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Experimental verification of a new method of loop resistance testing in low voltage systems with residual current devices

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***Abstract* – A periodical verification of the effectiveness of protection against electric shock shall be performed in low voltage systems. The scope of this verification includes loop impedance/resistance testing. If a residual current device is installed in a tested circuit, this testing is problematic. A residual current device trips out during the test, because of the high value of measurement current. This precludes the execution of the test. In the paper a new method of loop resistance testing in low voltage systems is presented. Experimental verification of this method has proved that it enables performing the verification of the effectiveness of protection against electric shock without nuisance tripping of residual current devices. The advantage of this method is the high value of the measurement current – many times higher than the rated residual operating current of commonly used residual current devices. It is very important in terms of measurement accuracy.**

***Keywords* – Industrial applications, loop resistance testing, low voltage systems, residual current devices**

I. INTRODUCTION

Every low voltage system should be periodically tested for the evaluation of the effectiveness of protection against electric shock. According to the standard [1] in a TN network, a loop impedance or resistance test is required. The principles of loop impedance testing is presented in Fig. 1. A meter used during the test is connected to a phase terminal (L1) and terminal of the protective conductor (PE). Thus, measurement current I_M is forced. Popular methods of earth fault loop resistance or impedance measurement utilized for periodical testing of low voltage systems [2]-[11] are based on the assumption that the tested circuit can be represented by a simplified equivalent circuit as shown in Fig. 2.

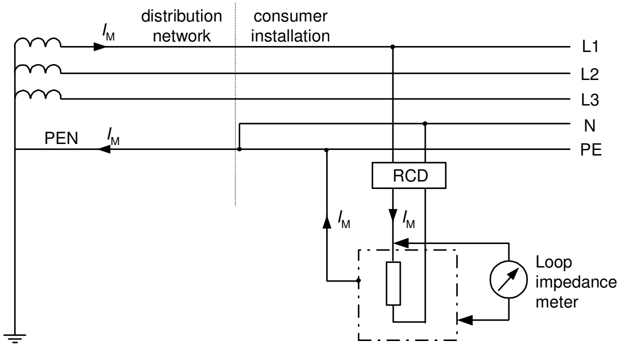


Fig. 1. Earth fault loop impedance testing in a TN network. RCD – residual current device

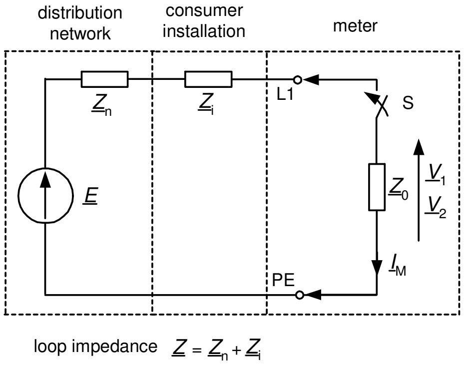


Fig. 2. Equivalent circuit during earth fault loop impedance/resistance testing

This circuit comprises a sinusoidal voltage source $\underline{E}$, system equivalent loop impedance $\underline{Z} = R + jX$ and measurement load impedance $\underline{Z}_0 = R_0 + jX_0$.

The loop impedance $\underline{Z}$ can be determined by measuring the voltage $\underline{V}_1$ (switch S is opened) and load voltage $\underline{V}_2$ (switch S is closed) between the phase conductor L1 and the protective conductor PE

$$\underline{Z} = \frac{\underline{V}_1 - \underline{V}_2}{\underline{I}_\mathrm{M}} = \underline{Z}_0\left(\frac{\underline{V}_1}{\underline{V}_2} - 1\right), \tag{1}$$

where $\underline{V}_1$ is voltage before S is switched on, $\underline{V}_2$ voltage after S is switched on, $\underline{I}_\mathrm{M}$ measurement current, $\underline{Z}_0$ measurement load.

