V. Grim, P. Ripka: Rogowski Coil with Ferromagnetic Powder Core, Magnetics Letters 13 (2022), pp. 1-4, Art no. 8102304 10.1109/LMAG.2022.3143470

Rogowski Coil with Ferromagnetic Powder Core

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We have used nanocrystalline powder to build a core for Rogowski coil suitable for application in energy meters. The sensor linearity error is 0.32 %FS of its 20 A range, which is acceptable for this application. The main advantages of the new core are: 15-fold increase in sensitivity, which results in lower noise, and high rejection of direct current. It operates at up to 1000 A_{DC} with 20 % change in sensitivity. Resulting accuracy of power measurement using single-chip digital power meter is 0.22 %FS.

***Index Terms*—Magnetic instruments, current measurement, energy distribution, Rogowski coils, soft magnetic materials.**

I. INTRODUCTION

ROGOWSKI coils (RC) measure magnetomotive force, which depends on the integral of the induced electrical voltage. If the coil ends are put together, the magnetic voltage is equal to the current flowing through the coil opening [1]. The main application of Rogowski coil is therefore measurement of AC currents [2]. In order to obtain the waveform of the measured current, the voltage should be integrated by analog or digital integrator.

Classical Rogowski coils are made of non-magnetic materials and they theoretically have zero non-linearity. Therefore, they are ideal sensor for the measurement of transient currents e.g. during welding process, during testing of power components such as circuit breakers, fault current detectors [3], and in particle accelerators [4], [5]. Practical linearity is typically limited to 0.1 % over three decades of current amplitude [6] by the following factors:

- ferromagnetic impurities in the used materials
- ferromagnetic objects in the sensor vicinity
- external stray fields such as leakage from nearby transformers

The system linearity is also affected by the following amplifier, analog integrator (if present), and analog-to-digital converter [7].

High linearity makes Rogowski coils resistant to DC current component or external magnetic fields, which can saturate the current transformer [8]. Therefore an attractive application of Rogowski coils is in electric power and energy meters, making them resistant to tampering [9]. Single-chip energy meters containing digital integrator for Rogowski coils are available from several manufacturers. Rogowski coils for power line frequency may achieve 0.05 % accuracy, their temperature coefficient of sensitivity can be compensated to 2 ppm/K [10], [11].

On the other side, low-cost Rogowski coils are made on flexible openable plastic core which allows them to be closed around the uninterrupted conductor [12]. Flexible Rogowski coil with ferromagnetic core was described in [13]. The relative permeability of its composite core is 18. However, no functional parameters of this sensor are reported. Rogowski coils can also be made in PCB technology [14].

Typical example of the Rogowski coil used for electric power meters is PA3202NL manufactured by Pulse Electronics [15]. The sensor with 7.5 mm inner diameter has accuracy class 0.2 and sensitivity of 8.33 μV/A/Hz. The winding inductance is 1.75 mH and its resistance is 57 Ω. The current noise heavily depends on the used electronics. The discrimination of external currents is not specified by the manufacturer. We measured these parameters and describe them in Section III in order to compare our new sensor to this off-the-shelf product.

The influence of the position of the primary conductor was analyzed in [16]. For perfectly homogeneous Rogowski coil this dependence is zero, however for commercial coils it may cause 1 % error. For single-layer rigid coils with precisely machined core this dependence is mainly caused by discontinuity between the first and last turns and may be compensated to below 0.1 %.

We therefore concentrated on the influence of external electric currents, which is more serious problem for practical applications. In [17] we made a theoretical analysis of this effect for the case of one missing turn, which is the worst case which may occur between the first and last turn. This maximum error is 0.6 % for the distance of 75 mm, and by using ferromagnetic core it can be reduced to 0.18 %. The real measured error was 0.08 % (i.e. the actual gap was smaller than one turn). Alternative way how to increase resistance against external fields is magnetic shielding [18]. Electrical shielding and winding pitch compensating turn are essential for every Rogowski coil [19].

