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APPLICATION OF GRAPHENE AND NEWLY DEVELOPED AMORPHOUS ALLOYS IN CURRENT TRANSFORMERS FOR RAILWAY APPLICATIONS

ZASTOSOWANIE GRAFENU ORAZ NAJNOWSZEJ KLASY MATERIAŁÓW MAGNETYCZNIE MIĘKKICH – MAGNETYKÓW AMORFICZNYCH W BUDOWIE PRZEKŁADNIKÓW PRĄDOWYCH NA POTRZEBY KOLEJNICTWA

A b s t r a c t

Paper present practical solutions based on the utilization of graphene and amorphous alloys for construction of DC current transformer. Proposed solution is competitive as for the metrological properties and overall dimensions, and is well suited for the measurements of large currents in the railway traction. Use of amorphous alloys as magnetic materials for low-hysteresis and high-permeability cores, and development of highly sensitive graphene-based Hall effect sensors, allow for substantial improvements in the open feedback loop DC current transformers construction. In order to verify the usefulness of the developed DC current transformer, its characteristic was investigated. High linearity of the sensor is confirmed by the R-square parameter exceeding 0.99. The repeatability of the measurements was in the range of 1%. The properties of these materials raise the prospect of changes in the construction of the DC current transformers and open up the perspective of a number of innovative projects in the railway industry, in the current measurements area.

Keywords: graphene, amorphous alloys, current transformer

S t r e s z c z e n i e

Artykuł przedstawia praktyczne zastosowanie grafenu i stopów amorficznych w aplikacji przekładnika prądu stałego. Zaproponowane rozwiązanie jest konkurencyjne co do parametrów metrologicznych i geometrycznych oraz jest dostosowane do pomiaru prądów o wysokim natężeniu występujących w kolejnictwie. Wykorzystanie magnetyków amorficznych jako materiałów do wykonania rdzeni, które charakteryzują się znaczną przenikalnością magnetyczną i znikomą histerezą, oraz wysokoczułych hallotronów wykonanych z grafenu pozwala na poprawę właściwości przekładników prądu stałego z otwartą pętlą sprzężenia zwrotnego. W celu sprawdzenia użyteczności skonstruowanego przekładnika została zbadana jego charakterystyka. Liniowość charakterystyki w badanym zakresie potwierdzono współczynnikiem determinacji liniowej wynoszącym 0,99. Uzyskano powtarzalność pomiarów na poziomie 1%. Właściwości użytych materiałów budzą perspektywę zmian w obszarze budowy przekładników prądowych i otwierają perspektywę wielu innowacyjnych projektów w kolejnictwie w obszarze pomiaru prądu.

Słowa kluczowe: grafen, stopy amorficzne, przekładnik prądowy

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1. Introduction

The tendency to change the electric energy payment method in railways, from lump-sum to charge for energy actually used, raises the need to develop new devices to measure the amount of used energy, or adapt old ones. The current draw by the locomotive is as high as several kiloamperes. The measurement of such currents, in combination with the Polish power supply lines standard, is not an easy task.

Presently, DC current transformers are most commonly used for this purpose [1]. There are several different kinds of solutions for these devices. In this paper, proposals for improvements in the DC current transformer with open feedback loop are presented, based on the modern materials: graphene and amorphous alloys.

The basic elements of the DC current transformer are: gapped magnetic core and magnetic field sensor [2]. Traditionally, for their construction, cores made of transformer plates or ceramic magnetics (ferrites) are used. As the magnetic field sensors, Hall effect sensors or fluxgates were utilised. Due to the easy utilisation and simpler electronic circuits, Hall effect sensors are more popular. They are mostly based on GaAs or InSb structures.

Experience in the use of amorphous alloys as magnetic materials for low-hysteresis and high-permeability cores [3], and the development of highly sensitive graphene-based Hall effect sensors [4], allow for substantial improvements in the open feedback loop DC current transformer's construction.

The aim of the paper is to present practical solutions based on the utilisation of graphene and amorphous alloys for the construction of a new type of DC current transformer.

One of the main advantages of electric vehicles is the possibility of energy recovery during braking, which is called recuperation. Recuperation allows for a reduction of the energy demand by re-using the breaking energy. In recent years, research in the field of storing and re-using regenerative braking energy has become very intensive. This is caused by an increasing number of vehicles equipped with recuperation systems and global demands for reducing the consumption of electrical energy.

In typical DC supply systems of the public transport (tramways, trolleybuses), recovered energy can be re-used by auxiliary receivers in a breaking vehicle or by the other vehicles. If there is no vehicle, which is accelerating, this energy is turned into heat in breaking resistors. In order to avoid such a situation, energy storage systems can be used, e.g. supercapacitors or flywheels. Nowadays, many energy storages are in operation in tram, trolleybus and metro systems. Optimisation of the parameters and location of storage devices for regenerative breaking energy has become very significant [1–6].