In practice, real loop impedance Z (magnitude) is measured as Z_p on the basis of the magnitude (not vectors) of V_1 and V_2 voltages. It leads to the following dependence

$$Z_\mathrm{p} = \frac{V_1 - V_2}{I_\mathrm{M}} = Z_0\left(\frac{V_1}{V_2} - 1\right). \tag{2}$$

The above simplification of the measurement leads to the measurement error expressed by the following formula:

$$\delta Z = \frac{Z_\mathrm{p} - Z}{Z} = \left[\frac{Z_0\left(\frac{V_1}{V_2} - 1\right)}{Z} - 1\right] \cdot 100\,\% \cdot \tag{3}$$

Loop impedance Z_p according to (2) may be calculated on the basis of the measurement of peak or rms or average values of V_1 and V_2 sinusoids. An analysis proved [12] that for particular parameters of measurement load, parameters of a low voltage network and the distortion of voltage (negligible distortion), the values of measurement errors are homogeneous regardless of the type of measurement: peak (δZ_peak), rms (δZ_rms) and average (δZ_av). However it is worth stressing that they are lower for a relatively high value of measurement current (Fig. 3).

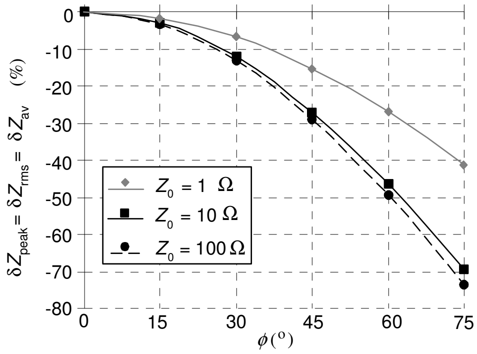


Fig. 3. Earth fault loop impedance ($Z = 1\ \Omega$) measurement error $\delta Z_{peak} = \delta Z_{rms} = \delta Z_{av}$ for various values of the measurement load impedance Z_0 [12]:
$Z_0 = 1\ \Omega \Rightarrow$ high measurement current,
$Z_0 = 10\ \Omega \Rightarrow$ medium measurement current,
$Z_0 = 100\ \Omega \Rightarrow$ low measurement current;
ϕ – argument of low voltage network impedance,
ϕ_0 – argument of measurement load impedance: $\phi_0 = 0°$

Therefore, proper fault loop impedance/resistance measurement can be performed using whatever: peak value of voltage waveform or rms value of voltage waveform or average value of voltage waveform, but the highest possible value of measurement current should be used.

Unfortunately, if a residual current device (RCD) is installed in the tested circuit (according to [13], in some circuits RCDs are obligatory, especially these with the rated residual operating current $I_{\Delta\mathrm{n}}$ = 30 mA), fault loop impedance/resistance measurement is problematic. The RCD trips out during the test, because the measurement current I_M is the residual current I_Δ for the RCD.

II. LOOP IMPEDANCE TESTING WITH THE USE OF CLASSIC METERS

Loop impedance or resistance meters (testers) provide various types of measurement current. The most popular are the meters of half wave current (Fig. 4a, 4b). The peak value of the current is equal even to 30 A (Fig. 4b). Methods which do not cause tripping of 30 mA residual current devices (RCDs), by using an extremely low value of measurement current (< 15 mA) (Fig. 4c), in many cases are not acceptable due to low measurement accuracy.

