LOW-COST CURRENT TRANSDUCER BASED ON CIRCULAR ARRAY OF MAGNETIC SENSORS

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Abstract – *A Low-cost current transducer based on circular array of magnetic sensors is proposed as a valid alternative to traditional current transformers for high-current industrial applications in poly-phase systems of conductors. Since the accuracy of a circular array can be limited by the effects of magnetic fields of nearby phases and by those of eddy currents in the conductors, a new method for the compensation of those effects is proposed in an analytical formulation and is experimentally investigated.*

Keywords – Magnetic sensors, sensor arrays, current measurement.

1. INTRODUCTION

The concept of circular arrays of magnetic sensors as current transducers have been already proposed in literature by [1] and [2], even if the cross-talk effects due to the magnetic fields of other current conductors that are near the current under measurement and the effects related to eddy currents have not been widely investigated. Since those effects are relevant in many industrial ac current sensing applications, a new method for their compensation is proposed. The paper is aimed at demonstrating that, thanks to this method, circular arrays of magnetic sensors can efficiently substitute traditional protective current transducers, at lower costs and with wider measuring range in amplitude and frequency.

In particular, a circular array has been applied for current measurement in a three-phase bus-bar system. First the new method for cross-talk effect compensation based on the orientation of the array has been analytically formulated (section 2). Then an array encircling a bus-bar has been experimentally calibrated at 50 Hz (section 3) and it has been metrologically characterized in a 50-500 Hz range (section 4). Finally the new method has been experimentally validated (section 4).

2. ANALYTICAL BACKGROUND

Let us consider a circular array of magnetic sensors and a current to be measured flowing in a bus-bar placed at array center (fig. 1). The sum of magnetic sensors signals is proportional to a discretization of the Ampère's circulation and so realizes the measurement of the encircled current *i(t)*, being:

$$i(t) = \oint \vec{H} \cdot dl \qquad (1)$$

$$\oint \vec{H} \cdot dl \cong d\,\frac{2\pi}{N}\sum_{n=1}^{N}\frac{v_n(t)}{S} \qquad (2)$$

where N is the number of the sensors, S is their sensitivity (equal for all sensors), d is the radius of the array and $v_n(t)$ is the output voltage signal of the n^{th} sensor.

If eq. (2) were not an approximation, then the measurement accuracy of the array would not be affected by cross-talk field effects that may be originated by current conductors near the current under measurement. But this is not the case and so cross-talk field rejection properties of circular arrays must be investigated.

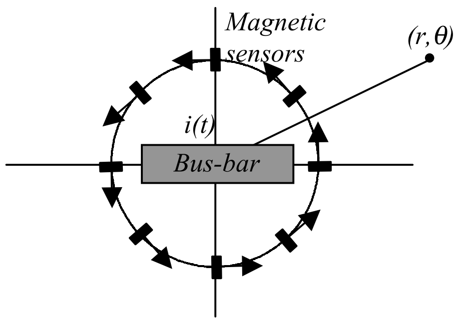

Fig.1 – A circular array of N=8 magnetic sensors and a bus-bar current under measurement. Arrows indicate the sensitivity direction of the sensors.

Obviously the higher is the number of sensors composing the array the better is the rejection of cross-talk field effect, since the right side of eq. (2) approximates better the left side. On the other hand if low costs are required, then a small number of sensors is mandatory.

In order to reduce the number of sensors, in [3] and [4] the authors have proposed algorithms for improving cross-talk error rejection by processing sensor data. Here we propose a useful property of circular arrays that holds for given symmetries of the system of conductors and provides a sufficient cross-talk error compensation with a small number of sensors.

