Frequency Response Testing of Zero-Sequence Current Transformers for Mining Ground Fault Protection Relays

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Abstract—In Polish coal mining, medium voltage power distribution networks operate with an insulated neutral point. Zero-sequence current transformers are the basic sensors that generate input signals for earth-fault protection relays. In the literature, the problem of frequency response analysis of various types of current transformers has been examined many times, e.g. [1] [2], but not for zero-sequence current transformers so far. As part of the work, two types of zero-sequence current transformers in the range from 0.1 Hz to 100 kHz were tested. Both the change of the current ratio and the angular shift between the transformer secondary current and the total primary current were analyzed.

Keywords—zero-sequence current transformers, ground-fault protection relays, frequency response

I. INTRODUCTION

IN the Polish coal mining industry, medium voltage distribution networks are characterized by the operation with an isolated neutral point. These networks are characterized by a small value of ground-fault current in relation to the values of operating line currents. But even this small current can cause major hazard of fire, explosion or electrical shock, so each ground-fault case should be cleared in a fast and reliable manner. Therefore protection of these power networks against earth-faults is based on zero-sequence currents and voltage signals, as they are much more significantly varying in the case of ground-fault and no ground-fault than line currents. The main component of the ground-fault current has a rated power frequency (50Hz), but here are also significant transient components with frequencies determined by capacitance and inductance of the faulted network. They decay fast, but can appear repetitively particularly in the case of intermittent arc ground faults. These transient current components can have a frequency (depending on detailed network parameters) in a range from several hundred up to a few thousand Hz [1]. There can also appear transients with frequency much lower than the rated power frequency – e.g. 25Hz or even a few Hz, as a result of post-fault oscillations, caused by a ferroresonance [2] connected with nonlinear inductivity of voltage transformers inserted into power network. Zero-sequence current transformers are the basic sensors generating input signals for

earth fault protection relays. In the literature the subject of analysis of frequency characteristics of various types of current transformers has been discussed many times e.g. [3][4][5][6]. However, so far such tests have not been performed for zero-sequence current transformers. The specific construction of this transformer based on summation of the magnetic fluxes generated by particular phase currents (Fig. 1) requires separate experimental research. The frequency response of zero-sequence current transformers can be not important in the case of old (and quite slow) electromechanical protection relays, but can be very important in the case of modern and fast electronic and digital protection devices – they can use transient components to increase selectivity and sensitivity of their protection algorithms. The magnitude errors can be very important even in the case of a simple overcurrent protection, and the phase errors are important in the case of directional relays and in the case of more sophisticated protection algorithms e.g. calculating a zero-sequence admittance as a criterion value.
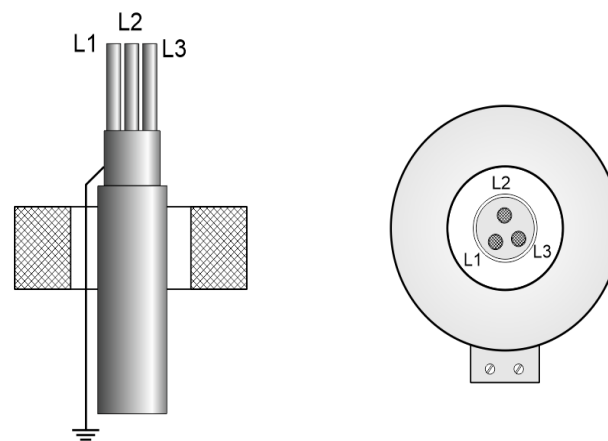

Fig. 1. Zero sequence current transformer mounted on the power cable (left – longitudinal cross-section, right axial view).

II. METHODOLOGY OF RESEARCH

For research purposes a zero-sequence current transformer type IO1s was used, which works properly with a secondary circuit load of 3.5 Ω.

The measuring system consisted of an AC source in the form of an SDG1025 arbitrary waveform generator and a two-channel oscilloscope measuring the sinusoidal current

waveforms on the primary and secondary side. The output signal from the waveform generator is amplified by the FPA301-20W power amplifier. As there was a risk of damaging the output due to short circuit, an additional resistor (set to 1 Ω) was plugged into the power circuit. In order to increase the accuracy of measurements on the primary side, the cable was wound on the measuring coil many times in order to obtain a total current of 3 A.

