point. Those changes depends on parameters of the tested network and applied measuring method. The duration of measuring process should be properly chosen to allow the impedance measurement during steady state. The measurement errors depend to a large extent not only on the phase difference ($\varphi - \varphi_0$) but also which harmonics occur, their share ratio, and phase angle of the voltage waveform. When the arguments of both impedances are equal ($\varphi = \varphi_0$), the measurement errors are equal to zero ($\delta Z_{rms} = \delta Z_m = 0$) irrespective of the shape of the voltage waveform.

From the tests conducted [6] it can be seen that the largest values of measurement error occur for δZ_m. This is characteristic for all universally operated meters based on the amplitudes of the voltages being measured. The effect of voltage waveform distortion δZ_{rms} is much less significant, even though measuring techniques based on rms values are inconvenient to apply in practice. Under unfavourable conditions the measurement error may exceed -70%.

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