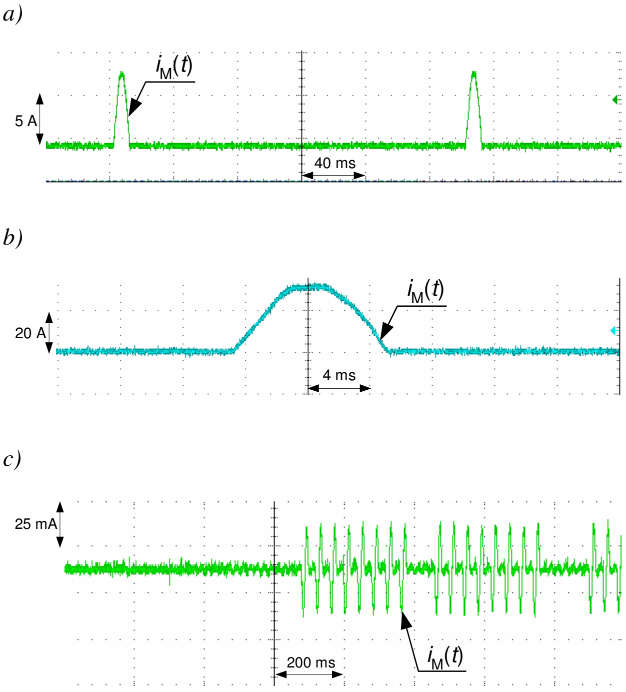


Fig. 4. Oscillograms of the measurement current $i_M(t)$ of the selected meters: a) "Meter_1", b) "Meter_2", c) "Meter_3"

Sensitivity of residual current devices to the waveform shape of residual current and their susceptibility to the nuisance tripping depend on the type of residual current devices. There are three main types of residual current devices:

- AC – for residual sinusoidal alternating currents (50/60 Hz);
- A – for residual sinusoidal alternating currents (50/60 Hz) and pulsating direct residual currents;
- B – for residual sinusoidal alternating currents up to 1000 Hz, pulsating direct residual currents and smooth direct residual current (very rarely used).

A time-delay in operation of the residual current devices should also be considered. Taking this into account there are three types of RCDs:

- General purpose RCDs, without intentional time-delay, without a special symbol;
- Short time-delayed RCDs (G-type), with a minimum non-actuating time of 10 ms;
- Time-delayed RCDs (S-type), with a minimum non-actuating time of 40 ms, to provide discrimination with downstream general purpose RCDs and G-type RCDs.

In order to check the immunity of residual current devices to the typical measurement current, a laboratory test of tripping of residual current devices ($I_{\Delta n}$ = 30 mA) with the use of Meter_1 and Meter_2 was performed. The waveforms of the measurement current of these meters are presented in Fig. 4a and Fig. 4b. The results of the test are presented in Table 1. Every residual current device (from RCD1 to RCD6) tripped at least once during the test. They were tested for both polarity of the half wave current. For each polarity there were three measurements (number of trails in Table 1). All three measurements were performed within less than 10 seconds. Some RCDs tripped every time, some in special polarity – it depends on the type of the tripping mechanism included in a given RCD. However, for these meters there is no guarantee that RCDs will not trip out.

Table 1. Results of the test of tripping of residual current devices of $I_{\Delta n}$ = 30 mA – classic meters

Meter type	Current polarity	Number of trials	RCD1	RCD2	RCD3	RCD4	RCD5	RCD6
Meter_1	positive (+)	1	T	T	T	T	T	T
		2	T	T	noT	T	noT	noT
		3	T	T	noT	T	noT	noT
	negative (-)	1	noT	T	T	T	T	T
		2	noT	T	noT	T	noT	noT
		3	noT	T	noT	T	noT	noT
Meter_2	positive (+)	1	T	T	T	T	T	T
		2	T	T	noT	T	noT	noT
		3	T	T	noT	T	noT	noT
	negative (-)	1	noT	T	T	T	T	T
		2	noT	T	noT	T	noT	noT
		3	noT	T	noT	T	noT	noT
Rated residual current $I_{\Delta n}$ [mA]			30	30	30	30	30	30
Type			A	A	AC	A	AC	AC
T – nuisance tripping noT – no nuisance tripping								

III. A NEW METHOD OF TESTING

A. Theoretical description

In order to use a relatively high value of measurement current and avoid nuisance tripping of residual current devices, a special waveform of measurement current must be used.

One of the main elements of residual current devices is an iron core current transformer CT (Fig. 5). This current transformer is responsible for delivering sufficient value of secondary current I_s flowing though electromechanical relay ER in the secondary circuit. A value of secondary current I_s depends on a value of induced secondary voltage E_s.

