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Active power analog front-end based on a Wheatstone-type magnetoresistive sensor

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ABSTRACT

In the proposed work a practical magnetoresistive wattmeter based on a commercial sensor is designed to measure active power at industrial frequencies. The electronic conditioning circuit uses differential blocks in order to preserve the sensor initial common mode rejection ratio. A 700 W power level has been reached with an uncertainty less than 1%. With few changes the proposed circuitry could be used in metering applications.

1. Introduction

In the digital era analog signal processing seems to be a rarely or obsolete electronic function. But in situations where the complexity is not a requirement or in high-speed systems the use of analog processors is a valuable solution in comparison with the cost and complexity that analog-to-digital and digital-to-analog converters offer. This is the case of analog multipliers, a classical processing function implemented in integrated building blocks that it continues generating important revenues [1]. In industrial or domestic applications the ac-power measurement is of great importance for metering purposes. Integrated analog multipliers have been used to design electronic conditioning circuits, a great number of them to process non-linear relationships [2,3]. In the sensors and instrumentation field the Wheatstone bridge is an electrical topology that allows a simple and easy way to process using an analog technique the product of two signals. Magnetic field magnetoresistive (MR) sensors have been designed in a Wheatstone type configuration and an important part of them used as current sensors measuring the magnetic field generated by this electrical signal. MR sensors offer an interesting alternative as analog multipliers in applications where processing requirements need compact and not complex solutions.

Different efforts have been dedicated to process with a MR sensor the product of the instantaneous voltage and current referred to a load. An experimental set-up was developed in [4] to measure active power in the order of various tenths of milliwatts requiring, at the same time, additional circuitry to satisfy the flipping coil requirements. MR watt-converters have been well developed and analysed using not-Wheatstone type MR topologies, [5,6]. Interesting results in power levels and frequency values of the processing signals were given using non-commercial MR sensors. Others types of watt-converters have been developed using a conversion to frequency, [7,8]. This technique required matched voltage-to-frequency converters and the use of ferrite cores to provide current signal isolation.

Various limitations are related to previous non-MR power measurement methods. Resistive current shunts have ohmic losses. Hall-based wattmeters need high permeability materials like ferrites, due to the low sensitivity of the Hall current sensors used. Therefore heat, high volume and weight are obtained using these technologies [3,9].

2. Active power magnetoresistive measurement method

A magnetoresistive sensor is constituted by four magnetoresistances connected in a Wheatstone bridge electrical association. Each resistance changes its value according to the surrounding magnetic field. If an electrical current I generates this magnetic field, the magnetoresistive sensor output will be proportional to the current instantaneous value. The differential output voltage of the Wheatstone bridge (Fig. 1) states that this circuit topology acts

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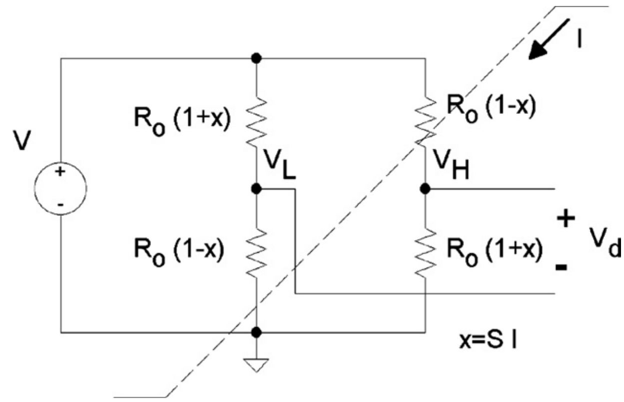

Fig. 1. Differential output voltage of the Wheatstone-type magnetoresistive current sensor.

as an analog multiplier with respect to the power supply V and the measurand x related to the current I.

The proportionality constant of this product is the magnetoresistive sensor sensitivity S. All these relationships are given by Eq. (1).

$$v_d = v_H - v_L = \frac{V}{2}\cdot(1+x) - \frac{V}{2}\cdot(1-x) = S\cdot V\cdot I \tag{1}$$

If the voltage–current pair of Eq. (1) came from a fraction of certain AC-mains voltage $v_{ac}(t)$ and its associated current $i(t)$ delivered to a load then the output of the sensor will contain information related to the instantaneous power processed by the load (Fig. 2).

