Smart Current Measurement in Modern Power Grids with a Raspberry Pi and GMR Effect-Based Sensor

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***Abstract*—The Giant magnetoresistance (GMR) effect has been presented as a highly viable current measurement alternative in electrical systems due to its low cost, versatility and high precision. This paper shows how the GMR effect can be used in current measurement in smart grids. The study contributes to the construction of a current measurement prototype which works by using the GMR effect. Subsequently, a data storage and processing server is created using a Raspberry Pi. Finally, a graphical interface capable of real-time monitoring of the data acquired by the sensor is designed and implemented. Different tests were carried out successfully, showing not only the viability of the GMR sensor as a current meter, but also the possibility of using other tools as a complement in order to create a product of great utility in intelligent measurement of smart grids.**

***Index Terms*—Current measurement, electrical sensor, GMR effect, harmonic measurement, phasor measurement, smart grids**

I. Introduction

In modern power grids it has become increasingly important to be able to measure electrical variables with lower cost and more accurate instruments [1]. This is since there are different applications for power measurement, particularly in smart grids [2]. For example, smart fault location relies on fair voltage and current measurements, otherwise a bad response means skyrocketing costs for utility companies. For such applications accurateness and response time are highly valuable [2]. In control systems it is also important to have measurements in a short time and in a very precise way, in order to guarantee a better response of the systems.

Nowadays, there are various methods to perform measurements of these signals, which can be classified according to their cost, versatility, operating range, sensitivity, among others. For example, the potential transformer applied to voltage acquisition (VTs) and the Current Transformer (CT), which are perhaps one of the most traditional instruments, have certain disadvantages such as the fact that they only work in AC systems. Therefore, when using a core made of ferromagnetic materials, they are subjected to hysteresis. On the other hand, the optical current transformer emerges as a recent alternative to current measurement, but it is highly expensive [3].

One of the latest alternatives for current measurement is the giant magnetoresistance (GMR) effect. This is a magneto-quantum effect, in which the material decreases its resistance quite noticeably under the application of external magnetic fields [4]. In this way, similar to Hall Effect current sensors, it becomes possible to measure the current passing through a line without the need to open the circuit, by measuring the magnetic field generated by the current in said circuit.

Although the GMR effect has been discovered more than 30 years ago, its use to measure current in electrical systems is still in the early state-of-the-art [3, 5, 6]. The GMR effect used to measure current in electrical systems has numerous advantages over other existing measurement methods. For example, GMR sensors work to measure both AC and DC systems. They have a current operation rate that goes from milliamps to kiloamps and up to MHz for the signal frequency [7]. Compared to other measurement methods, it is quite sensitive and accurate. For these reasons, the aim of this study is to show how the GMR effect can be used to perform high-precision and low-cost measurements in smart grids [8]. To achieve this, it is proposed to build a measurement prototype using the GMR effect, which must be able to perform current measurements in real-time, then store them on a server and finally display the data in a graphical interface [9]. This study was carried out based on a GMR measurement model presented in reference [6].

This paper presents a detailed design of the proposed printed circuit, which contains the GMR sensor for current measurements through the magnetic field. The design also has a DC current source, used to generate a DC magnetic field level on a toroidal solenoid, since the GMR sensor does not distinguish between magnetic field polarizations. Finally, a digital analog converter is used to acquire the signal through an Arduino, and through serial communication the information is stored in the Raspberry Pi. Such low-cost solutions have been also implemented in practical applications for microgrid inverter models [10,

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11]. A Samba application and the Python PYSMB library are used to create a server on the Raspberry Pi. PYSMB is an experimental SMB/CIFS library written in Python. It implements the client-side SMB/CIFS protocol (SMB1 and SMB2) which allows your Python application to access and transfer files to/from SMB/CIFS shared folders as Windows file sharing and Samba folders. Data is sent each second to the graphical interface for visualization and, on the other hand, historical data can be stored. Finally, a graphical interface is created using Python, which receives the data from the Raspberry Pi and displays time-plots. The interface can connect to different devices, phasors, harmonics, power factor active and reactive Power.

II. Legacy Power Measurement Instruments and Advantages of GMR Sensors

To understand the motivation behind the development of techniques such as the GMR effect for current measurement, it is important to start by distinguishing between the different legacy alternatives.

TABLE I: TYPE SIZES FOR CAMERA-READY PAPERS

Type	Cost	Freq	DC Measure	Current
CT	***	0.05-10 KHz	X	1A-100kA
Rogowski	*	0.1-100 MHz	X	0.1-100kA
Shunt	*	kHz-MHz	✓	mA-kA
Optic	*****	3˜00MHz	✓	1A-3kA
Hall effect	**	1˜MHz	✓	10mA-35kA
GMR	*	5˜MHz	✓	1mA-10kA

Table I summarizes the main technologies of current measurement available today. The comparison focuses on cost, frequency, current operating range, among others. In this way, over the existing alternatives, it is possible to show that current measurement using the GMR effect presents the best relationship between versatility, cost, and versatility. However, the literature regarding the use of the GMR effect in power systems is very limited, due to its recent appearance. This opens the doors to research on it.

