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TESLAMETER FOR MAGNETIC FIELD MEASUREMENT IN HIGH VOLTAGE FACILITIES

Abstract: *This paper presents a low-cost three-axis teslameter capable of measuring magnetic field intensity in industrial environments and high voltage facilities. It is based on an MFS-3A three-axis magnetic field sensor, and it can measure magnetic flux density up to ±5 mT in all three axes, with accuracy better than ±0.5% and excellent temperature stability. The proposed teslameter was calibrated using a state-of-the-art reference instrument, Helmholtz coil and temperature chamber. The paper describes the development and the calibration of the proposed teslameter. The obtained results are presented as well.*

Key words: magnetic field, teslameter, MFS-3A, high voltage facilities, calibration.

INTRODUCTION

Humans' immune system successfully performs its function in the preservation of human health under the Earth's natural magnitude field intensity. However, the intensity of the environmental magnetic field is often considerably above Earth's natural magnitude field intensity. Professional workers in power plants and high voltage facilities are exposed to magnetic fields on a daily basis [1]. In order to collect data about exposition and improve health status, it is essential to carefully monitor the magnetic field exposure of each worker.

Society and science, according to the state of art in the field of bioelectromagnetic, set a few recommendations regarding the exposure limits for magnetic fields generated by 50/60Hz electric current. A couple of recommendations are given in Table 1.

Table 1. *Recommended exposure limits*

Recommendation	Limit
IRPA/ICNIRP recommendation for "private individuals" (daily, constant)	100 µT
IRPA/ICNIRP recommendation for occupational exposure (daily, constant)	500 µT
IRPA/ICNIRP exposure limit for "private individuals" (daily exposure for a few hours)	1 mT
IRPA/ICNIRP recommendation for occupational exposure (daily exposure for a few hours)	5 mT

An instrument called teslameter, comprised of a magnetic field probe and an electronic processing circuit, measures magnetic flux density. Hall effect sensors emerged as the preferred selection for magnetic field probes due to their growing accuracy and low prices [2]. Proper exposure to the magnetic field monitoring requires measuring its intensity in all three axes, meaning that a three-axis magnetic field probe is mandatory.

There are many commercially available three-axis teslameters capable of performing measurements in the range of ± 5 mT, but they are usually either expensive or bulky. On the other hand, there is a handful of available yet portable, accurate and battery-powered three-axis teslameters with the same measurement range and prices less than 100$. It should be noted that there are no commercially available magnetic field dosimeters i.e. devices device that measures dose uptake of external magnetic field. There are a couple of similar devices, which can record measurements, but they are not commercially available [3, 4].

A cost-effective yet accurate three-axis teslameter can be realized using inexpensive off-the-shelf components in a similar way as the teslameter presented in the research [5].

SYSTEM DESIGN

The proposed teslameter was built around an 8-bit PIC18F2550 microcontroller (MCU) due to its performance-size ratio.

The key design requirements the proposed teslameter must accomplish are:

- simple design,
- low cost of components,
- good temperature stability and accuracy,

Following these requirements, an analogue three-axis magnetic field sensor MFS-3A was selected to measure magnetic flux density in all three axes. The MFS-3A consists of three CSA-1V single-axis Hall effect sensors mounted in a way their sensitive areas are mutually perpendicular so that each CSA-1V measures one direction of a magnetic field [6]. The CSA-1Vs are soldered on two perpendicular PCBs as shown in Figure 1 with angular alignment better than ±3° and then, they are sealed in a plastic case.