Considering that a Wheatstone sensor will have a residual output offset voltage V_{off} Eq. (1) could be expressed by

$$v_d(t) = v(t)\cdot[\bar{S}\cdot i(t) + \bar{V}_{off}] \tag{2}$$

where $\bar{S}$ and $\bar{V}_{off}$ are the normalized values of the sensitivity and offset output voltage of the magnetoresistive sensor, $[\bar{V}_{off}] = V/V_{sup}$, $[\bar{S}] = mV/(A\cdot V_{sup})$. Taking into account a power delivered by an ac-mains both voltage and current will be harmonic signals of the type:

$$v_{ac}(t) = V_m\cdot\sin(\omega\cdot t) \tag{3}$$

$$i(t) = I_m\cdot\sin(\omega\cdot t+\varphi) \tag{4}$$

being V_m and I_m the voltage and current amplitudes of the voltage and current line signals respectively and φ the phase-shift between both. With the above two expressions and considering Eq. (2), the differential output voltage of the magnetoresistive sensor will be:

$$\begin{aligned} v_d(t) &= A\cdot v_{ac}(t)\cdot[\bar{S}\cdot i(t)+\bar{V}_{off}] = A\cdot V_m \\ &\cdot\sin(\omega\cdot t)\cdot[\bar{S}\cdot I_m\cdot\sin(\omega\cdot t+\varphi)+\bar{V}_{off}] = A\cdot\bar{S}\cdot I_m\cdot V_m \\ &\cdot\sin(\omega\cdot t)\cdot\sin(\omega\cdot t+\varphi) + A\cdot\bar{V}_{off}V_m\cdot\sin(\omega\cdot t) \end{aligned} \tag{5}$$

Considering the trigonometric formula

$$\sin(\omega\cdot t)\cdot\sin(\omega\cdot t+\varphi) = \frac{\cos\varphi - \cos(2\cdot w\cdot t+\varphi)}{2}$$

Eq. (5) gives to

$$\begin{aligned} v_d(t) &= \frac{A\cdot\bar{S}\cdot I_m\cdot V_m}{2}\cdot\cos\,\varphi - \frac{A\cdot\bar{S}\cdot I_m\cdot V_m}{2} \\ &\cdot\cos(2\cdot\omega\cdot t+\varphi) + A\cdot\bar{V}_{off}V_m\cdot\sin(\omega\cdot t) \end{aligned} \tag{6}$$

Therefore, the sensor output voltage $v_d(t)$ contains one term that it is constant with respect to w and two harmonics depending on w and $2w$. The constant term in w is related to the active power delivered to the load while the others two could be effectively filtered by a proper filter design. In this way, a cut-off frequency of $w/10$ will be enough to reach a 1% dynamic error of the low-pass filtering action [10]. On the other hand the common-mode voltage present at the output of the differential low-pass filter will be done by the expression

$$v_{oC}(t) = 4.07\,\text{V}\cdot\sin(\omega\cdot t) - 50.4\,\mu\text{V}\cdot\cos(2\cdot\omega\cdot t+\varphi) \tag{7}$$

The w component is dominant in amplitude but at line frequency this amplitude is low enough to be rejected by a standard instrumentation amplifier (IA). The absolute error at the output of the IA (single-ended voltage v_o) will be done by

$$e_{v_o} = \frac{A_{dm}}{CMRR_{IA}}\cdot v_{oC} \tag{8}$$

with A_{dm} and $CMRR_{IA}$ the differential gain and the common-mode rejection ratio of the IA respectively.

A detailed analysis is included in an appendix at the end of the paper showing that the common-mode voltage will not influence the projected measurements.

3. Experimental measurement set-up

The experimental measurement set-up is shown in Fig. 3. Between the ac-line source $v_{ac}(t)$ and the load, a reference wattmeter was placed to measure the actual power delivered to the load. In order to have information related to the active power, the magnetoresistive sensor needs to process electrical signals involving the ac-mains voltage $v_{ac}(t)$ and the current through the load

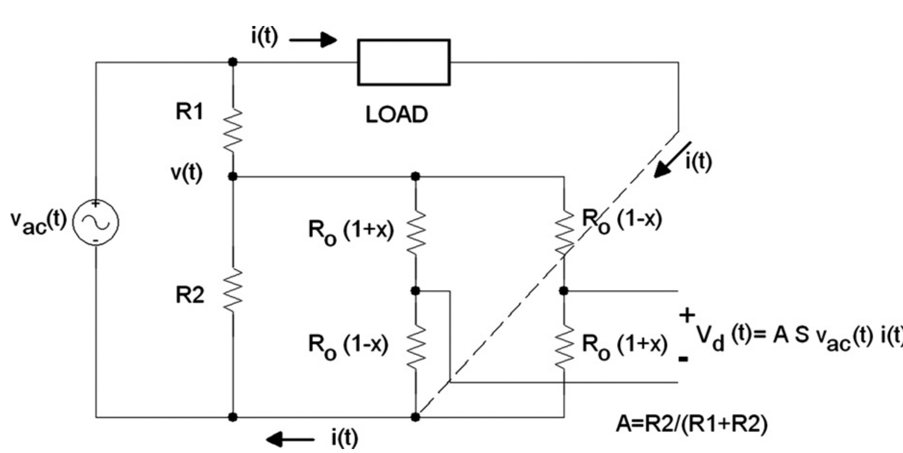

Fig. 2. Principle of power measurement with a Wheatstone-type magnetoresistive current sensor.