A. Power Measurement Using the GMR Effect

A common denominator within a large part of current measurement methods is that it is measured indirectly by measuring a magnetic field. This magnetic field can be produced by an AC source, through Faraday's induction, or DC through Ampere's law. Thus, one of the magnetic field response effects is the GMR effect [12, 13]. This is a quantum-mechanical effect, where the resistance of a material is varied by applying a magnetic field. These materials are composed of intercalated thin sheets of different alloys of ferromagnetic materials, with diamagnetic metals [4]. Now, the relationship between magnetic field and current for a line is given by Ampere's law for stationary electric fields:

$$\vec{\nabla} \times \vec{\mathbf{B}} = \mu_0 \vec{\mathbf{J}} \tag{1}$$

where $\vec{\mathbf{J}}$ is the current density, $\vec{\mathbf{B}}$ is the magnetic field vector and μ_0 is the permeability of the free space. In this way, the current on the line generates a rotational magnetic field around the line, which is inversely proportional to the distance from the line.

B. Importance of Harmonic Measurement

Given the high sensitivity in modern power grids to the impact of power electronics, one of the possible uses that can be given to the sensor is the current harmonics measurement [14], particularly for smart grids [15]. Harmonic measurement may be of interest because active power is defined as $|V||I|\cos(\varphi)$. If the current is not only composed of a sinusoidal signal but also has harmonics, then it can be described by a Fourier series as follows:

$$I = \sum a_n e^{i2\pi ft} \tag{2}$$

so that the current amplitude would now be given by:

$$|I|^2 = \sum a_n^2 \tag{3}$$

Therefore, the measurement of the current harmonics can provide a much more accurate measure of the power consumed by the grid elements, since normally only the value of a_0 is considered.

III. Proposed Solution of GMR Effect-Based Sensor

This section presents the main tools used for the construction of the three stages of the study. The first stage consists of the measurement and acquisition of current data through the GMR effect sensor, an instrumentation operational amplifier, an analog-digital converter (ADC) and an Arduino UNO. Subsequently, these data are read with a serial communication by a Raspberry Pi, which performs data processing and stores all the data (as a server). Finally, the data is sent through a TCP protocol to a graphical interface built in Python, which can be operated from any computer, and it is used to monitor the data in real-time.

A. Current Measurement and Data Acquisition Using the GMR Effect

The current measurement is carried out by means of the GMR effect sensor AA002-02E from NVE. This sensor consists of a Wheatstone bridge, in which two of the resistors are GMR resistors, and the other two are 5kΩ resistors, as shown in Fig. 1. GMR resistors vary their resistivity proportional to the magnetic field, which in turn is proportional to the current on the line. The relationship between the sensor output voltage and the GMR resistors is approximately given by:

$$V_{\text{out}} = \frac{\Delta R}{R}\left(V^{+} - V^{-}\right) \tag{4}$$

where R corresponds to the 5kΩ resistors, and ΔR corresponds to the change in resistance in the GMR resistors due to the change in the magnetic field according to [2]. Since the magnetic field is proportional to the current, and the change in resistance is proportional to the magnetic field, the sensor output voltage will be directly proportional to the current on the measured line.

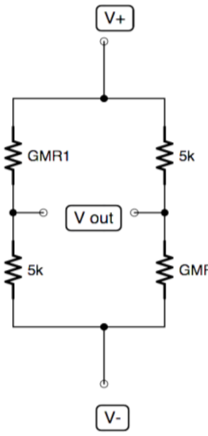

Fig. 1. Wheatstone bridge used to perform the magnetic field measurement.

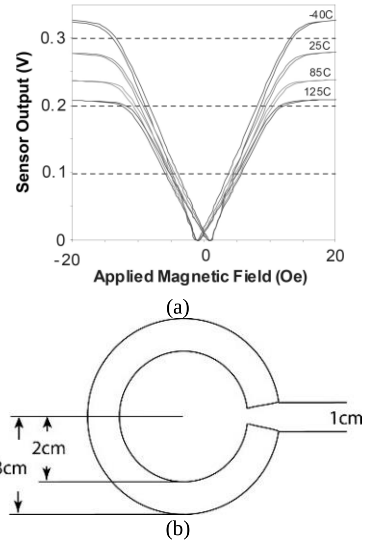

Fig. 2. (a) Relationship between sensor input and output, for a 5V supply. It is observed that the sensor does not distinguish between polarities of the magnetic field. (b) Design of the toroidal solenoid to generate the DC magnetic field.