Before starting the proper measurements, the influence of the cable winding method on the measurement results was checked. It turned out that in the case of this type of zero-sequence current transformer the way of winding the wires does not affect the results. Therefore, due to easier way of total current measurement, the method shown in Fig. 2 and 3 was chosen. Both currents were measured by current probes. The waveforms were presented on the oscilloscope display.
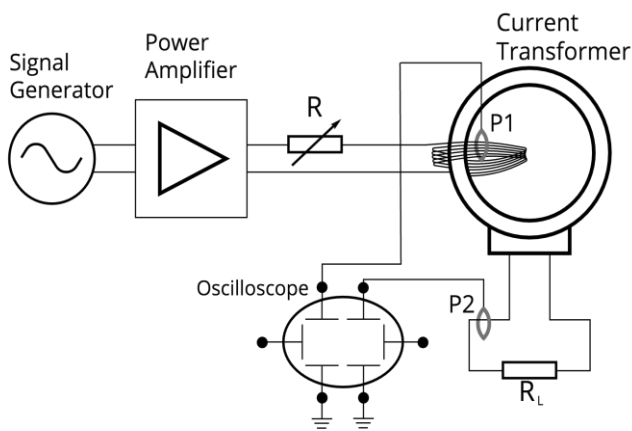

Fig. 2. Scheme of measuring circuit

Recorded sinusoidal waveforms for selected frequencies in the range from 0.1 Hz to 100 kHz were saved as a *.txt file. After several preliminary measurements, it was found that the optimum solution would be to record from 7 to 28 thousand samples per period (depending on the frequency).
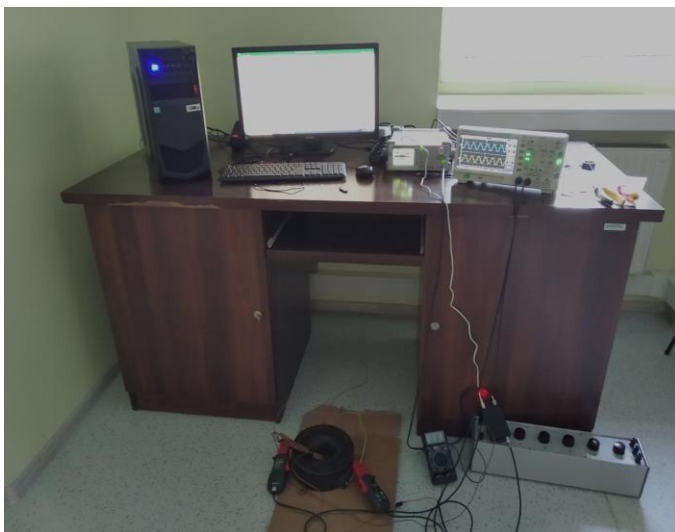

Fig. 3. A view of the research stand

The proper selection of the method for determining current values appropriately to the recorded raw data may affect the results obtained and their subsequent interpretation. The first method uses directly definitions of mean and rms current: (where 'a' is a total):

$$I_{DC} = \frac{1}{aT} \int_{t}^{t+aT} i_x(t)dt \qquad (1)$$

$$I = \sqrt{\frac{1}{aT} \int_{t}^{t+aT} i_x^2(t)dt} \qquad (2)$$

where a is an integer number,   T is a waveform period

The equations presented above only make sense for continuous signals. For discrete waveforms, the above formulas can be approximated to the following forms:

$$I_{DC} = \frac{1}{n} \sum_{k=1}^{n} i_k \qquad (3)$$

$$I = \sqrt{\frac{1}{n} \sum_{k=1}^{n} i_k^2} \qquad (4)$$

where 'n' is the number of samples of two full periods.

For further considerations, it was assumed that the waveforms consist of one harmonic and a constant component. In this case the first harmonic rms value can be calculated using the following relationship:

$$I_{1h} = \sqrt{I^2 - I_{DC}^2} \qquad (5)$$

Based on the above information, the sinusoid-based general equation for the recorded current waveform can be written as:

$$i_x(t) = I_{1h}\sqrt{2} \sin(\omega t + \phi) + I_{DC} \qquad (6)$$

To determine the phase shift between recorded waveforms one more information is necessary. Relatively simple to determine is an instantaneous value of current at the time instant t = 0. But at this point it is important to eliminate possible noise influence. For this purpose it is assumed that $i_x(0)$ is the arithmetic mean of the sample for the time t=0, seven previous and seven subsequent samples as described below:

