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Comparison of performance of available current converters under distorted waveform conditions

Abstract. *Paper presents result of analysis and investigations of metrological properties for selected current converters employed in circuits with distorted current waveforms. Both commonly used current transformers, Rogowski coil and current-voltage converters with amorphous core were tested. Current and angle errors for different current value and its frequency in wide range were specified. On the basis of the investigated results conclusions on effective application of the selected current converters when used for measurements in circuits with distorted current waveforms are formulated.*

Streszczenie. *W artykule przedstawiono wyniki badań i analiz właściwości metrologicznych wybranych przetworników sygnałów prądowych zastosowanych w obwodach z odkształconymi przebiegami prądowymi. Przebadano klasyczny przekładnik prądowy, cewkę Rogowskiego i przetwornik prądowo-napięciowy z rdzeniem amorficznym. Wyznaczono błędy prądowe i kątowe tych przetworników w funkcji wartości natężenia prądu oraz jego częstotliwości. Przedyskutowano wyniki badań i wyciągnięto wnioski dotyczące możliwości zastosowania wybranych przetworników do pomiaru wartości skutecznych prądów w układach, w których występują przebiegi odkształcone. (**Analiza porównawcza właściwości metrologicznych dostępnych przetworników prądowych zastosowanych w obwodach z prądami odkształconymi**).*

Keywords: current transformer, Rogowski coil, current-voltage converter with amorphous core, distorted current waveform measurement.
Słowa kluczowe: przekładnik prądowy, cewka Rogowskiego, przetwornik prądowo-napięciowy z rdzeniem amorficznym, pomiar prądu odkształconego.

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Introduction

High power electric drives are almost commonly controlled in nowadays by frequency converters of different types. It is considered as advantage however, it is related to generation of high harmonics that can significantly deform as current as well as voltage waveforms resulting among others in quality degradation of electrical energy in supplying power network. Besides, accuracy of measurements of both power, electric energy do not mention about current and voltage being used as operation criterion for protections can be significantly reduced. Therefore the high harmonics content in measured and analyzed electrical quantities waveforms have to be specified for accurate estimation of electric machines and equipment operation. To be able to depict properly both instantaneous as well as rms current values an application of the right measuring devices is a key factor [1,2,3].

Measuring transformers should provide accurate waveform of the measured quantity independently on value and deformation level of the input (primary) signals. Unfortunately, the investigations indicated that the commonly used commercial current transformers and Rogowski coils (being recommended) do not meet requirements when used for measurements of distorted current waveforms [4-7].

It was found that alternatively current-voltage converters with magnetic core made of amorphous material can be used as a choice [8,9]. The amorphous materials are usually alloys composed of metallic elements like Fe, Ni and Co in 80%. The remaining 20% (in mass) is due to nonmetallic elements such as boric B, carbon C, germanium Ge, phosphorus P or silicon Si. Such materials are characterized by their crystallographic structure similar to that of liquid metals.

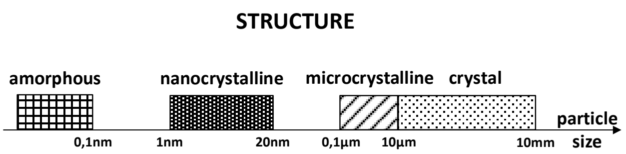

Fig.1. Ranges of oriented atoms and related structures

The amorphous materials are fabricated under rapid cooling of liquid alloy processing what results in creation of amorphous structure. Due to their tiny and fragile structure they are called glossy materials – among magnetic compositions they are distinguished by smallest size of areas of oriented atoms (Fig.1).

In the paper the investigated results of metrological parameters for selected structures of current converters like commercial commonly used current transformer, Rogowski coil and newly developed current-voltage converter with core made of amorphous magnetic tape are presented and discussed. Main goal of the investigations was to estimate the transformation accuracy of the distorted current waveforms and to find the influence of primary current frequency on the metrological properties required to meet in practice.

Method and range of investigations

The investigations were carried out for selected measuring converters as follows:

- Rogowski coil of 40mV/A turns ratio,
- commercial current transformer of 200/5 A/A turn ratio and 10VA rated power, class 1,
- developed current-voltage converter with amorphous core of 1mV/A turn ratio.

Under the test provided primary current waveforms was respectively distorted to depict these registered in real machinery circuits supplied via frequency converters as illustrated for example in Fig.2.