B. DC Magnetic Field Generation with a Toroidal Structure.

The GMR effect has the property of varying the resistivity of the material, proportionally to the magnitude of the magnetic field. For this reason, the sensor is not capable of distinguishing the direction of the magnetic field, making it only possible to measure the magnitude of the current, but not its direction. For this reason, in order to measure AC currents, it is necessary to add a DC magnetic field to the sensor, so that now the AC magnetic field would oscillate on a DC level and the negative current information would not be lost. The DC level is subsequently removed using signal processing, thus recovering the original signal.

The graph of input versus output of the sensor, taken from the data sheet of the sensor is shown in Fig. 2 (a). To generate the DC magnetic field, a toroidal solenoid is used, with the dimensions shown in Fig. 2 (b).

The winding has approximately 400 turns, which generates a sufficient DC magnetic field to fully recover the AC signal. A current source is built using a Ti OPA552, which feeds the solenoid winding. Using a potentiometer, it is possible to easily vary the current and the magnetic field produced by the solenoid. The core of the solenoid is made of ferrite, which has a low cost, and a fairly high relative magnetic permeability (μr). This core also helps to increase the magnetic field of the sensor and decreases the interference of external magnetic fields [2]. With this setup the magnetic field on the sensor is approximately given by:

$$B \approx \frac{\mu_0 I}{d} \quad (5)$$

where I is the current to be measured and d is the separation shown in Fig. 2 (b).

C. Signal Amplification and Data Acquisition

The sensor used has a sensitivity between 3.2 mV/V/Oe and 4mV/V/Oe, which varies depending on the temperature. This means that, using the relationship shown in Fig. 2 (a), and a 10V supply to the sensor, the reached output is 34mV/A. For this reason, it is necessary to use an instrumentation amplifier, which decreases the noise and increases the output signal according to the gain. In this case, the INA114 amplifier was used. The gain of the amplifier is given by:

$$G = 1 + \frac{50\text{k}\Omega}{R_g} \quad (6)$$

where R_g is the variable resistance as observed in Fig. 3.

In the assembly, a potentiometer is used to modify the gain variable of the circuit. Once the signal is amplified, the analog-digital conversion process is performed using the Adafruit ADS1115 ADC. This ADC has a resolution of 16 bits. Subsequently, the ADC is connected to an Arduino UNO, which is responsible for performing the sampling at a frequency of 128 samples per second. Initially, the Raspberry Pi was used directly to acquire digitized data, but since it runs on an operating system, the sampling intervals were not constant.

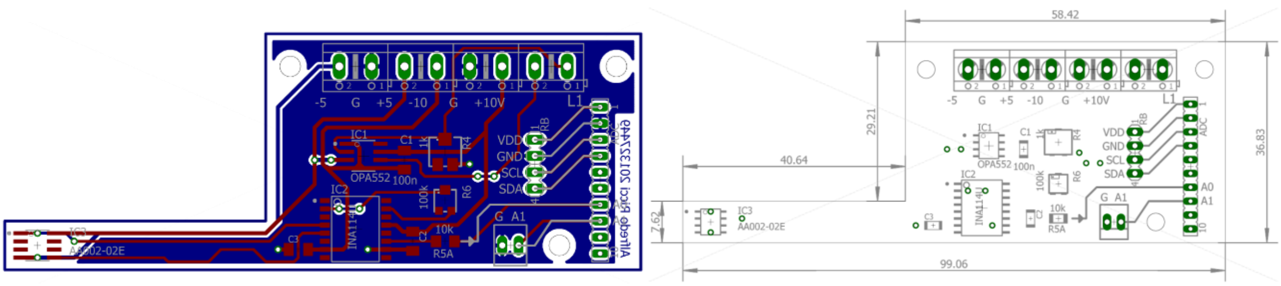

Fig. 3. Design of paths, dimensions, and components of the printed circuit.

D. Current Measurement and Data Acquisition Using the GMR Effect

One of the main advantages a Raspberry Pi is its low cost and high versatility. In this case, the Raspberry Pi is going to be used for two purposes. The first one, is to acquire the serial data produced by the Arduino and process it.

The second, is to use it as a server to be able to remotely access the acquired data. Since there are Raspberry Pi operating systems that run on Linux, it is possible to create executable programs in conventional programming languages such as C/C++ or Python. In this way, a Python program responsible for performing serial data acquisition is created, using the serial library, and creating an instance of type serial.Serial.