$$i_x(0) = \frac{i_j + \sum_{k=1}^{7}(i_{j-k} + i_{j+k})}{15} \qquad (7)$$

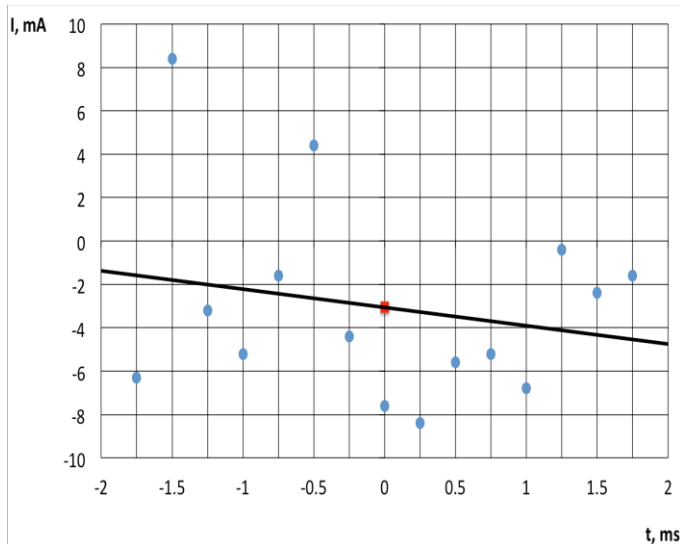An example of such calculation is presented in Fig. 4.

Fig. 4. Example of $i_x(0)$ calculation

With such a small number of samples, the sinusoidal waveform in this range can be approximated to a straight line. For the time t = 0, the relation ωt is 0. Therefore, the value of the phase shift can be calculated using the following formula.

$$\phi = \arcsin \frac{i_x(0) - I_{DC}}{I_{1h}\sqrt{2}} \qquad (8)$$

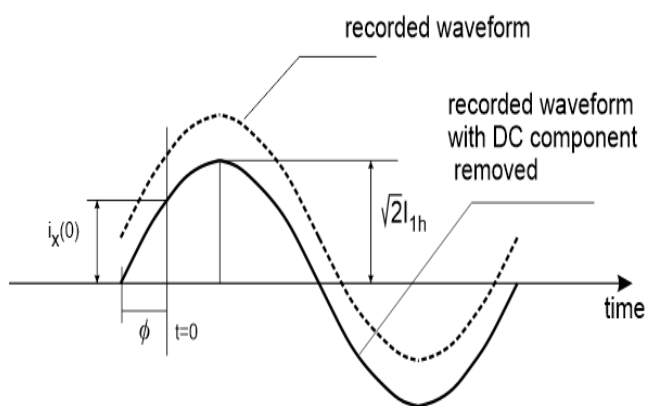The principle of this method has been shown in Fig. 5

Fig. 5. Principle of the phase shift calculation

The above method is very good if higher harmonics make up no more than a few percent of the first harmonic value. Otherwise, there is a need for another method.

The alternative (but much more computationally-intensive and time-consuming) method was to fit the resulting recorded waveforms (both primary and secondary) to the equation of the sinusoidal waveform by the method of least squares, where the fit criterion was based on matching the magnitude, constant component and a phase shift.

Since the primary current was not dependent on the load and transformer parameters and the waveform generator together with the output amplifier have a very high precision, the uncertainty of the current value calculation by the method of the least squares was below 1% (Fig. 6).
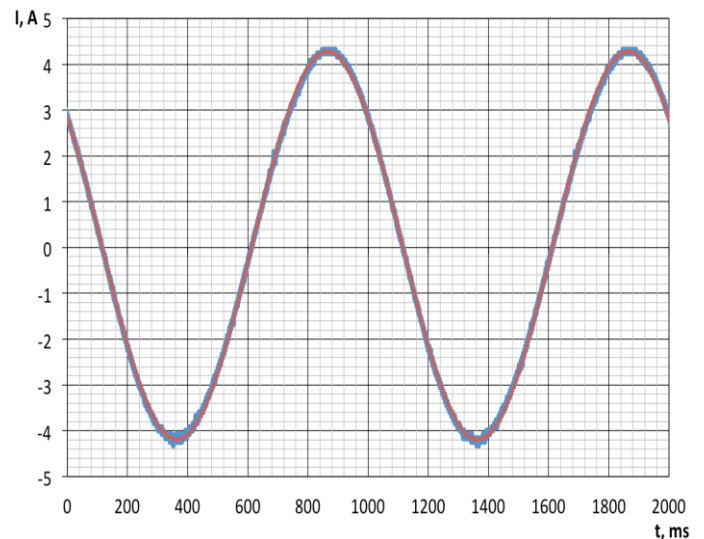

Fig. 6. Primary current sinusoidal waveform fit by the method of least squares. Waveform frequency is 1 Hz, load resistance is 3.5 Ω.