The resolution of Rogowski coil for small currents is limited by its low sensitivity resulting in high noise. In this case the total noise strongly depends on the input voltage and current noise of the attached amplifier or integrator. Noise can be reduced by increasing of the coil sensitivity by increasing of the number of turns, but this has side effects: multi-layer coils are less homogeneous which increases their sensitivity to external fields and currents, and they have larger parasitic self-capacitance, which is detrimental to their frequency response.

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For this reason we use weakly ferromagnetic core, which can increase sensitivity while keeping its linearity error low. This idea was already used in self-integrating Rogowski coils for high-frequency currents or short pulses, which use self-capacitance of the coil for integration [20], [21].

In this paper we concentrate on applications at power line frequency, which is too low for self-integrating Rogowski coils. We also believe that self-capacitance of a RC is not stable enough to be relied upon in high precision measurements. In our previous paper [17] we have elaborated upon Rogowski coil with core made of powder cores of Sendust type. The 75 mm diameter sensor had ±0.2 % linearity in the 500 A range and amplitude error below 0.5 % up to 1 kHz frequency. In this paper we use nanocrystalline powder core of decreased diameter aiming the application as current sensor for energy meters. Compared to [17] we analyze more parameters relevant to this application, such as sensor noise, phase error and total error for digital energy meter with such Rogowski coil as a current sensor.

II. SENSOR DESIGN

We have used nanocrystalline flakes produced from Fe81Ni9.7B2.5Nb5.5Cu1.3 nanocrystalline tape with mean particle size of 200 µm [22] [23]. The annealed tape was processed in a crushing machine and Vibratory Disk Mill [22]. The relative permeability measured on uncured powder sample was 8.4. The powder was mixed with epoxy resin at 90:10 weight ratio and molded into a soluble (BVOH) 3D printed toroidal shell. We have experimented with curing the core in radial magnetic field of 7 kA/m which was created by 1 kA axial DC current, however we did not observe any significant anisotropy similar to reported in [24]. The core and winding parameters are:

Inner diameter $R1$ (mm)	40
Outer diameter $R2$ (mm)	50
Height (mm)	5
Powder mass (g)	14
Mean grain size (μm)	200
Rel. Permeability	15
Number of turns	524
Wire diameter (mm)	0.2 (nominal)
Inductance at 1 KHz (μH)	1034
Resistance at 1 KHz (Ω)	6.023
Sensitivity (μV/A/Hz)	12.52

The results were compared with a reference specimen wound with 622 turns (0.17 mm nominal dia.) and containing no magnetic material. The difference in number of turns is caused by using wire from different manufacturer for each winding. The inductance and resistance of the non-magnetic coil is 93.7 μH and 9.620 Ω, respectively.

III. TESTING RESULTS

A. Linearity

Linearity across the rated operational range was measured with sinewave current source and lock-in amplifier. In the 20 A range the linearity error is 0.32 %FS (Fig. 1). The sensor's resistance to overload was tested by incremental sensitivity method; a large direct current together with smaller alternating current was passed through the sensor. At 1000 A the error in sensitivity is below 20 % (Fig. 2).

FIG. 1 HERE

FIG. 2 HERE

B. Frequency dependence

The frequency response was measured with a lock-in amplifier (HF2LI) against a LEM Ultrastab reference current sensor. Results are summarized in Fig. 3. The samples were measured without their electrostatic shielding. Adding a shield results in peaking, which can be adjusted by changing the winding-to-shield distance. From this perspective the ferromagnetic sample is more favorable, because it allows for correction by the shield capacitance without the need for damping resistors.

FIG. 3 HERE

C. Cross-sensitivity to external currents

External current rejection was tested with current $I_{ext} =$ 20 A at 1 kHz. The output voltage was measured with a lock-in amplifier (HF2LI). External current was placed at a distance corresponding to sensors placed side by side (Fig. 4, 55 mm for samples N and P, 40 mm for PA3202NL), at different angles α.

FIG. 4 HERE

The resulting cross-sensitivity (Fig. 5) of the ferromagnetic core is comparable to a non-magnetic control sample. The rejection of external current is given mostly by the uniformity of core cross-section and winding pitch. In case of multi-phase power meters the relative position of each phase is constant and this cross-sensitivity can be corrected during data post-processing. The ripples visible in the measurement of commercial sensor PA3202NL are caused by the internal construction of the coil, which consists of six solenoidal segments in circular arrangement.