Let us consider a circular array of radius d with N sensors that are at equidistant angular positions $\theta_n = 2\pi n/N + \theta_0$, n=1, …, N, with θ_0 indicating the orientation of the array, and a polar coordinate system (r,θ) centered in the array. In many applications the cross-talk field is generated by a density current distribution that is symmetric with respect to the axis $\theta = 0$; then the corresponding magnetic scalar potential of the cross-talk field can be expressed in M cylindrical harmonics with coefficients b_m [5]:

$$\Psi_{cross-talk}(r,\theta,t) = \sum_{m=1}^{M} b_m(t) r^m sin(m\theta) \qquad (3)$$

Equation (3) implies that the tangential component of the cross-talk magnetic field over the circular array of radius d has only cosinusoidal components:

$$\left(H_{cross-talk}(d,\theta,t)\right)_\theta = -\frac{1}{d}\frac{\partial \Psi}{\partial \theta} - = $$
$$= -\sum_{m=1}^{M} m b_m(t) d^{m-1} \cos m\theta \qquad (4)$$

and also that the output signals $v_n^{cross-talk}(t)$ of the N sensors are:

$$v_n^{cross-talk}(t) = -S\sum_{m=1}^{M} m b_m(t) d^{m-1} \cos m\theta_n$$
$$n=1, \ldots, N \qquad (5)$$

From eq. (5) a useful property can be derived that states:

$$\frac{1}{N}\sum_{n=1}^{N} v_n^{cross-talk} \cong -SNd^N b_N \cos N\theta_0 \quad \text{if } N \le M$$
$$=0 \text{ otherwise} \qquad (6)$$

Eq. (6) says that rotating the array at values of θ_0 that are multiple of $\pi/2N$ the contribution of the external field to measurement error becomes zero. This property can be usefully applied in many poly-phase systems. As an example it has been applied for current sensing in a three-phase bus-bar system, typical of low-voltage protection circuit-breakers (Fig. 2), designed for rated current I_n=3200 A. Thanks to property (6) four sensors per-phase are enough for cross-talk error rejection rotating the arrays at $\theta_0 = \pi/8$.

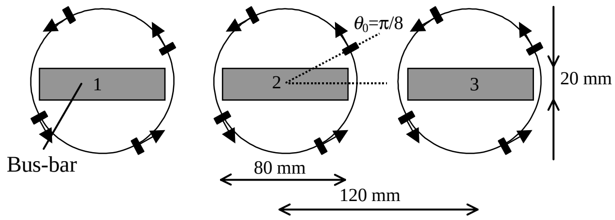

Fig. 2 – Properly rotated four sensor arrays in a three-phase bus-bar system

3. EXPERIMENTAL PROTOTYPE CALIBRATION

Each circular array has been realised by mounting four Toshiba Hall sensors (GaAs ion implanted planar type, THS126, whose cost is approximately 1 \$) with nominal sensitivity 1.5 V/T on a printed circuit board. The sensors are tangentially directed and placed at equidistant angular positions on a circumference of 48 mm radius. In order to allow the rotation of the array around the bus-bar, the board was fixed on a special support.

Signal conditioning were provided by adjustable gain differential amplifiers. The front-end circuitry made it possible to manually adjust both the gain and the offset of each channel (sensor and amplifier). The gain adjustment procedure for each channel was indeed an equalization: rotating the board, every sensor was placed in the same position with respect to the bus-bar; then the ratio between the amplifier signal output and the reference current was equalized. During this phase the other conductors have been placed far enough in order not to introduce cross-talk effects.

After the equalization procedure, the whole array was calibrated for two different orientations, at θ_0=0 and at θ_0=π/8, at 50Hz. As a matter of fact experimental testing was aimed at validating the better efficiency of the orientation of $\theta_0 = \pi/8$ than that of another orientation, for example of θ_0=0.

For calibrating the array at 50 Hz in the two different orientations, the following procedure has been applied. Indicating with $\widetilde{W}$ the sum of the output signals phasors $\widetilde{V}_n$:

$$\widetilde{W} = \sum_{n=1}^{4} \widetilde{V}_n \qquad (7)$$

due to the linearity of magnetic sensors, the measurement model can be expressed in phasorial version by the equation:

$$\widetilde{W} = \widetilde{G} \cdot \widetilde{I}\ , \qquad (8)$$

where $\widetilde{I}$ is the current phasor, and $\widetilde{G}$ is a complex calibration coefficient of the overall measurement system.