The "/dev/ttyACM0" is the serial port used, and 115200 is the baud rate. Once the serial type instance is created, serial readings can be done using the connection.read() command. This reading is done until completing blocks of 128 data, corresponding to 1 second. Once a block of data is complete, an instance of type Thread is created, which is responsible for processing the data in parallel while data is still being taken. Data processing consists of obtaining the magnitude and phase of the fundamental harmonic of the block to be processed, and the magnitude of the subsequent 5 harmonics.

This process is done first, by removing the DC level from the block and then performing a discrete Fourier transform (DFT) on it. The DFT is defined as:

$$X_k = \frac{1}{N}\sum_{n=0}^{N-1} x_n \left[\cos\left(\frac{2\pi kn}{N}\right) - j\sin\left(\frac{2\pi kn}{N}\right)\right] \quad (7)$$

where X_k is the signal in the frequency domain, x_n is the signal in the time-domain, and N = 128 is the block length. Since the aim is to find the amplitude of the first six harmonics, then k = 1, 2, ···, 6. Equation 8 could be written as:

$$X_k = \frac{1}{N}\sum_{n=0}^{N-1} x_n \left[\cos\left(\frac{2\pi kn}{N}\right)\right] - j\frac{1}{N}\sum_{n=0}^{N-1} x_n \left[\sin\left(\frac{2\pi kn}{N}\right)\right] \quad (8)$$

Let define $C_k = \cos(2\pi kn/N)$ as the kth cosine and $S_k = \sin(2\pi kn/N)$ as the kth sine of the previous equation, and x as the data to compute each value of the six harmonics. Equation 9 could now be written as:

$$X_k = \frac{1}{N} xC_k - j\frac{1}{N} xS_k \quad (9)$$

Therefore, to reach higher computational efficiency, the following equation is implemented in the script:

$$X_k = \overline{x \otimes C_k} - j\overline{\otimes S_k} \quad (10)$$

where $a \otimes b$ represents the element-by-element product of the set of values. In this way, it would suffice to compute the average of the product element by element, between the sine and cosine vectors to find the different values of the Fourier transform.

E. Raspberry Pi Configuration as a Server

Once the seven values of each processed block are obtained, these values are stored in two text files. The first consists of a file that only stores the last processed value. This means that in each cycle it is overwritten. This will be the file that the graphical interface will use later.

The second file is a history file which is not overwritten, but the data of the last processed block is added to it in the last row. This is done in order to be able to access said data later. For the last data file, use the command f=open("last_data.txt","w"), where the parameter "w" indicates that the file is going to be overwritten, while for the historical file, use the command, f=open("historico.txt","a"), where the parameter "a" indicates that the data will be added to the last row.

In order to write the data to the file, the f.write() command is used. In order to access these files remotely, the Samba program must be installed on the Raspberry Pi, and a shared folder must be created in which the files are stored. In this way the Raspberry Pi would now be working as a server that can be accessed remotely. The data is stored with the following structure: Date, Voltage, Power factor, Fundamental current, Harmonic 1, Harmonic 2, Harmonic 3, Harmonic 4, and Harmonic 5.

F. Graphical Interface

One of the objectives of the research is to be able to create a monitoring tool suitable for smart grids. It is necessary then, to create a graphical interface that can be run from any computer. Until now, the functional requirements of such interface are the following:

- Show values: The following values: voltage, current, power factor, active power, reactive power and apparent power must be displayed in real time.
- Generate report: It must be possible to generate two types of report. The first type of report is built on existing data, stored in the history file. The second type of report is built from new data.
- Connect device: The interface must allow the user to connect to the device on which data is being collected.
- Start acquisition once connected to a device, you must be able to start data acquisition so that it starts to be displayed on the interface.
- Real-time power graph: the interface must show both active and reactive power and its history in real time on a graph.
- Power factor graph in real time: It must be possible to show the power factor and its history in a graph.
- Real-time power phasor plot: You must be able to display the power phasor on a real-time polar plot.
- Harmonics graph: Finally, the interface must graphically show the harmonics in real time.

In order to meet these requirements, the interface must access the shared folder of the Raspberry Pi, where both the latest data and the history file are stored. Once in the folder, you must generate a temporary copy of the historical file on the computer, read said file and carry out the necessary operations to display and graph the values. To create the connection to the shared folder, the Python pysmb library is used. This library is used to send and receive data using the TCP protocol.

IV. Tests, Results and Performance of the Prototype

After completing the assembly of the prototype, the server and the interface were successfully carried out in different tests. Initially, a calibration test was carried out, where a sweep from 40mA to 400mA was done, to obtain the relationship between the value of the current and the digital voltage that comes out from the digital analog/converter. Subsequently, triangular, and square signals were injected into the system to note the consistency of the harmonics. The operation of the interface and the server are also shown. In Fig. 4. As well as the interface in Fig. 5.