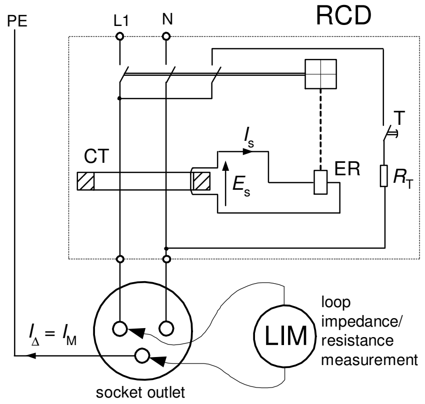


Fig. 5. Earth fault loop impedance/resistance measurement in a circuit with a residual current device (RCD); LIM – loop impedance/resistance meter, CT – current transformer of the RCD, I_Δ – residual (primary) current, I_M – measurement current (here $I_M = I_\Delta$), E_s – secondary induced voltage of the current transformer, I_s – secondary current

Induced secondary voltage E_s in an iron core current transformer is a function of magnetic flux increment in the core. For sinusoidal measurement current I_M, magnetic flux increment ΔB is very high (Fig. 6a). Thus, induced secondary voltage E_s and secondary current I_s are relatively high. If a measurement current is a half wave current with smoothing, the magnetic flux increment ΔB is not high enough (Fig. 6b) to produce sufficient induced secondary voltage E_s (phenomenon utilized in a new method). In such a condition a residual current device does not trip during measurement.

Taking into account the properties of a residual current transformer for unidirectional primary current, a meter for loop resistance testing, utilizing these properties, is proposed (Fig. 7). This meter enables measuring only resistance, but in circuits with 30 mA RCDs it is sufficient (resistance dominates definitely – consumer installations, small cross section of conductors). The meter comprises: diode D, measurement load R_0, smoothing capacitor C_0, switch S, and auxiliary resistors R_1, R_2, R_3 with thyristors T_1, T_2, T_3. It is important to keep the proper connection of the meter to the low voltage network terminals L1 – line, N – neutral, PE – protective, as shown in Fig. 7.

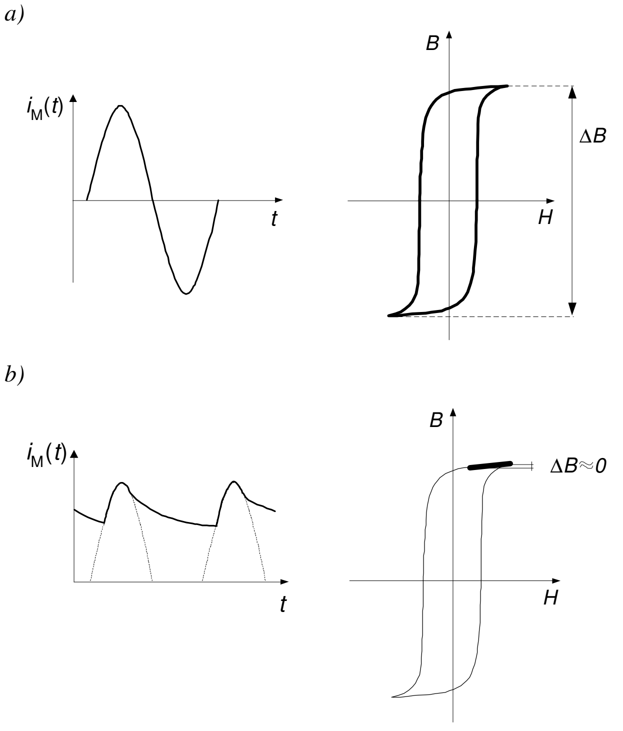


Fig. 6. Magnetic flux increment ΔB for primary (measurement) current: a) sinusoidal, b) half wave with smoothing

Before closing switch S, sinusoidal voltage $v_1(t)$ (Fig. 8) is measured and recorded. After closing switch S, the residual current device does not trip, because a smooth non-sinusoidal current $i_M(t)$ flows – the voltage $v_2(t)$ is measured and recorded. The peak values are determined from the sampled voltages $v_1(t)$ and $v_2(t)$ (Fig. 8).

Auxiliary resistors R_1, R_2, R_3, and thyristors T_1, T_2, T_3 (switched consecutively) enable the slow rising of the measurement current in order to avoid the nuisance tripping of RCDs.