Storage devices can be divided into two groups: on-board energy storage devices, which are placed in the vehicles and off-board energy storage devices, situated in traction substations or between them. Current research is focused mainly on two objectives. The first is to reduce the energy demand by introducing on-board energy storages in light electric vehicles like trams, trolleybuses or electrobuses [7–9]. The latter is to provide a supplying system for heavy electric vehicles (trains, metro) with an off-board energy storage [10–13]. In contrast to this, a lack of research in the field of off-board storage energy systems for light electric vehicles can be noticed. Tram and trolleybus transportation is highly developed in plenty of European cities. Many tram and trolleybuses operators consider putting into service off-board energy storage systems. This motivated the authors to analyse the efficiency of regenerative breaking in the trolleybus supplying system using off-board energy storage.

2. Principle of operation

According to the Ampere's Law, electric current flow in the conductor generates a magnetic field around it. The generated magnetic field is directly proportional to the current in the conductor and inversely proportional to the distance from the conductor, as given in the equation:

$$B = \frac{\mu \cdot I}{2\pi R} \tag{1}$$

where:

- B – Magnetic field induction value,
- I – current in the conductor,
- R – distance from the conductor,
- μ – magnetic permeability.

The magnetic field induction vector direction is following the right hand rule. The generated magnetic field is concentrated by the DC current transformer core. The air gap in the core is cut to accommodate the magnetic field sensor. The sensor measures the air gap magnetic field and converts it into a voltage signal proportional to its value.

The layout of the device is schematically presented in Figure 1.

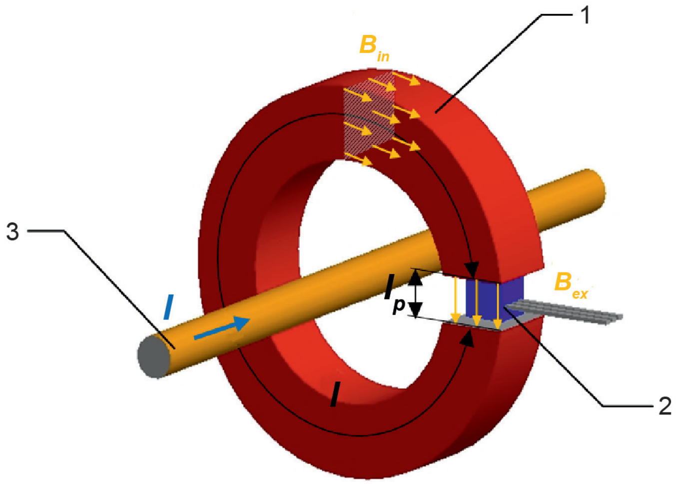

Fig. 1. Schematic diagram of current sensor: 1 – magnetic field concentrator, 2 – Hall sensor, 3 – wire under test

The relationship between the magnetic field in the core and the field in the gap is described by the formula (2) [1, 6].This formula indicates that, as the gap width increases, the field value in the gap decreases.

$$B_{ex} = \frac{I}{l_p \mu_0} - \frac{l - l_p}{l_p} \frac{\mu}{\mu_0} B_{in} \tag{2}$$

where:

- B_{ex} – magnetic field induction in the gap,
- B_{in} – magnetic field induction in the core,
- I – electric current,
- l – magnetic path in the core,
- l_p – air gap width,
- μ – relative permeability of the material,
- μ_0 – magnetic permeability of the vacuum.

The air gap in the core serves as the mounting place for the magnetic field sensor – Hall effect sensor. It measures the magnetic field value and outputs a proportional voltage signal.

By measuring the magnetic field induced by the primary circuit, and not directly the current, we obtain galvanic isolation between the primary winding and the measuring system. It is especially important for the measurement of high voltage currents.

3. The technical solution of the developed DC current transformer

The designed measuring system consists of a few basic elements: the primary winding – conductor of the measured current, the gapped magnetic core and a Hall effect sensor. A schematic diagram of the developed DC current transformer is shown on Figure 2.

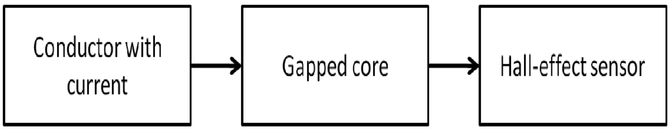

Fig. 2. Schematic diagram of a digitally controlled current transformer

As the magnetic sensor inside the gap, an innovative graphene Hall effect sensor is used. The sensors based on graphene have a very high sensitivity (3000 V/AT) [4] and good resolution as well as stability of the parameters as a function of temperature [6]. Exemplary graphene based Hall effect sensor characteristic is shown in Figure 3.