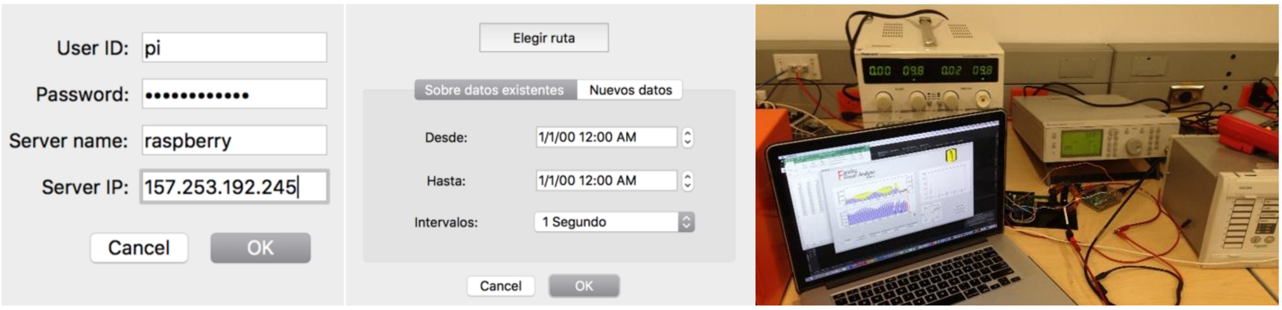

Fig. 4. Log-in interface, historical data request interface and full assembly of the proposed prototype

