

GMR Sensors and Neural Networks Applied to the Contactless Measurement of Direct Electrical Currents

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Abstract: Clamp ammeters based on coils are restricted to the measurement of alternating currents, through the associated magnetic field. There are also commercial versions able of measuring direct currents, based on Hall effect sensors. This manuscript presents improvements of a previously presented prototype of a contactless ammeter based on commercial giant magnetoresistance magnetometers, associated with neural networks for signal processing, able to measure direct electrical currents and to infer the distance between the sensor and the electrical current conductor.

Keywords: ammeter, giant magnetoresistance, GMR, neural networks.

1. INTRODUCTION

There are several types of ammeters applicable for measurement of electric currents in conductors, depending on their physical principle and on the need to interrupt the circuit for the current to be measured [1]. The goal of the present development is to perform measurements of direct currents with high resolution, in relation to clamp ammeters based on Hall effect sensors. The system, initially presented in [2-4], is able to also estimate the distance between the sensor and the conductor. The present work enhances the previous prototypes, by replacing the permanent magnet used to polarize the GMR sensors by a solenoid, and by employing artificial neural networks to estimate currents and distances.

Section 2 presents the design of the ammeter and its electronic circuit. Section 3 presents the measurement and processing of experimental data. The inverse problem solution based on neural networks is described in Section 4. At last, Section 5 presents the conclusions.

2. GMR BASED AMMETER

2.1. GMR Sensors

A GMR sensor is characterized by the large variation of its resistance as a function of an external magnetic field [5], typically between 10 and 20%. This project is based on the GMR AA005-02, manufactured by NVE Corporation. The topology of the sensor is a Wheatstone half-bridge, having two magnetically shielded GMRs and two GMRs that are sensitive to the magnetic field, all in the same SOIC integrated circuit.

Without the presence of an external magnetic field the bridge is balanced and the output of the bridge is zero. In the presence of an external magnetic field, the field-sensitive GMRs change their values, unbalancing the bridge and generating a differential voltage output.

The output signal of the bridge is directly proportional to the supply voltage/current, with a typical sensitivity of 0.45 mV/V/Oe and a linear region ranging from 10 Oe to 70 Oe.

2.2. Ammeter Requirements

The goal of the ammeter under development is to measure electric currents in the range of -20 A to 20 A, passing through electrical conductors at close distance, from 1 cm up to 4 cm. An electric current passing through a wire generates a circular magnetic field around it that varies with the intensity of the current and with the distance from the conductor to the measuring point. By applying the Biot-Savart law to a straight conductor it is observed that the magnetic field H , generated is given by

$$H = \frac{I}{500r_1}, \quad (1)$$

where I is the electric current in amperes, r_1 is the distance between the conductor and the sensor in meters and H is the magnetic field in oersteds (1 Oe = 1000/4 π A/m). Considering the values for current and distance above indicated, the maximum magnetic field to be measured by the GMR sensors is 4 Oe. For comparison purposes, the Earth's magnetic field is about 0.5 Oe.

2.3. Ammeter Design

As the GMR sensor behavior around $H = 0$ Oe is highly non-linear, it is necessary to apply a DC biasing magnetic field so that the sensors operate in their linear region. In the previous versions of the ammeter, this biasing field was generated by a permanent magnet, but it was quite difficult to control precisely its value. The present design uses a solenoid with 10 turns and 1.5 A to generate a biasing field of 16 Oe, so as to provide a dynamic range of ± 6 Oe in the linear region with high accuracy and stability.

Also, the use of only one GMR sensor is not sufficient, as it is necessary to know the distance r_1 to estimate the electric current I . Thus, the ammeter is based on two GMR sensors separated by a fixed distance ($D = 3$ cm), in addition to the solenoid above described that generates the biasing magnetic field, as shown in Figure 1.