In order to estimate $\widetilde{G}$, six measurements $\widetilde{W}_k$ of the analog sum of the sensor signals (FFT of 1024 samples acquired by a 12 bit @12.8 ksample/sec data acquisition system) have been performed for six different values $\tilde{I}_k$ of currents. Then a least squares estimation of $\tilde{G}$ has been calculated, starting from the linear system:

$$\begin{bmatrix} W_1^{re} \\ W_1^{im} \\ \vdots \\ \vdots \end{bmatrix} = \begin{bmatrix} I_1^{re} & -I_1^{im} \\ I_1^{im} & I_1^{re} \\ \vdots & \vdots \\ \vdots & \vdots \end{bmatrix} \begin{bmatrix} G^{re} \\ G^{im} \end{bmatrix} \qquad (9)$$

where *re* and *im* indexes indicate real and imaginary components of the phasors, obtaining $\tilde{G}$= 2.1385·10^{-4}-i4.8696·10^{-6} [VA^{-1}] for the orientation of θ_0=0 and $\tilde{G}$=1.9128·10^{-4}-i8.2927·10^{-6} [VA^{-1}] for the orientation of $\theta_0 = \pi/8$.

3. EXPERIMENTAL RESULTS

In the following we will call *current error* the quantity defined as

$$e_c = 100 \cdot (I_{meas} - I_{ref}) / I_n \qquad (10)$$

where I_{meas} and I_{ref} are the r.m.s. values of the measured and reference currents; and we will call *phase error* the phase difference between the phasors of the measured and reference currents.

Once the array has been calibrated at 50 Hz, current and phase errors at higher frequencies have been investigated. Those errors are due to the frequency dependence of the skin effect that takes place in the conductor and the consequent dependence of the magnetic field in the proximity of the bars. The errors are plotted in figures 3-4 for the orientation of $\pi/8$. Ten repeated measurements have been performed and the corresponding type A standard uncertainty is reported for each value. Uncertainty at 50 Hz is higher than those estimated at the other frequencies due to environmental interference effects.

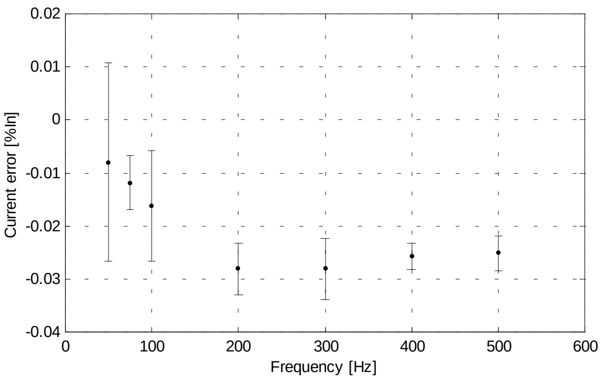

Fig.3 – Current error vs. frequency with uncertainty bars

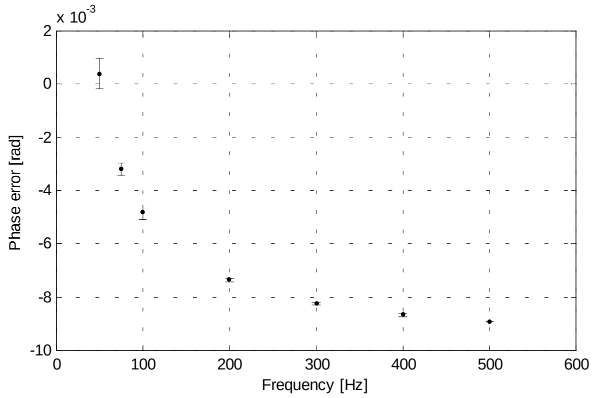

Fig. 4 –Phase error vs. frequency with uncertainty bars

The effects of a bus-bar carrying a return path-current for the two orientation of the array at θ_0=0 and θ_0=π/8 have been first investigated and compared at different frequencies and at different current amplitudes. The experimental set-up is described in figure 5.