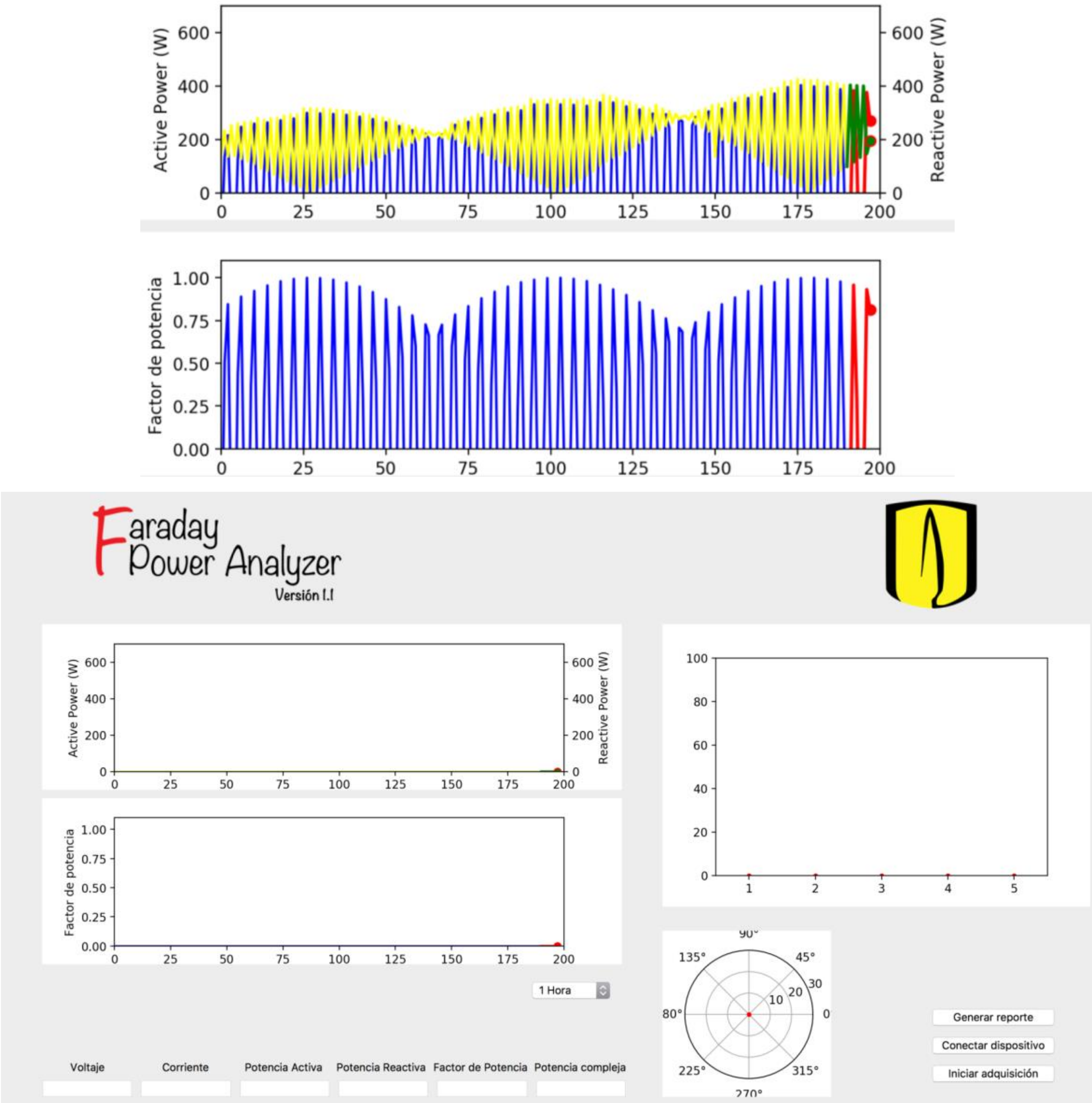

Fig. 5. Graphical interface and operation of the power and power factor graphs.

A. Sensor Calibration

The data obtained is presented in Fig. 6. The data taken had a duration of 10 seconds. In other words, the measurement was carried out on 10 data blocks. An average uncertainty of 2.48% in the data is shown. The relationship found between digital current, and voltage is given by a line defined as:

$$V_d = 1.02 \times 10^3 I + 2.68 \times 10^{-1} \tag{11}$$

where the current I (A), shows not only a great precision due to low uncertainty but also high accuracy due to almost inexistent zero shift.

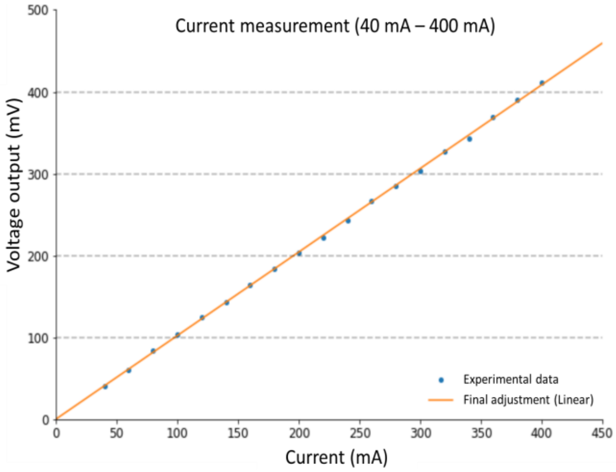

Fig. 6. Calibration data between 40mA and 400mA.

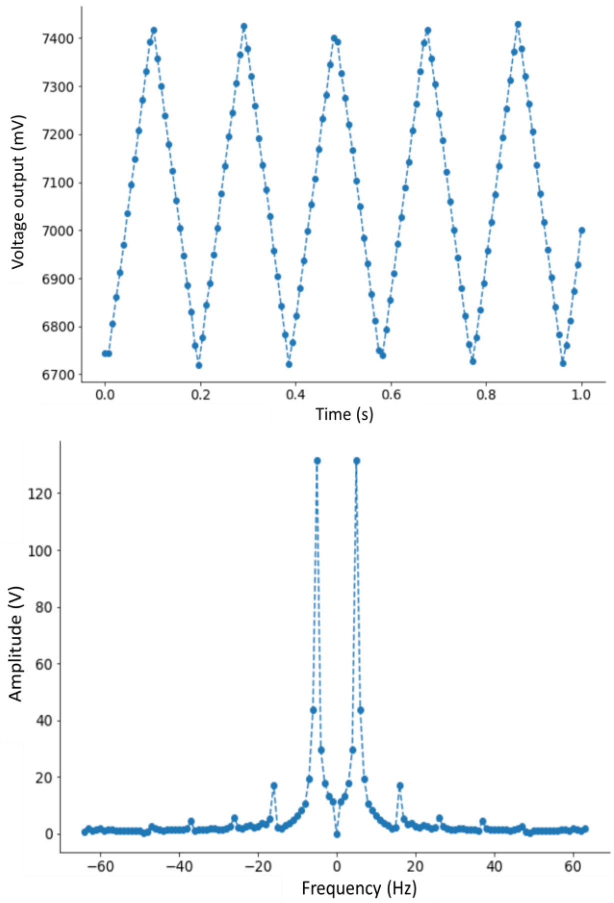

Fig. 7. Measures and spectrum of the triangular test signal.

B. Input Test Signals: Triangular and Square Currents

A test is performed by injecting a triangular signal of 400mA peak-peak and the signal obtained by the system is observed. An FFT of it is also performed in order to analyze the frequency spectrum. The results are shown in Fig. 7. The possibility of measuring harmonics in the current using the sensor is now tested. For this, the current is injected using a sine signal, a saw signal and a square signal. The results are shown in Fig. 8. Note that for a sinusoidal signal, there is no harmonic stands out particularly. The values shown in the graph basically correspond to noise. Now, when generating a triangular signal, it is observed how the first three harmonics stand out.