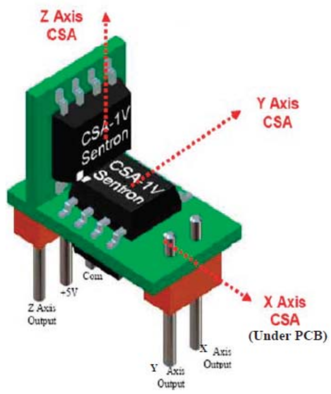

Figure 1. *Structure of the MFS-3A magnetic field sensor [6]*

The CSA-1V is a single-axis Hall effect magnetic field sensor fabricated using a conventional CMOS technology with an additional ferromagnetic layer placed above the sensitive area (see Figure 2), which amplifies the magnetic field by 10 times [7]. Output voltage can be either ratiometric or single ended. It also incorporates the spinning current technique to increase the output signal without increasing the inherent electrical noise [8, 9]. Moreover, the spinning current method can completely remove the 1/*f* noise.

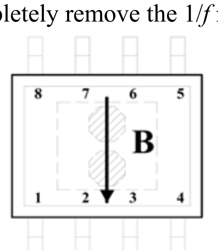

Figure 2. *Direction of sensitivity and location of sensing element [7]*

The high sensitivity of the CSA-1V and low-noise features make it suitable for accurate electric current measurement applications [10-13]. Key parameters of the CSA-1V are given in Table 2.

Table 2. *Key parameters of the CSA-1V Hall Effect sensor [7]*

Parameter	Value
Magnetic field measurement range	±7.3 mT
Sensitivity	280 mV/mT
Bandwidth	100 kHz
Accuracy on magnetic sensitivity trimming	±2%
Offset voltage	±20 mV
Nonlinearity	±0.2%
Magnetic sensitivity temperature drift	±0.02%/°C
Offset Temperature Drift	±0.2 mV/°C

Although the CSA-1V saturates around ±7.3 mT, it will not be damaged even if exposed to the magnetic field as high as ±1 T. Saturation recovery time is less than a few microseconds.

Figure 3 shows the block diagram of the proposed teslameter.

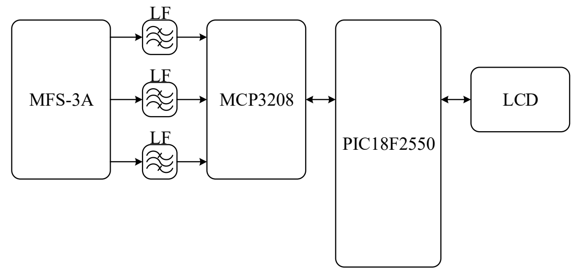

Figure 3. *Block diagram of the proposed dosimeter*

The output voltage of each CSA-1V is filtered with a low-pass Sallen-Key filter with a cut-off frequency of 500 Hz, unity gain and quality factor of 0.707, built around the AD822 rail-to-rail op-amp. The filtered voltages are then fed in the 12-bit MCP3208 analogue to a digital converter (ADC). Based on the output voltage of the corresponding CSA-1V, the MCU calculates magnetic field intensity of each axis per following expression:

$$B = \frac{V_{OUT} - V_{OFFSET} \pm V_{COMP}}{S} \quad (1)$$

wherein V_{OUT} is the CSA-1V output voltage in [V], S is its sensitivity in [mV/mT], V_{OFFSET} is the sum of offset and quiescent voltages, i.e. output voltage of the CSA-1V when no magnetic field is applied and V_{COMP} is compensation voltage of ADC.

After the MCU calculates the magnetic flux density of each axis, it calculates total magnetic field intensity per the following expression:

$$B_{SUM} = \sqrt{B_X^2 + B_Y^2 + B_Z^2} \quad (2)$$

MCP1541 voltage reference provides a 4.096 V reference voltage for the ADC, which means that the ADC quant is exactly 1 mV. In other words, the magnetic field resolution is equal to 3.5 µT. Based on the above mentioned, it can be concluded that the ADC resolution is perfectly acceptable since the resolution of the MFS-3A is equal to ±10 µT [6]. The absolute accuracy of the MCP3208 ADC is ±4 LSB, which equals ±14 µT.