FIG. 5 HERE

D. Noise

Sensor noise was measured with Agilent 35670A FFT spectrum analyzer from 0 Hz to 12.8 kHz at zero current inside a three-layer magnetic shielding. The resulting noise voltage spectral density was divided by the sensor's approximate transfer function $H(s) = s \cdot \frac{V_{out,I=Irated}}{2\pi f I_{rated}}$ to obtain the equivalent current noise spectral density (Fig. 6).

FIG. 6 HERE

The noise of the sensor itself is too low to be measured, the result consists solely of the noise floor of the measuring instrument. The thermal noise of the winding is around 30 dB below the instrument noise. Therefore in practical applications the parameters of the ADC and integrator determines the overall noise performance of the system.

E. Accuracy of power measurement

In this section we demonstrate the performance of the new sensors in conjunction with a single-chip power meter containing a digital integrator STPM34 manufactured by ST Microelectronics.

FIG. 7 HERE

The block diagram of the measurement setup is shown in Fig. 7. A 2.35 Ω power resistor was used as a load. Tektronix PA1000 power analyzer with internal shunt was used as a reference instrument. Power was sourced from Techron 7548 power amplifier at 50 Hz.

FIG. 8 HERE

Full scale current of 20 A was chosen to match the maximum range of the reference instrument. The results are summarized in Fig. 8. The proposed sensor creates additional linearity error of 0.22 %FS. Maximum phase error (without applying the phase compensation available in the STPM34) is below 0.3°.

IV. CONCLUSIONS

A small size Rogowski coil with nanocrystalline powder core is suitable as AC current sensor for energy meters. The achieved linearity error is 0.32 % for 20 A range. The new sensor is also highly resistant to DC component in the measured current: 100 $\mathrm{A_{DC}}$ only causes 1.6 % error, and remains operational even for overcurrent of 1 000 $\mathrm{A_{DC}}$ with 20 % error. Compared to the air core the nanocrystalline sensor noise was reduced 15-fold to 36 $\mu\mathrm{A}/\sqrt{\mathrm{Hz}}$ at 50 Hz.

The sensor was tested together with a single-chip power meter containing a digital integrator. The resulting error for the measurement of power was 0.22 %FS.

Compared to a commercially available air-cored sensor of comparable size, we achieved 50 % increase in sensitivity, and noise reduced by 3.5 dB. The suppression of the external current is comparable. The main factor limiting the latter parameter is the mechanical precision of the core. Composite cores of this type can be manufactured in arbitrary shapes for specific applications.

ACKNOWLEDGMENT

This study was supported by the Grant Agency of the Czech Republic within the Nanofluxgate project (GACR GA20-27150S).

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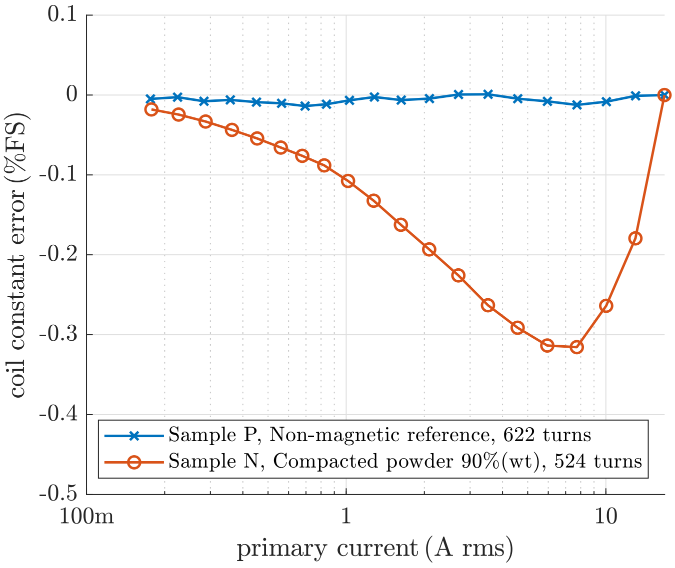

Fig. 1. Measured linearity error of the developed sensor with ferromagnetic core compared to the reference sensor based on air core.