It was checked as an example converters performance used for fluent speed regulation of asynchronous motors operated in mine drivers. Currents in the stator windings are characterized by a high change both if about the value and frequency (from about 10 Hz up to 50 Hz). While, waveform of the currents driven by frequency converters from the networks are significantly distorted with high harmonics contribution up to about 70% of the basic harmonic.

To keep the same measurement conditions the inputs of primary sides of all converters under the test was connected in series to provide identical both value and waveform of the primary current to be registered. Thus the secondary current rms values as well as their waveforms were respectively measured and analyzed. We have focused mainly on accuracy of transformation therefore on current and angle error of the inspected current converters. Simplified scheme of the measuring system under laboratory conditions is presented in Fig.3.

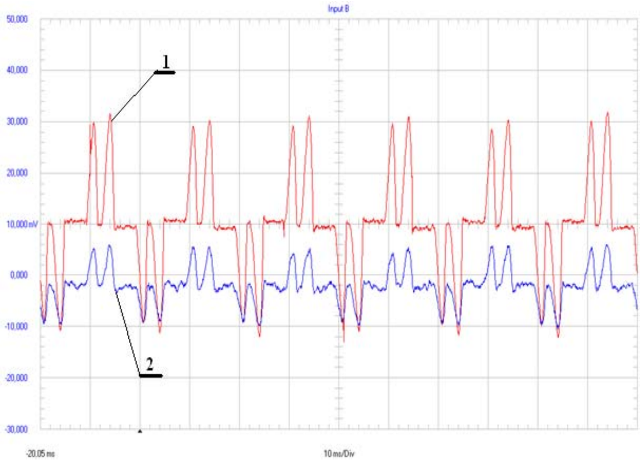

Fig.2. Registered secondary current waveform in circuit supplying a frequency converter (1 – converter with amorphous core, 2 – commercial measuring current transformer)

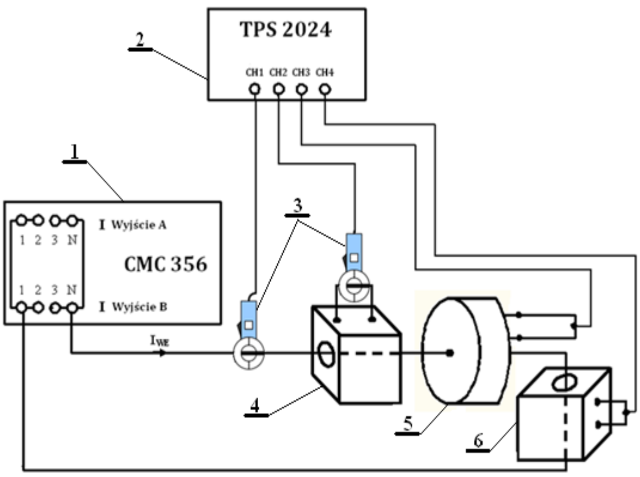

Fig.3. Simplified electric scheme of the measuring system for laboratory testing of the current converters; 1 – signal simulator, 2 – current waveforms recorder, 3 – Dietz measuring probes, 4 – measuring current transformer, 5 – Rogowski coil, 6 – current-voltage converter with amorphous core

The signal simulator controlled by dedicated program allowed for generation of sine waveforms of required amplitude and frequency. Therefore, the respectively distorted current waveforms of precisely defined high harmonics contents were able to be generated (required current wave shape initial phase and amplitude). Angle errors of the generated signals do not exceed 0.02° and these of amplitude – 0.1% respectively. The secondary converters current measurements were respectively collected and stored in the register memory. Next, on the sample sets processing the characteristic quantity of the current signals were able to be calculated like rms value, amplitude (referred to the primary side) as well as content of high harmonics. To compare accuracy of measurements of the primary current rms value additional current meter was applied in the primary common circuit of all converters. Therefore, the registered current waveform was used as the reference pattern for the converters angle errors derivation. At first the current as well as angle errors of the tested converters were specified for non distorted primary waveform. The current error DI was derived on the basis of comparison of amplitude of the registered secondary current with thus of the signal being generated according to equalization (1):

$$DI = \frac{I_{OUT} - I_{IN}}{I_{IN}} \cdot 100\% \qquad (1)$$

where: I_{OUT} – rms value of the output (secondary) current referred to the primary side in [A]; IIN – rms value of the primary current, being set in the signal simulator in [A].