In order to minimize the power consumption, the obtained results are displayed on a 2x16 LCD COG (Chip-On-Glass) display instead on classic LCD with background light. The proposed dosimeter is designed to be powered from a simple 5 V DC power bank used to charge tablets and cell phones via a micro USB port. This being said, the total power consumption of realized teslameter is less than 75 mA/h.

When the proposed dosimeter powers on, it begins measuring magnetic field intensity in all three axes after which the MCU calculates total magnetic field intensity, per Equation (2), and displays all four values on a LCD COG display. Sampling rate of measurements is 500 ms.

Photo of the proposed dosimeter is shown in Figure 4.

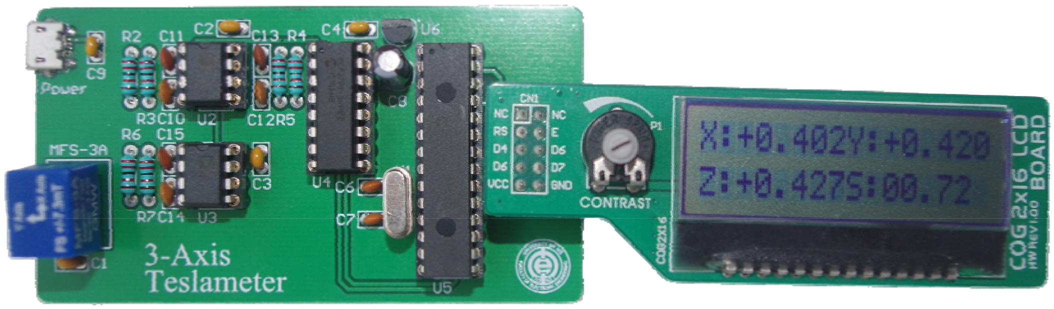

Figure 4. *Photo of the proposed dosimeter*

As can be seen from Figure 4, COG LCD is soldered on a separate PCB in order to minimize a size of enclosure as well as to provide greater selection of plastic boxes. In this case, connection between main board and LCD board can be realized using a 10-wire flat cable.

Although the proposed teslameter uses trough hole electronic components, thanks to its simplicity, the main PCB is only 85x45 mm in large. Greater minimization can be obtained with better track routing and by employing SMD components except for MFS-3A. Moreover, the proposed teslameter can be easily upgrade, with minimal costs, to record real-time measurements on a SD card, i.e. it can become a magnetic field dosimeter.

The total cost of realization of the proposed teslameter is well below 100 $ wherein the most expensive item is in fact a MFS-3A magnetic field sensor. Additional cost is a USB power bank whose price is determined by the user according to the desired power capacity.

CALIBRATION AND TEST RESULTS

Brand new CSA-1Vs have unequal specifications significantly different from the ones rated in [7]. For this reason, calibration of each CSA-1V is an essential procedure during their manufacturing process. Namely, the sensitivity of non-programmed CSA-1Vs is around 150 mV/mT, which is during calibration increased per the following expression:

$$S_{GAIN} = 1 + A \tag{3}$$

wherein *A* represents the sum of one or more (or even none) following coefficients: 0.5, 0.25, 0.125, 0.0625, 0.03125 and 0.015625.

Due to a limited number of combinatons, it is almost impossible for each CSA-1V to have the exact sensitivity, which is why the sensitivity has a tolerance of ±5 mV/mT. This means that in order to obtain the most accurate measurements from the proposed teslameter, it is necessary to calibrate all three CSA-1Vs individually.

Calibration of all three CSA-1Vs is performed in the range between -5 mT and 5 mT by subjecting them to a homogeneous magnetic field generated by a Helmholtz coil. Reference measurements are obtained using a digital teslameter Senis 3MH3A [14], which has a resolution of 10 µT and accuracy better than ±0.05% in the range of -100 mT and 100 mT.

To accurately calibrate each CSA-1V and minimize angular errors, it was essential to precisely aligne the MFS-3A and the 3MH3A probe so they sit in parallel in the Helmholtz coil. During the calibration, the output voltage of each CSA-1V was measured by a highly accurate Agilent 34401A voltmeter. Figure 5 shows a photo of the Helmholtz coil used in the calibration procedure.