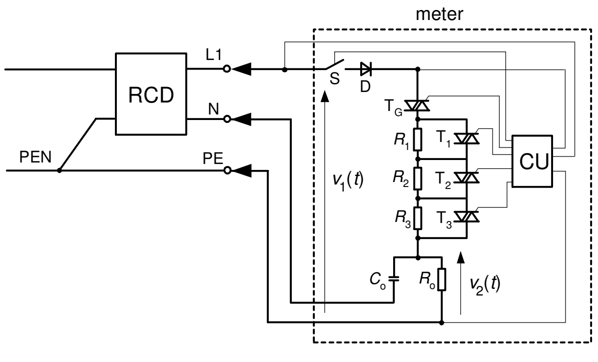


Fig. 7. Structure of the proposed meter

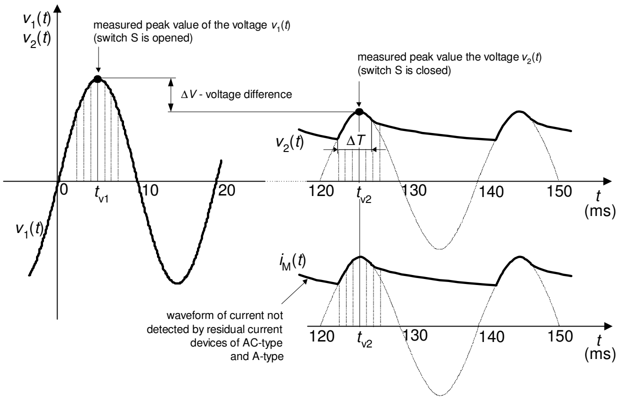


Fig. 8. Measured and recorded voltages during earth fault loop resistance measurement. $v_1(t)$ – voltage before closing switch S, $v_2(t)$ – voltage after closing switch S; t_{v1}, t_{v2} – time points when peak values of the respective voltages occur

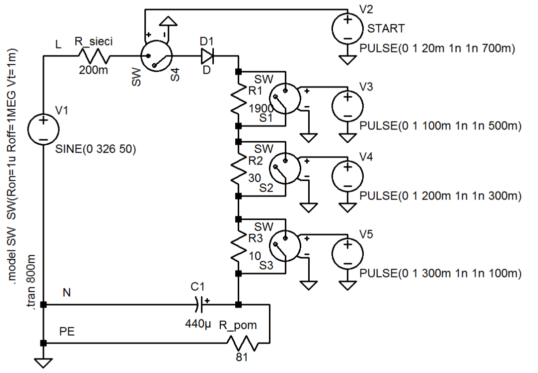
B. Experimental verification

The proposed method and meter were verified under laboratory condition.

In the first stage of verification, a computer model of the meter was prepared with the use of LTspice software. Figure 9a presents this model. The model reflects the design of the meter, which is shown in Fig. 7. The measurement current obtained from computer simulations is presented in Fig. 9b. It is visible that during the first stage of a current flow, its value rises slowly. It is necessary to avoid nuisance tripping of the tested RCD. Fast current rising may generate a magnetic flux increment that can be too big, in the iron core, and the RCD may trip out. After the indicated current rising, a quasi-steady state current flow occurs – in this period the measurement of peak value $v_{2\text{peak}}$ of voltage $v_2(t)$ should occur. Both the measured peak voltages $v_{1\text{peak}}$ and $v_{2\text{peak}}$ and the given load resistance R_0 leads to the searched value of loop resistance $R_p \approx Z_p$.

$$R_p \approx Z_p = R_0 \left(\frac{v_{1\text{peak}}}{v_{2\text{peak}}} - 1 \right). \qquad (4)$$

a)