While, these of the angle DK were able to be found when compare the registered current waveforms (due to the signal simulator and these in the secondary winding of the convertors) with respect to their delay time difference at the zero moment.

Investigated results and discussion

It was found that for the rms current range value from 10A up to 100A at frequency of 50 Hz all the tested converters full-fill requirements if about linearly of transformation what can be compared from Fig.4.

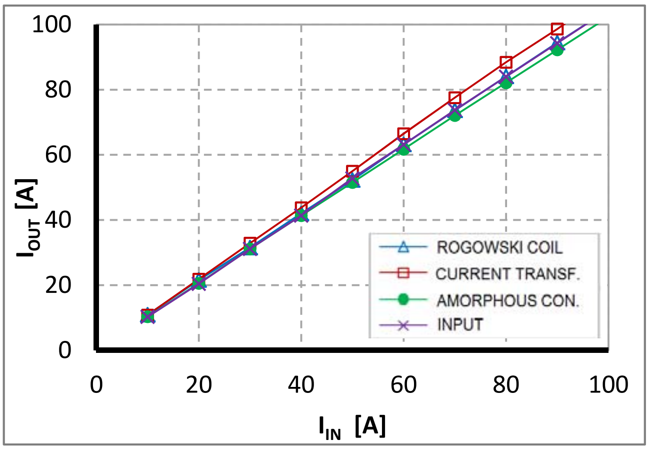

Fig.4. Output current (I_{OUT}) rms value versus input (I_{IN}) rms value for tested converters from 10A up to 100A at 50 Hz

The current waveforms are transferred with negligible deformations what is depicted by small as current as angle errors. With increase of the primary current value the Rogowski coil transformation is even improved. They angle errors do not exceed 9% at 10 A rms value and being decreased up to about 2% at 100 A respectively. The higher current errors however, was found for the commercial current transformer. It is increases linearly with the current value up to about 10%. On the contrary the current converter with amorphous core material indicates the smallest current errors (less than 4%) and its secondary waveforms is almost identical with its of the input signal. Over 40 A rms the current angle between vectors of the primary current and thus of the secondary winding can even be practically neglected.

After the testing under no distorted sinusoidal current waveform (of 50 Hz) was completed the investigations of performance at relatively wide range of both rms value (from 1 A up to 960 A) and frequency (from 10 Hz up to 650 Hz) were carried out. The result of testing are illustrated as an example in Figures 5-8.

From the investigated results it was found that at small frequency (what is common for operation of electrical machines supplied via frequency converters) the current waveform registered in secondary windings of both commercial current transformer and Rogowski coil indicate high error value as current as well angle what can be compared from Fig.5 - Fig.8. The error values decrease with the increase of the primary current frequency. While, the accuracy of transformation is the highest for the amorphous core current-voltage converter – its error values are negligible.

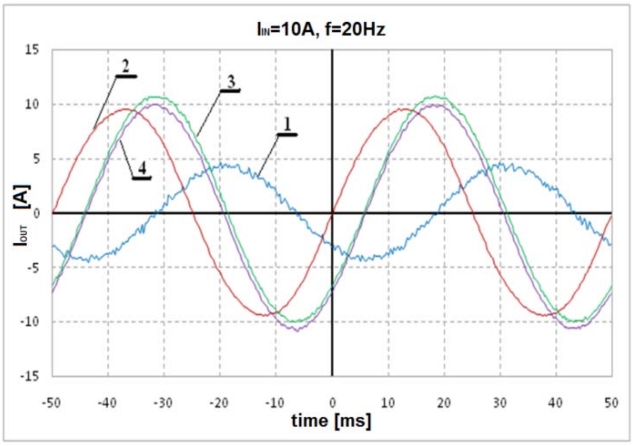

Fig.5. Secondary current waveforms for sinusoidal primary (input) current (I_{IN} = 10 A rms) at frequency of 20 Hz (1 – Rogowski coil, 2 – current transformer, 3 – amorphous core converter, 4 – primary current)