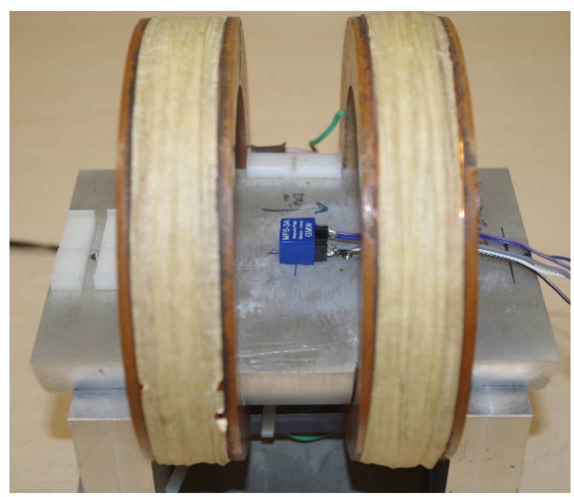

Figure 5. *Helmholtz coil used in the calibration procedure*

Calibration of each axis was performed by taking 12 measurements in the specified range. Additionally, zero flux measurements were recorded by inserting the MFS-3A in the zero gauss tube. Figure 6 shows the accuracy of all three axes relative to the Senis 3MH3A teslameter before calibration in the case when the sensitivity is assumed to be 280 mV/mT.

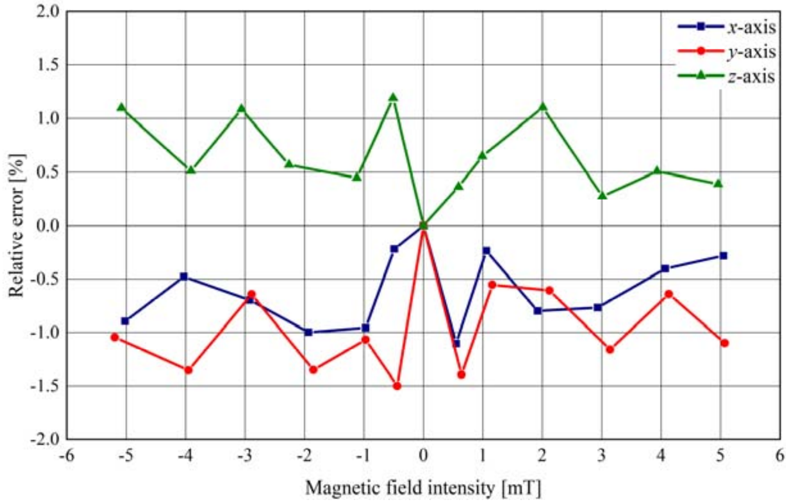

Figure 6. *Measurement results before calibration*

As can be seen from Figure 6, the relative error of obtained measurements is less than ±1.5%, when it is assumed that sensitivities of all three CSA-1Vs are exactly 280 mV/mT.

Exact sensitivities of each CSA-1V are calculated after based on comparative measurements taken by the Senis 3MH3A teslameter and they are 278.2 mV/mT for *x*-axis, 277.3 mV/mT for *y*-axis and 282.2 mV/mT for *z*-axis.

Figure 7 shows the accuracy of all three axes after proper sensitives are inserted in Equation 1, and it is apparent that the relative error is less than ±0.5%, which is quite good considering the fact that the proposed teslameter doesn't employ any linearization technique.