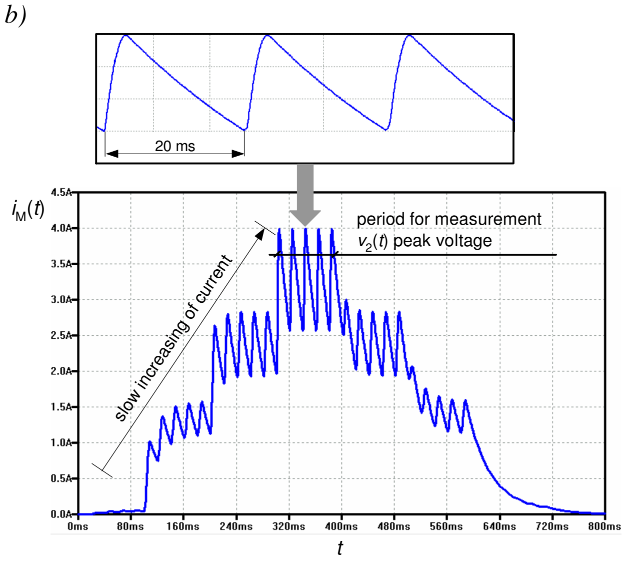


Fig. 9. Structure of the proposed meter in LTspice (a) and example waveform of measurement current (b)

During the last period of measurement, a slow decrease in the measurement current value is also necessary. The loop resistance (impedance) test is performed within 0.5–1.0 s.

In the second stage of verification, a test of the immunity of the residual current devices to the proposed measurement current was performed. Figure 10 presents an oscillogram of the measurement current. After the comparison of the oscillograms with the simulated waveform of measurement current (Fig. 9b), it may be concluded that the laboratory prototype version of the meter reflects the theoretical assumptions, and it proves that the computer model is correct. A tripping/no tripping test of residual current devices was performed with the use of the prototype version of the meter. The same residual current devices (from RCD1 to RCD6) that were mentioned in Table 1 were tested. The results of the test with the new meter are presented in Table 2.

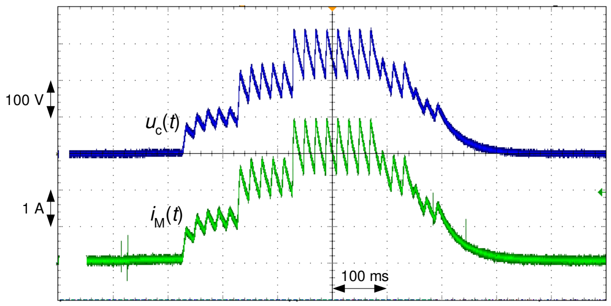


Fig. 10. Oscillogram of capacitor C_o voltage $u_c(t)$ and proposed measurement current $i_M(t)$; peak value of current i_{M_peak} = 3,98 A

The test results are optimistic. The RCDs did not trip out at each measurement. This test showed that residual current devices with the rated residual current $I_{\Delta n}$ = 30 mA do not trip out even if the peak value of the measurement current is about 4 amperes – 100 times higher that their rated residual current! The test proved that the idea proposed by the authors gives a possibility for testing loop resistance (impedance) with a relatively high value of measurement current. It is very important in terms of the accuracy of the measurement, and in consequence, for electrical safety in low voltage systems.

Table 2. Results of the test of tripping of residual current devices of $I_{\Delta n}$ = 30 mA – proposed meter

Meter type	Current polarity	Number of trials	RCD1	RCD2	RCD3	RCD4	RCD5	RCD6
Proposed_meter	positive (+)	1	noT	noT	noT	noT	noT	noT
		2	noT	noT	noT	noT	noT	noT
		3	noT	noT	noT	noT	noT	noT
	negative (-)	1	noT	noT	noT	noT	noT	noT
		2	noT	noT	noT	noT	noT	noT
		3	noT	noT	noT	noT	noT	noT
Rated residual current $I_{\Delta n}$ [mA]			30	30	30	30	30	30
Type			A	A	AC	A	AC	AC

T – nuisance tripping
noT – no nuisance tripping

IV. NOVELTIES IN THE PAPER

The authors have presented a new method of loop resistance (impedance) testing which enables verifying the effectiveness of protection against electric shock in low voltage systems without nuisance tripping of residual current devices. The results of the experimental verification of this method have been described in detail. They prove the advantages of the method. The measurement current (4 amperes in peak) is significantly higher than the rated residual current of commonly used residual current devices (30 mA). A patent application for this method and meter has been prepared [14].