In case of the secondary current there has been recorded a significant noise, strongly dependent on frequency of the primary current. For frequencies higher than 5 Hz, the noise was practically unnoticeable, whereas for lower frequencies (Fig. 7), the noise made it more and more difficult to match the sine wave correctly.
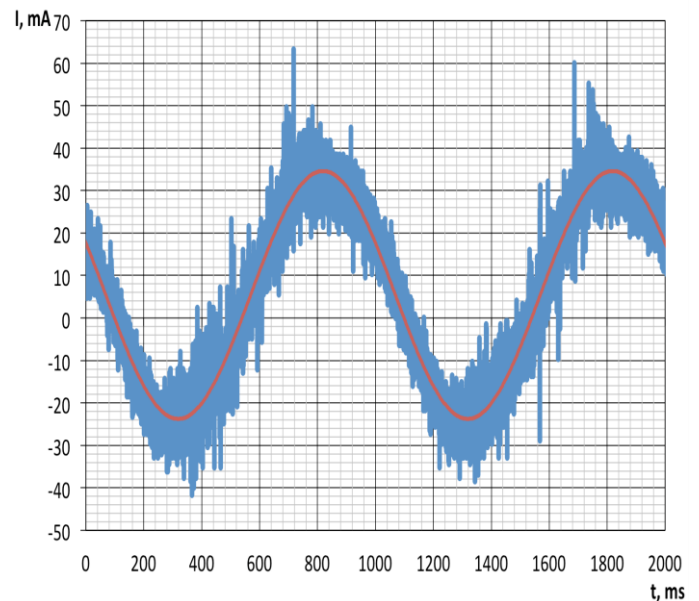

Fig. 7. Secondary current sinusoidal waveform fit by the method of least squares. Waveform frequency is 1 Hz, load resistance is 3.5 Ω.

III. RESULTS

The least squares method seems to be a more reliable method, because at lower frequencies various noises overlap the first harmonic. Table I compares the two methods presented above. The following relationships (describing relative errors) were used for the comparison of these two methods:

TABLE I
COMPARISON OF THE LEAST SQUARES METHOD WITH THE INTEGRAL METHOD

f, Hz	$\delta_{\Delta\varphi}$, %
0.1	14.11
0.2	-48.61
0.5	-25.90
1	5.96
2	2.37
5	0.00
10	0.00
20	0.00
50	0.00
100	0.00
200	0.00
500	0.00
1000	0.00
2000	0.00
5000	0.00
10000	0.00

TABLE II
COMPARISON OF THE LEAST SQUARES METHOD WITH THE INTEGRAL METHOD

f, Hz	δ_{Z21}, %
0.1	36.70
0.2	18.77
0.5	10.38
1	8.05
2	3.69
5	1.04
10	-0.28
20	-0.18
50	0.06
100	-0.81
200	-0.07
500	-0.11
1000	-0.39
2000	0.07
5000	-0.10
10000	-2.30

$$\delta_{Z21} = \frac{z_{21}^A - z_{21}^B}{z_{21}^A}100\% \tag{9}$$

$$\delta_{\Delta\phi} = \frac{\Delta\phi^A - \Delta\phi^B}{\Delta\phi^A}100\% \tag{10}$$

Since for frequencies higher than 1 kHz the current ratio and the phase shift of the results for this zero-sequence current transformer have not changed, the following characteristics are only shown for the range from 0.1 Hz to 1 kHz.

As shown in the graph (Fig. 8), the current ratio of this zero-sequence current transformer above 5 Hz is more or less constant. Any deviation in this range may be due to the oscilloscope's sampling error. However, at lower frequencies, this current ratio begins to decrease. Near 1 Hz, these characteristics are flat, but below 0.7-0.8 Hz they drop rapidly again.

Hz, depending on the load, the measuring current reaches a value between 68 and 75% of the nominal value. For 1 Hz at the rated load, the measuring current only reaches 70% of the current ratio at 50 Hz. At 0.1 Hz, this value is already slightly above 50%. Analyzing the above mentioned waveforms it can be concluded that this transformer is not suitable for measuring currents with frequency components lower than 3 Hz.