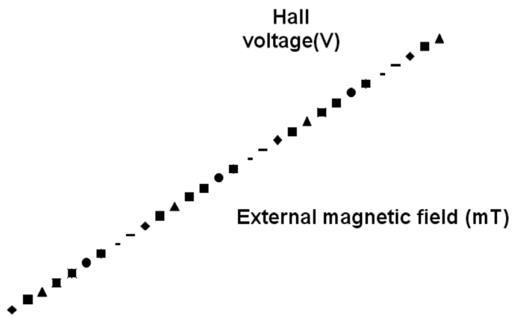

Fig. 3. Hall effect sensor characteristic

M-333 magnetic core made of amorphous ribbon, produced by Magnetec, was used in the device. The core made of such material has very high relative permeability (~30000) [8], linear characteristic, external influence resistance and low temperature coefficient [9]. Geometric dimensions of the core: 50×45×5 mm. Air gap width: 2 mm.

The DC current transformer made of the abovementioned elements is presented in Fig. 4.

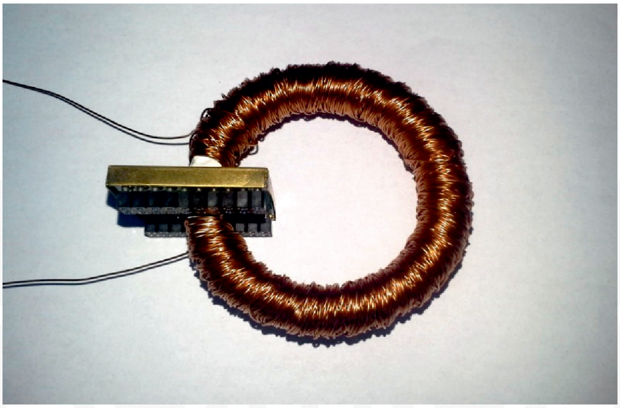

Fig. 4. Constructed DC current transformer

4. Measuring stand

In order to verify the usefulness of the developed DC current transformer, its characteristic was investigated. For the measurements, the laboratory test stand presented schematically in figure 5 was built. It consist of the Inmel industrial calibrator, primary winding with $n = 1000$ number of turns, the developed DC current transformer, Fluke 8808A precision voltmeter and Motech laboratory power supply. Data acquisition was done on a PC.

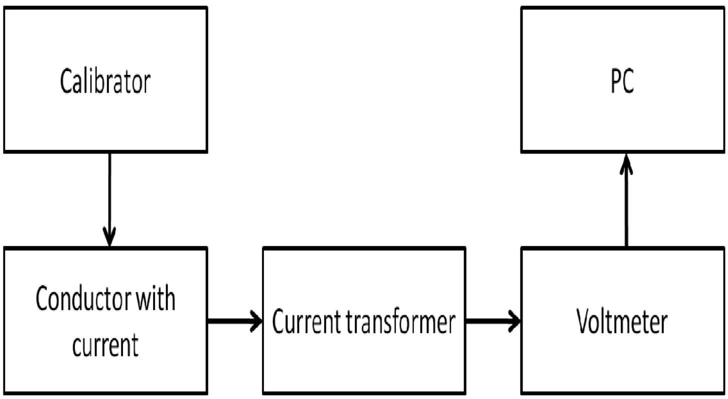

Fig. 5. Schematic of the test stand

The calibrator current was set in the range of 0–200 mA, which taking into account the primary winding, induced a magnetic flux in the core corresponding to the current range of 0–200 A.

5. Measurement results

The results of the measurements for the developed DC current transformer are presented in Figure 5. It should be indicated that a linear characteristic of the device's output voltage was achieved for the measured currents in the range of up to 200 A.

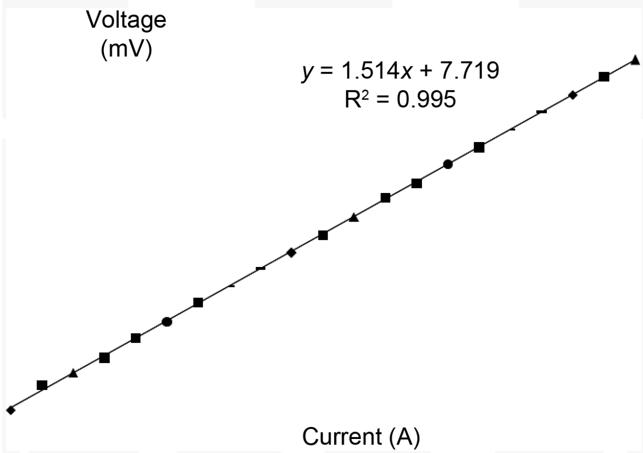

Fig. 6. Experimentally measured characteristic of the developed DC current transformer with its linear fit

Linear fit of the function $f(x) = k \cdot x + b$, where $k = -0.0015$ V/A and $b = 7.72$ V was made by the least square method. High linearity of the sensor is confirmed by the *R*-square parameter exceeding 0.99. The repeatability of the measurements was in the range of 1%.

6. Conclusions

The proposed solution is competitive because of the metrological properties and overall dimensions, and is well-suited for the measurements of large currents in the railway traction. The good linearity and high sensitivity of the DC current transformer utilising an amorphous alloy core and graphene Hall effect sensor was confirmed. The properties of these materials raise the prospect of changes in the construction of the DC current transformers and open up the perspective on a number of innovative projects in the railway industry, in the current area of measurements.

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