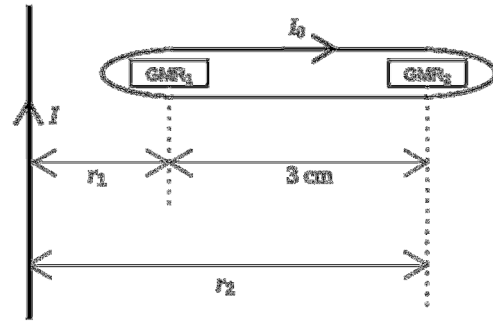


Figure 1. Schematic diagram of the ammeter.

By measuring the voltage generated by both GMR sensors it is possible to estimate the current I and also estimate the distance r_1 between the sensor GMR₁ and the conductor.

2.4. Electronic Circuit

The electronic conditioning and reading circuit shown in Figure 2 was designed and implemented. The electronic circuit has the functions of feeding the GMR sensors with a DC current of approximately 3 mA (current source based on the LM318 operational amplifier), as well as reading the differential output voltage of the bridge and amplifying it by 50 times (instrumentation amplifiers INA129, with gain defined by the 1 k Ω resistor).

The offset voltage level of -5.4 V allows a zero output voltage, V_{out} , to be obtained when $H = 16$ Oe (polarization field). Thus, for a current of 0 A in the wire, there will be an output of 0 V. To minimize the effect of external interferences and improve the ANN performance, a differential reading of the sensors outputs is also made, by the third INA129 indicated in Figure 2.

3. EXPERIMENTAL DATA

To observe the effect of the hysteresis and any other fluctuations, 15 tests with currents varying between -3 A and 3 A were performed, in steps of 0.2 A. The tests were performed with five different distances r_1 , from 1.0 to 2.1 cm, with three repetitions for each distance.

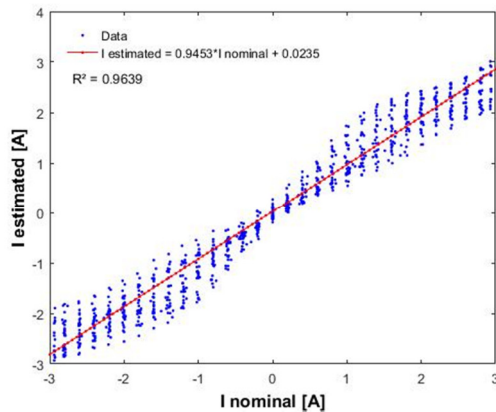


Figure 4. Regression analysis.

4.2. Estimation of Distance

A two-layer feed-forward network, with sigmoidal transfer function in the hidden layer and softmax transfer function in the output layer was created using Matlab's Neural Network Pattern Recognition and Classification Tool. The input variables are the same described in section 3, plus the electric current values, in a total of 3 inputs. However, as the distance can't be estimated when $I = 0$, these values were excluded from the final data set. After that, the new data set was randomly divided into training, validation and testing, respectively 70%, 20% and 10% of the data. The network was trained with scaled conjugate gradient algorithm. Training process automatically stops when generalization stops improving [6]. The tests were performed using 20 neurons in the hidden layer. The ANNs were trained 10 times, and the one with best percent of correctly classified cases was chosen.

Even though this ANN originally performs a classification between 5 measured distances, it is still possible to calculate the error between the actual distances and the classified distances. When using the actual current values as inputs the RMSE for the distance was 0.29 cm and, when using the current values estimated by the first ANN, this RMSE error increases slightly to 0.39 cm.

5. DISCUSSION AND CONCLUSIONS

The prototype described in this paper, as expected, presents a better performance than the one in [3], but it is less accurate than the one in [4]. This behavior can be explained by the inclusion of different distances and the interferences observed in the GMR2 signal.

In future works it is predicted to magnetically isolate the sensor, as well as improve the conditioning circuit, in order to eliminate the offset variations and interferences observed and obtain more consistent data, so as to improve the obtained uncertainty and RMSE.

6. ACKNOWLEDGEMENTS

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