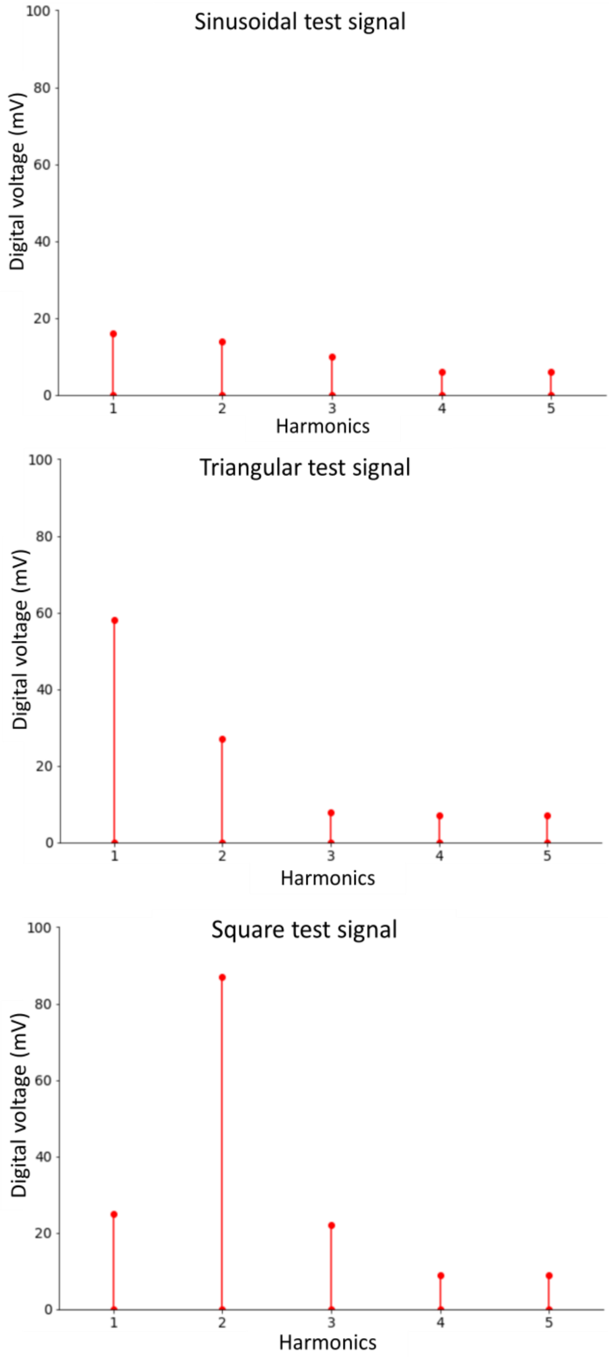

Fig. 8. Harmonic response for test signals.

This is because the expansion of a Fourier series saw signal is given by:

$$f(x)=\frac{1}{2}-\frac{1}{\pi}\sum_{i=1}^{\infty}\frac{1}{n}\sin\left(\frac{n\pi x}{T}\right) \tag{12}$$

so that both even and odd harmonics survive and decay as 1/*n*, as shown in the graph. When injecting a square signal, it is observed in Fig. 7 that the second harmonic stands out strongly. This is because the Fourier series expansion of a square signal is given by:

$$f(x)=\frac{4}{\pi}\sum_{i=1}^{\infty}\frac{1}{n}\sin\left(\frac{n\pi x}{T}\right) \tag{13}$$

so that only odd *n* values survive. Since the fundamental signal is being taken as the zero harmonic, in this case the even harmonics remain. Results have shown how the GMR effect can be used to make measurements in smart grids. A prototype capable of measuring currents from milliamps up to 10 Amps was designed for a 5Hz signal. Also using a Rapsberry Pi, a digital signal processing system was built which took blocks of 1 second, and the current phasor and the amplitude of the first five harmonics of the current signal were obtained. In addition to this, the Raspberry Pi also functioned as a server where, on the one hand, the data obtained by the sensor is stored, and on the other hand, these data are communicated with a client.

To show the correct functioning of the system, different tests are made. The first consists of sweeping the current, from 40mA to 400mA, taking data every 5mA. In this test, a linear relationship was found as expected with an average uncertainty of 2.48%. It should be noted that it is expected to carry out applications where the measured current is greater than 1A, so that the measured values are at the noise level, showing the high precision with which, the measurement was achieved. Subsequently, a harmonic generation test was carried out.

Different sine, saw and square signals were injected into it and the harmonic values were obtained, showing the possible use of the GMR effect in harmonic measurement. All these tests were performed from the interface, connected remotely.