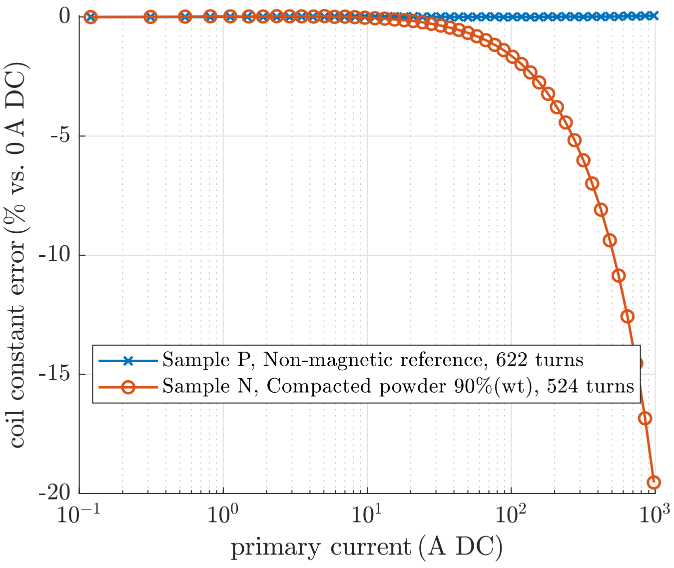

Fig. 2. Measured differential linearity error of the developed sensor compared to the air core reference sensor.

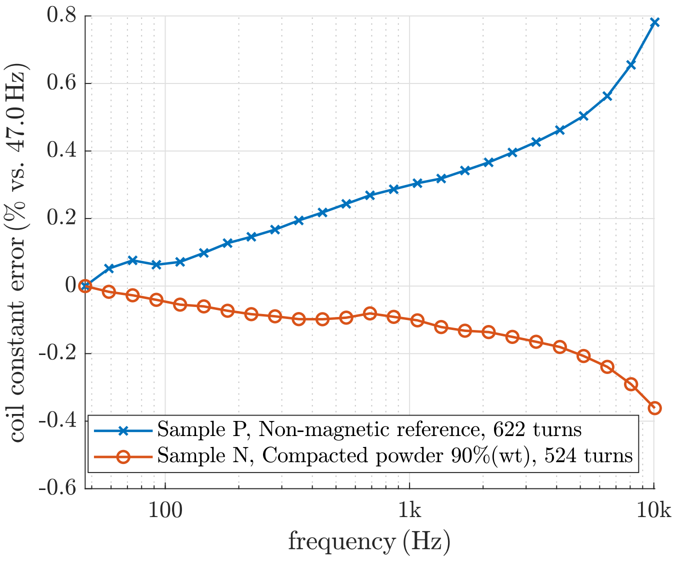

Fig. 3. Measured frequency response of the developed sensor compared to air core reference.

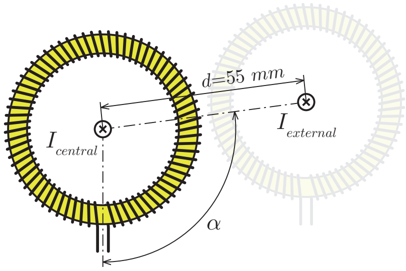

Fig. 4. Two sensors in minimum distance: this geometry was used for the testing of external current rejection.

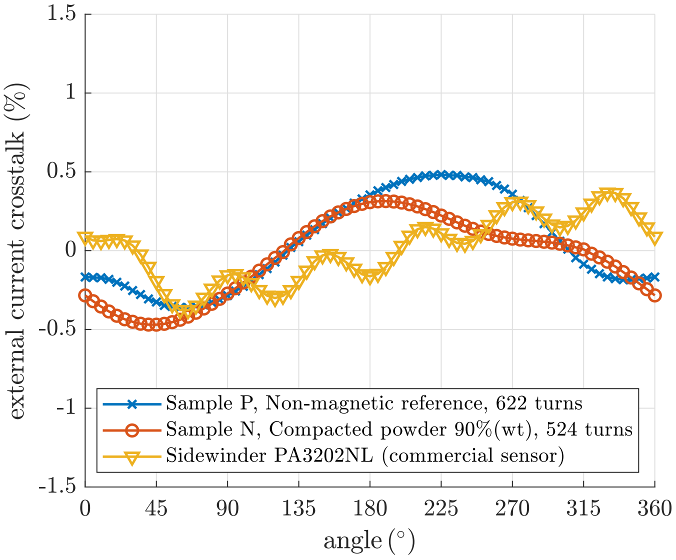

Fig. 5. Measured external current suppression. Coil terminals are coincident with 0° position. The performance of samples N and P is very similar.