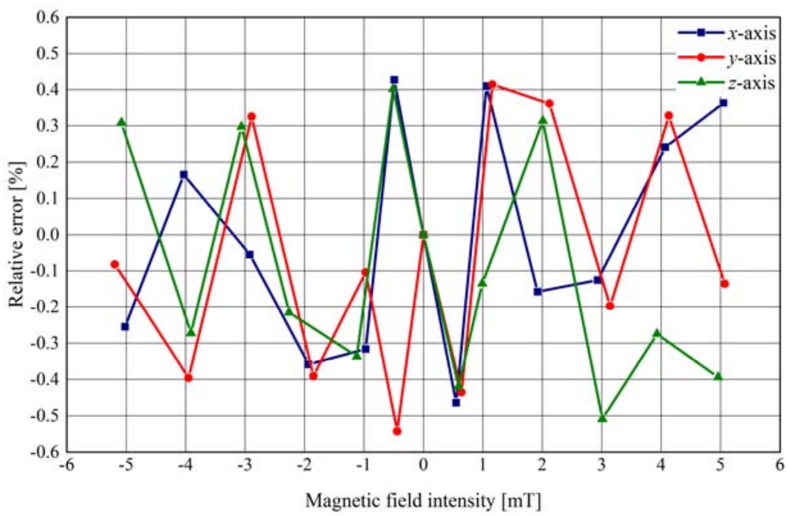

Figure 7. *Measurement results after calibration*

According to the specifications, the CSA-1V has good temperature stability. Magnetic sensitivity temperature drift is better than ±0.02%/°C while offset voltage temperature drift is better than ±0.2 mV/°C. However, magnetic sensitivity temperature drift can be adjusted during a calibration on a brand new CSA-1Vs, hence it is necessary to evaluate this parameter in order to determine whether a temperature compensation should be implemented.

In order to evaluate offset voltage temperature drift, the MFS-3A is inserted in the zero gauss tube and both of them are subjected to temperatures in the range between 25°C and 100°C in the temperature chamber TestEquity Model 115A. Figure 8 shows the results of this experiment for the *x*-axis.

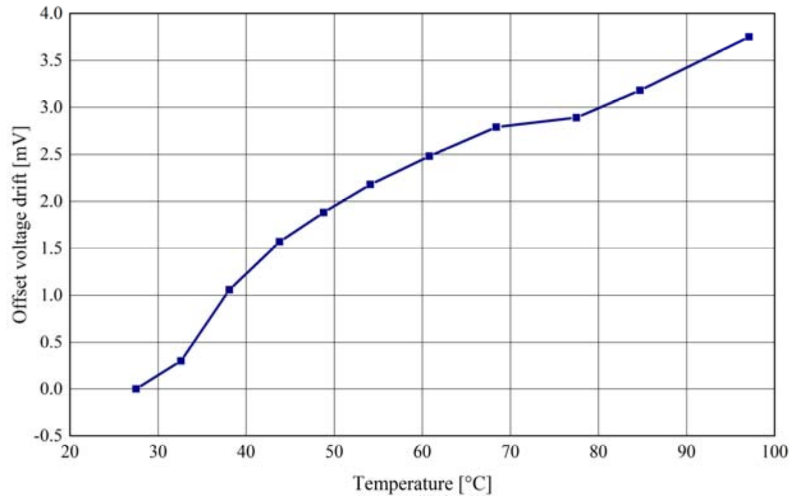

Figure 8. *Offset voltage temperature drift of x-axis*

As can be seen from Figure 8, maximal offset voltage drift is less than 4 mV or 0.06 mV/°C, which is far better than specified ±0.2 mV/°C.

To evaluate sensitivity temperature drift, the MFS-3A is inserted in the Helmholtz coil and both of them are placed in the temperature chamber TestEquity Model 115A where the temperature is gradually increased from 25°C to 100°C while the magnetic field generated by the Helmholtz coil is kept constant. Figure 9 shows the results of this experiment for the *x*-axis.