The phase shift (Fig. 9) between the secondary and primary current above 5 Hz is maintained at around 0°. Below this value, the angle of the phase shift reaches positive values. This relationship reaches a local maximum at 2-3 Hz and a local minimum at about 0.5 Hz. The load resistance significantly influences this angle. At the local maximum the value of this angle increases with the load from 15 to 25°, while at 0.1 Hz the relationship oscillates between 18 and 45°.
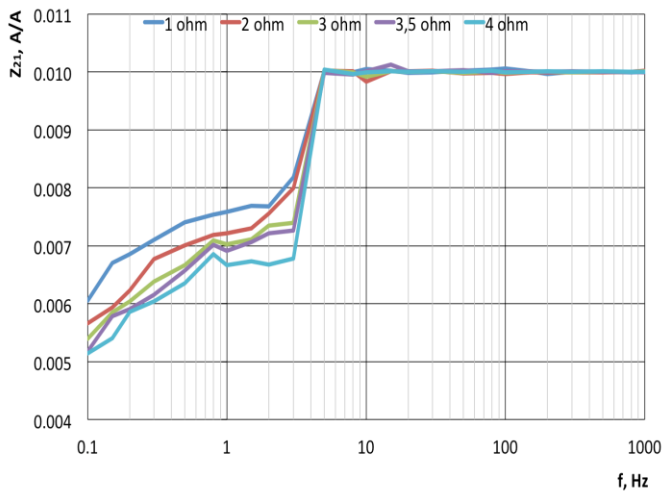

Fig. 8. Current ratio between primary and secondary current with different values of load resistance.

It should be noted that the greater the load resistance, the greater the "damping" of the output current. For example, for 1
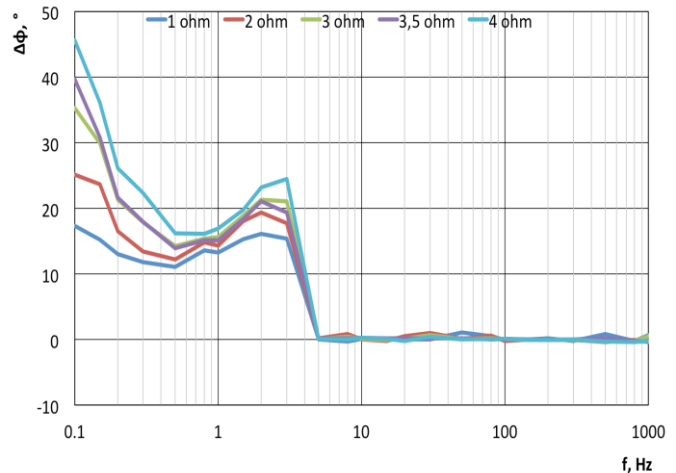

Fig. 9. Phase shift between secondary and primary current with different values of load resistance
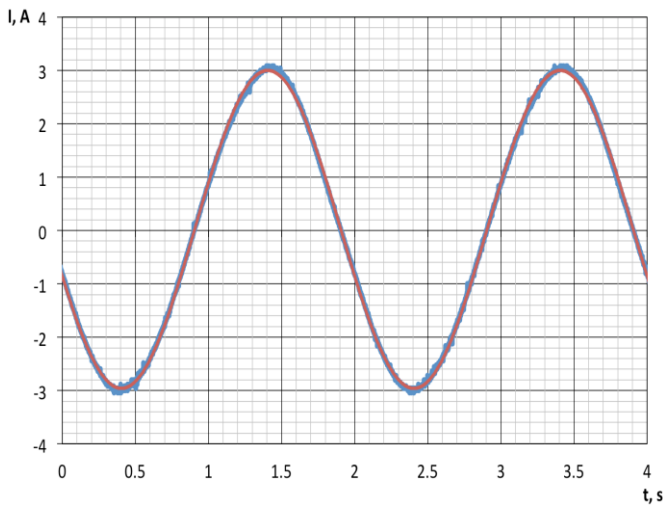
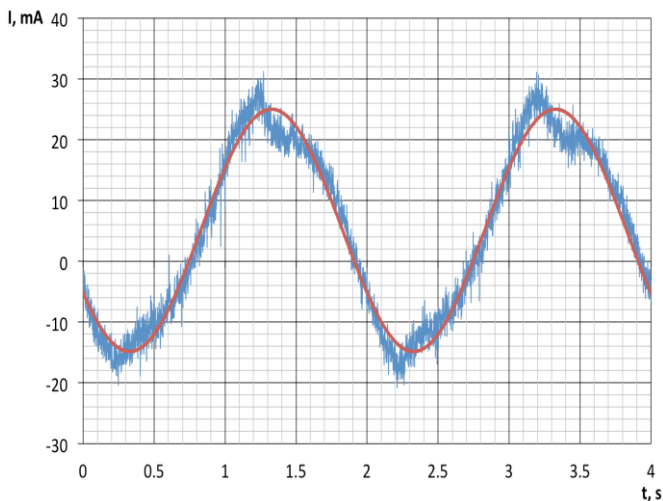Fig 10. Primary current waveform at signal frequency 0.5 Hz load resistance is 3.5 Ω