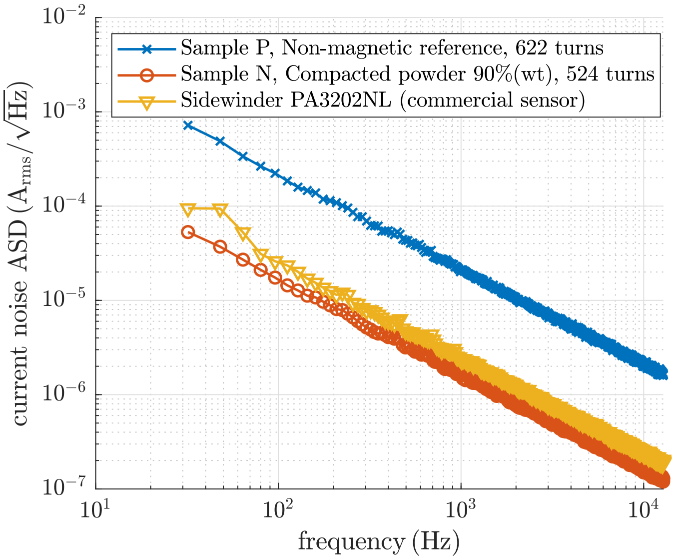

Fig. 6. The measured equivalent current spectral density of the new sensor is one order of magnitude lower than that of the reference air-core sensor.

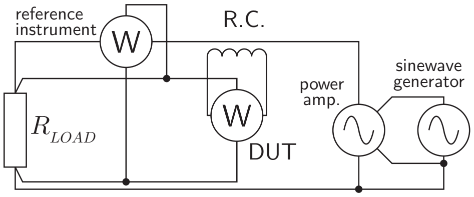

Fig. 7. Schematic diagram of power measurement. Two wattmeters (W) are used: a single-chip electronic power/energy meter with digital integrator with Rogowski coil (RC) as a current sensor (labeled *DUT* = Device Under Test), and a reference wattmeter Tektronix PA1000 with internal shunt resistor (labeled *reference instrument*).

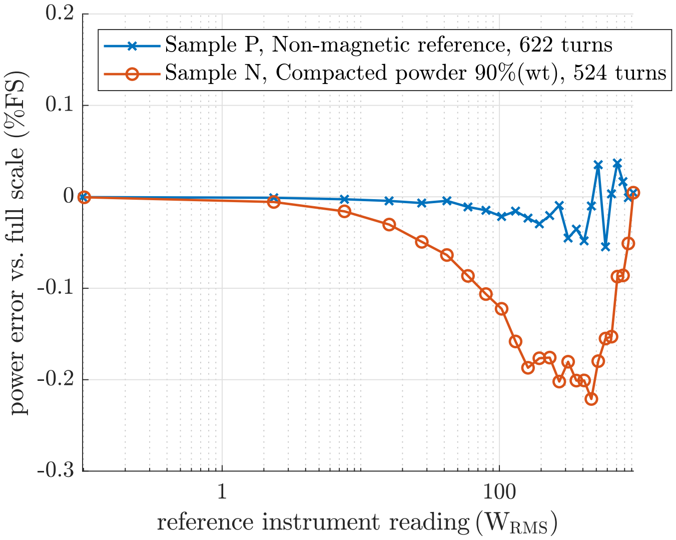

Fig. 8. Power measurement with resistive load: the nonlinearity of the ferromagnetic core material causes increased error of $-0.22\,\%\mathrm{FS}$, which is acceptable for domestic energy meters.