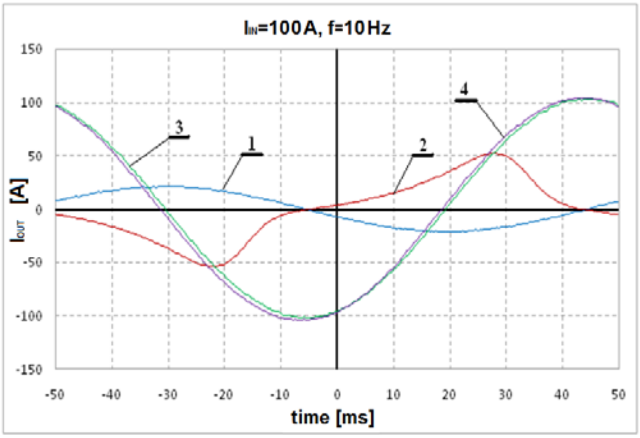

Fig.6. Secondary current waveforms for sinusoidal primary (input) current (I_{IN} = 100 A rms) at frequency of 10 Hz (1 – Rogowski coil, 2 – current transformer, 3 – amorphous core converter, 4 – primary current)

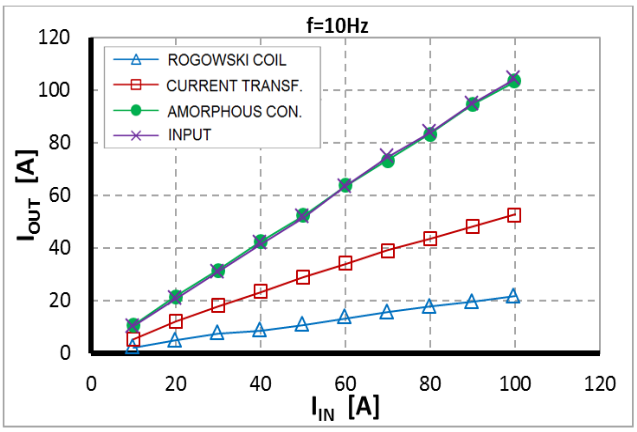

Fig.7. Rms value of output current (I_{OUT}) versus rms value of sinusoidal input current (I_{IN}) of the selected converters for the I_{IN} ramped from 10 A up to 100A at frequency 10 Hz

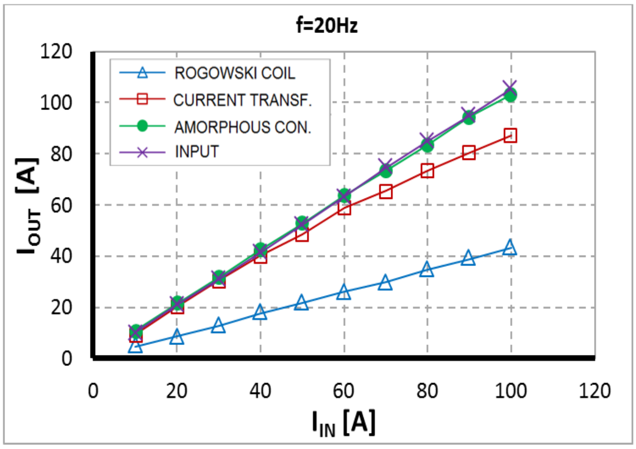

Fig.8. Rms value of output current (I_{OUT}) versus rms value of sinusoidal input current (I_{IN}) of the selected converters for the I_{IN} ramped from 10 A up to 100A at frequency 20 Hz

Under the following investigations the primary current waveforms were respectively distorted with high harmonics content. The current value was ranged from 1 A up to 100 A while its basic frequency was fixed to 10 Hz, 20 Hz and 50 Hz. The results of testing are illustrated in Fig.9 and 10 as an example where, at Fig.9 one can compare the transmission accuracy for input current I_{IN} = 90 A rms at 20 Hz frequency with superimposed fifth harmonics of 20% of basic harmonics, while at Fig.10 for I_{IN} = 90 A rms at 50 Hz with superimposed harmonics contents as is indicated in table 1 respectively.