Fig 11. Distorted secondary waveform at signal frequency 0.5 Hz load resistance is 3.5 Ω
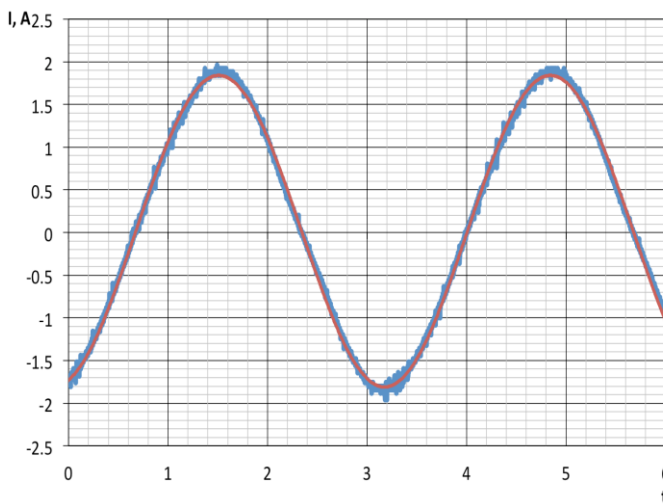

Fig 12. Primary current waveform at signal frequency 0.3 Hz load resistance is 3.5 Ω
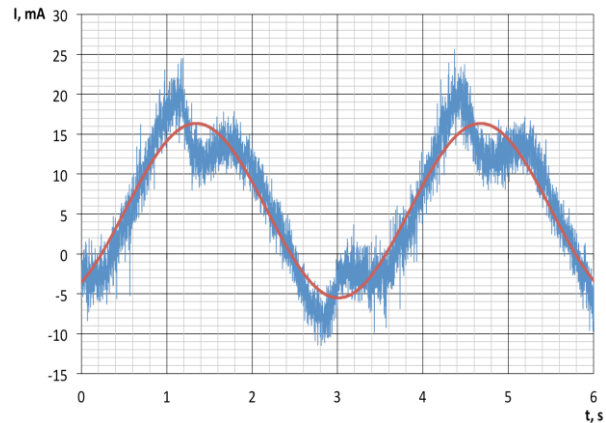

Fig 13. Distorted secondary waveform at signal frequency 0.3 Hz load resistance is 3.5 Ω

It should be noted that below 1Hz the secondary current waveforms become heavily distorted. The lower is the frequency, the more distorted is the waveform. This waveform distortion has a great influence on the current ratio of the zero sequence current transformer, as it is defined for sinusoidal currents (so it can be straightly extended only to first harmonics). Below there have been presented examples of these distorted waveforms recorded for two low frequencies – 0,5 Hz (Fig. 10 and Fig. 11) and 0,3 Hz (Fig. 12 and Fig. 13).

IV. CONCLUSION

On the basis of these measurements presented above it can be stated that the zero-sequence current transformer quite well measures fault current components with frequencies higher than 10Hz (including rated power frequency 50 Hz). The magnitude and phase errors are negligibly small for the proper operation of protection relays, but in the lower frequency range (below 10Hz and particularly below 1Hz there is a significant waveform distortion - probably connected with the saturation of the magnetic circuit. The zero-sequence current transformers are quite sensitive to the value of the load impedance (i.e. input impedance of the protection relay). The lower is the load impedance the lower are the magnitude and phase errors, so particularly in some cases where it should be desirable to measure low frequency components it could be useful to apply load impedance much lower than the rated value. It doesn't affect the higher frequency range accuracy but greatly reduces errors in the lowest frequency range.

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