V. CONCLUSIONS

The new method of loop resistance testing presented above enables the periodical verification of a low voltage circuit without nuisance tripping of residual current devices, which is very important for the accuracy of the test. The application of residual current devices in some types of circuits is obligatory. Therefore it is necessary to design and perform an industrial meter utilizing this new method of measurement.

REFERENCES

[1] *HD 60364-6, "Low voltage electrical installations – Part 6: Verification"* (2007)

[2] M. Aigner, E. Schmautzer, Ch. Sigl, T. Wieland, L. Fickert, *"Fehlerschleifenimpedanz-Messung in Niederspannungsnetzen mit Wechselrichtern"*, 8. Internationale Energiewirtschaftstagung an der TU Wien, IEWT 2013, Wien, 13-15 Feb., 2013

[3] S. Czapp, *"Measurement of the earth fault loop impedance in a low voltage network with operating loads"*. Int. Journal of Power and Energy Systems, vol. 29, no. 4, pp. 266-271, 2009. doi.org/10.2316/Journal.203.2009.4.203-4493

[4] S. Czapp, *"Fault loop impedance measurement in low voltage network with residual current devices"*. Elektronika ir Elektrotechnika, vol. 122, no. 6, pp. 109-112, 2012. doi.org/10.5755/j01.eee.122.6.1833.

[5] S. Czapp, R. Roskosz, A. Skiba, *"Vectorial method for measurement of short-circuit loop impedance in network with operating load"*. Proc. 16th IMEKO World Congress, Vienna, Sept. 25-28, 2000

[6] M. Faifer, G. M. Foglia, R. Perini, L. Rocca, *"The calibration of loop impedance meters: A proposal"*. IEEE Trans. on Instrumentation and Measurement, vol. 56, no. 4, pp. 1285-1291, 2007, DOI: 10.1109/TIM.2007.899851

[7] M. Kaspirek, D. Mezera, *"Voltage quality parameters in LV distribution grids in dependence on short circuit impedance"*, 22nd International Conference on Electricity Distribution, Stockholm, 10-13 June, 2013, DOI: 10.1049/cp.2013.0580

[8] K. O. H. Pedersen, A. H. Nielsen, N. K. Paulsen, *"Short-circuit impedance measurement"*, IEE Proc.-Gener. Transm. Distrib., vol. 150, no. 2, pp. 169-174, 2003, DOI: 10.1049/ip-gtd:20030193

[9] R. Roskosz, *"A new method for measurement of earth fault loop impedance"*. IEEE Trans. on Power Delivery, vol. 6, no 2, pp. 546-549, 1991, DOI: 10.1109/61.131110

[10] R. Roskosz, M. Ziolko, *"Measurement accuracy of short-circuit loop impedance in power systems"*. Proceedings, XVII IMEKO World Congress, TC4, , Dubrovnik, Croatia, pp. 903-907, June 22-27, 2003

[11] R. Roskosz, *"New solution for measurement of power system loop impedance in the presence of distorted voltage waveform"*, ELEKTRYKA no. 79, Gdansk University of Technology, Gdansk, Poland, 1995 (in Polish)

[12] S. Czapp, K. Borowski, K. Dobrzynski, J. Klucznik, Z. Lubosny, *"A new method of fault loop resistance measurement in low voltage systems with residual current devices"*. International Conference „PowerTech 2015", Eindhoven, The Netherlands, 29 June – 2 July 2015, DOI: 10.1109/PTC.2015.7232279

[13] *HD 60364-4-41, "Low voltage electrical installations – Part 4-41: Protection for safety – Protection against electric shock"* (2007)

[14] S. Czapp, K. Borowski, *"Method and arrangement of a fault loop resistance measurement in circuits with AC-type and A-type residual current devices"* (in Polish: Sposob i uklad do pomiaru rezystancji petli zwarciowej w obwodach chronionych wylacznikami roznicowopradowymi typu AC i typu A). Patent application no. P407795, Poland, 2014