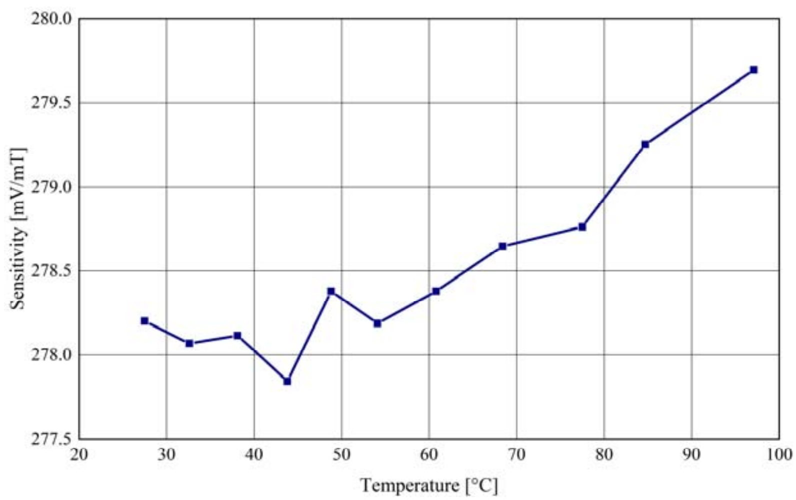

Figure 9. *Sensitivity temperature drift of x-axis*

Based on the results shown in Figure 9, the calculated sensitivity temperature drift is better than 0.01 %/°C, which is two times better than specified.

CONCLUSION

The low-cost teslameter based on the MFS-3A three-axis magnetic field sensor is realized. Measurement range of the proposed teslameter is ±5 mT.

The proposed dosimeter was calibrated using the Helmholtz coil and the state of the art Senis 3MH3A teslameter employed as the reference instrument. During the calibration, it was important to minimize angular errors and this was achieved by carefully paralleling the MFS-3A and 3MH3A probe inside of the Helmholtz coil. After the calibration, the maximal relative measurement error recorded in the entire measurement range was less than ±0.5% compared to the corresponding measurements taken by the Senis 3MH3A teslameter.

Temperature stability of the proposed dosimeter was evaluated in the temperature range between 25°C and 100°C. Temperature stability of offset voltage is better than 0.06 mV/°C and temperature stability of sensitivity is better than 0.01 %/°C. Based on these parameters, it can be concluded that the proposed teslameter has excellent temperature stability.

Due to its simplicity and small sizes, the proposed teslameter can be easily upgraded to be a magnetic field dosimeter that can be easily worn by professional workers in power plant facilities to evaluate dangerous impact of increased magnetic field.

Thanks to its low price, good accuracy and excellent temperature stability, the proposed teslameter represents good alternative to commercially available teslameters with similar properties.

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BIOGRAPHY of the first author

Uglješa Jovanović received the MSc and Ph.D. degrees in electronics from the University of Niš, Faculty of Electronic Engineering in Niš. His research areas are embedded systems, electric current and magnetic field measurement, radiation dosimeters and photovoltaic systems.

He is currently working as a Teaching Assistant at the Faculty of Occupational Safety in Niš, University of Niš.

TESLAMETAR ZA MERENJE MAGNETNOG POLJA U VISOKO NAPONSKIM OBJEKTIMA

Uglješa Jovanović, Dejan Krstić

Rezime: *U radu je predstavljen ekonomičan troosni teslametar namenjen za merenje intenziteta magnetnog polja u industrijskom okruženju i visokonaponskim objektima. Realizovani teslametar je zasnovan na MFS-3A troosnom senzoru magnetnog polja i može meriti gustinu magnetnog fluksa do ±5 mT u sve tri ose, sa tačnošću boljom od ±0.5% i odličnom temperaturnom stabilnošću. Predloženi teslametar je kalibrisan pomoću vrhunskog referentnog instrumenta, Helmholcovog kalema i temperaturne komore. Rad sadrži opis realizacije i kalibracije predloženog dozimetra. Prikazani su i dobijeni rezultati.*

Ključne reči: magnetno polje, teslametar, MFS-3A ,visokonaponska postrojenja, kalibracija.