Tab.1. Higher harmonics content I_H (in percent) in input current I_{IN}=10 A rms of 50 Hz frequency

Harmonics number -	I_H [% I_{IN}]
3	9
5	11
7	9
9	5
11	8
13	8

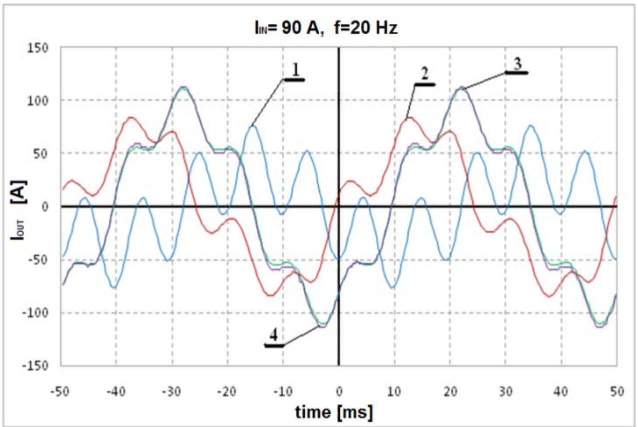

Fig.9. Output (secondary) signal waveform for tested current converters at input current value I_{IN} = 90 A rms at 20 Hz with superimposed 5^{th} harmonics of 20% of basic harmonics (1 – Rogowski coil, 2 – commercial current transformer, 3 – amorphous core converter, 4 – primary current)

The investigated result confirmed that only the current-voltage converter with amorphous core is able to transfer the distorted primary current waveform to the secondary side with high accuracy acceptable in practical applications. On the contrary the secondary current for both commercial current transformer and Rogowski coil does not fulfill requirements due to excessive values of current as well as angle errors.

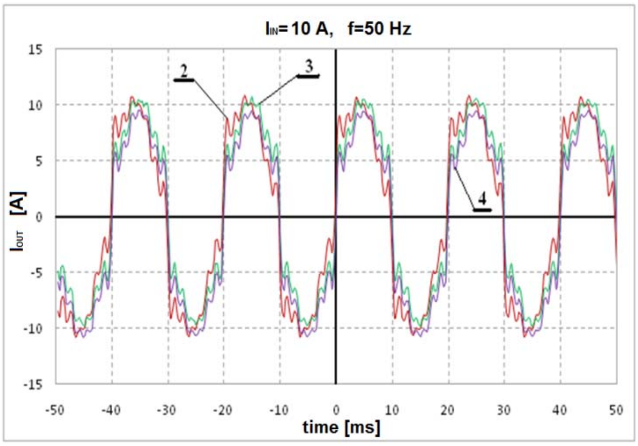

Fig.10. Output (secondary) signal waveform for tested current converters at input current value I_{IN} = 10 A rms at 50 Hz due to superimposed 3, 5, 7, 9, 11 and 13 harmonics respectively (1 – commercial current transformer, 2 – amorphous core converter, 3 – primary current)

Even that the distorted current waveform is (at 50 Hz of the basis component) relatively good transferred to the secondary side by both the commercial current transformer as well as the amorphous core converter but the last one indicate (Fig.10) the smallest error values like under all others conditions of operation being investigated.

Conclusions

The study of traditional current transformers, Rogowski coils and newly developed (in Institute of Electrical Power Engineering - Wroclaw) current-voltage converter with amorphous core showed that:

- for sinusoidal waveforms of fundamental frequency of 50 Hz all the tested current converters display acceptable small errors both angle and current. The amorphous core current converter however, displayed the highest accuracy of transformation,
- if the current sine-waves were provided with frequency bellows 50 Hz the only acceptable for practical use is found to be the current converter with amorphous core. It possesses a linear characteristic of transformation for all current rms values under test (from 1 A to 100 A). On the contrary the commercial current transformer's errors are significant, whereas, if in addition to the current of a low frequency will also appear noise current even of a low value but of frequency close/equal to this of resonance of resultant electrical circuit of Rogowski coil at its terminal one can observe respective output signal deformation,
- transformation characteristics of all current converters are practically improved with the increased frequency of the primary current waveform from 150 Hz up to 650 Hz. Still, because of good properties of the amorphous material in wide range of frequency the converter with core made of this material displays linear transformation characteristic within in all tested range both current and frequency values,

Therefore, under selection of the current measuring equipment for use in electrical power system with operating electric power converters one has to particularly consider its suitable transformation characteristics in a wide variation range of both current and frequency values. It must be especially noted that in power transformation substations the measurements of electric quantities for the propulsion systems supplied via frequency converters can be loaded by high error values of both current and angle particularly at low primary current frequency (around 10 Hz). Therefore, only the amorphous core current converter can be recommended for such applications.

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