V. Conclusion

The versatility shown by the system shows that there are several applications for the built prototype. For example, it can be implemented in three-phase systems and used for fault detection. The system can also be used for smart metering whether in the residential, commercial, or industrial sector. Also in the industrial sector it can be used together with the interface as a monitoring system. Since the system is used for measurements in AC and DC systems, with a wide range of operating frequency and current, its use in smart grids and microgrids can be a great alternative.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

A. Ricci and D. Celeita conducted the research, the sensor implementation, test, and validation of the proposed solution; A. Ricci analyzed the data collected through the raspberry pi; A. Ricci and D. Celeita wrote the manuscript; G. Ramos advised the project and wrote some parts of the introduction; all authors had approved the final version.

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References

[1] R. Moghe, F. Lambert, and D. Divan, “A novel low-cost smart current sensor for utility conductors,” *IEEE Trans. on Smart Grid*, vol. 3, no. 2, pp. 653-663, June 2012.

[2] A. Abdukhakimov, S. Bhardwaj, G. Gashema, and D. S. Kim, “Reliability analysis in smart grid networks considering distributed energy resources and storage devices,” *International Journal of Electrical and Electronic Engineering & Telecommunications*, vol. 8, no. 5, pp. 233-237, September 2019.

[3] Z. Wang, J. Hu, Y. Ouyang, *et al*., “A self-sustained current sensor for smart grid application,” *IEEE Trans. on Industrial Electronics*, vol. 68, no. 12, pp. 12810-12820, Dec. 2021.

[4] J. Han, J. Hu, Y. Yang, Z. Wang, S. X. Wang, and J. He, “A nonintrusive power supply design for self-powered sensor networks in the smart grid by scavenging energy from AC power line,” *IEEE Trans. on Industrial Electronics*, vol. 62, no. 7, pp. 4398-4407, July 2015.

[5] P. Shrawane and T. S. Sidhu, “Performance evaluation of GMR and TMR sensors to estimate current phasors in smart grids,” in *Proc. of 2020 IEEE Electric Power and Energy Conf.*, 2020, doi: 10.1109/EPEC48502.2020.9320111.

[6] J. Hu, G. Zhao, T. Cheng, S. Gao, L. Zhang, and L. Wang, “A wide range transient current sensor based on GMR effect for smart grid applications,” in *Proc. of 2020 IEEE Int. Conf. on High Voltage Engineering and Applications*, 2020, doi: 10.1109/ICHVE49031.2020.9279571.

[7] M. N. Baibich, J. M. Broto, A. Fert, *et al.*, “Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices,” *Phys. Rev. Lett*., vol. 61, no. 21, pp. 2472–2475, 1988.

[8] Z. Liu, P. Li, B. Tian, *et al.*, “Current and voltage measurement method based on magnetic and electric field sensors for smart grid applications,” in *Proc. of 2020 IEEE 4th Conf. on Energy Internet and Energy System Integration*, 2020, pp. 2783-2786.

[9] Y. Ouyang, J. He, J. Hu, and S. X. Wang, “A current sensor based on the giant magnetoresistance effect: design and potential smart grid applications,” *Sensors (Basel)*, vol. 12, no. 11, pp. 15520-15541, Nov. 2012.

[10] P. Pai, L. Chen, F. K. Chowdhury, and M. Tabib-Azar, “Non-intrusive electric power sensors for smart grid,” in *Proc. IEEE Sensors Proc.*, 2012, doi: 10.1109/ICSENS.2012.6411383.

[11] I. Chowdhury, S. Hossain, N. K. Das, T. Ahmed, and M. M. Hasan, “Arduino-based three-phase inverter using power MOSFET for application in microgrid systems,” *International Journal of Electrical and Electronic Engineering & Telecommunications*, vol. 10, no. 6, pp. 416-424, Nov. 2021.

[12] M. Sheng, M. H. Alvi, and R. D. Lorenz, “GMR-based integrated current sensing in SiC power modules with phase shift error reduction,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 3, pp. 3477-3487, June 2022.

[13] T. J. Brauhn, M. Sheng, B. A. Dow, H. Nogawa, and R. D. Lorenz, “Module-integrated GMR-based current sensing for closed-loop control of a motor drive,” *IEEE Trans. on Industry Applications*, vol. 53, no. 1, pp. 222-231, 2017.

[14] C. Baruah and D. Chanda, “A comparative study of wavelet transform techinque and SVD in the estimation of power system harmonics and interharmonics,” *International Journal of Electrical and Electronic Engineering & Telecommunications*, vol.

3, no. 4, pp. 22-29, Oct. 2014.
[15] Y. Ouyang, Z. Wang, G. Zhao, *et al.*, "Current sensors based on GMR effect for smart grid applications," *Sensors and Actuators A: Physical*, vol. 294, pp. 8-16, Aug. 2019.

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