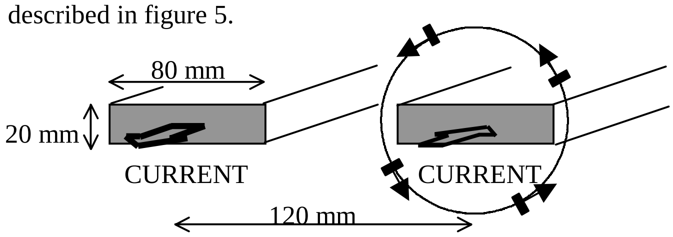

Fig. 5 –Experimental set-up

Current and phase errors vs. current r.m.s. value are reported in fig. 6-7. As it can be noted in particular by fig. 6 the orientation of $\pi/8$ is much more efficient for cross-talk rejection, as predicted by eq. (6). Repeated measurements have been performed only for the orientation of $\pi/8$ for its better characterization.

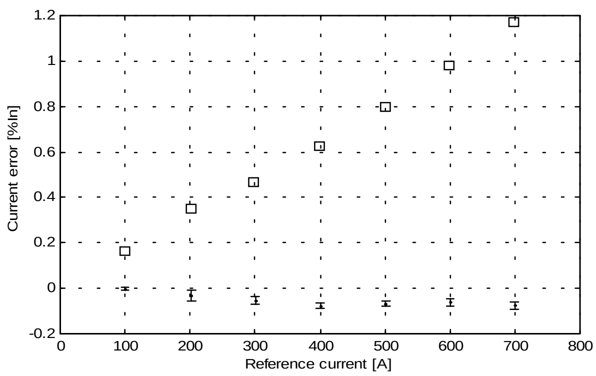

Fig. 6 –Current error vs. reference current r.m.s. value (squares correspond to the orientation of θ_0=0 *rad* while points with uncertainty bars correspond to the orientation of θ_0=π/8)

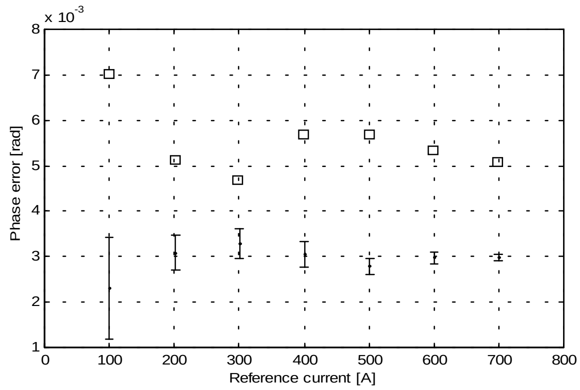

Fig. 7 – Phase error vs. reference current (squares correspond to the orientation of $\theta_0=0$ *rad* while points with uncertainty bars correspond to the orientation of $\theta_0=\pi/8$)

Errors vs. frequency are plotted in fig. 8-9 at the same current amplitude (200 A r.m.s.). Accuracy specifications for protective current transformers (1% accuracy class) are fulfilled in the bandwidth 50-500 Hz [6].

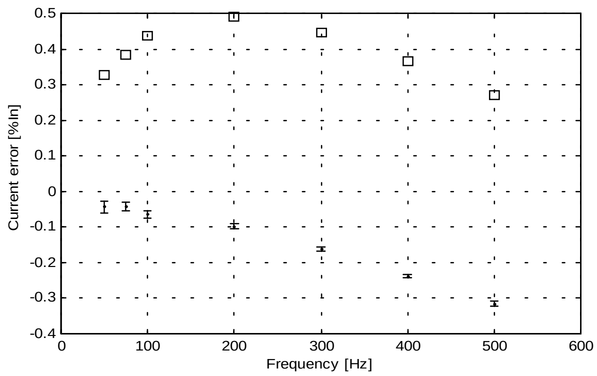

Fig. 8 – Current error vs. frequency (squares correspond to the orientation of $\theta_0=0$ while points with uncertainty bars correspond to the orientation of $\theta_0=\pi/8$)

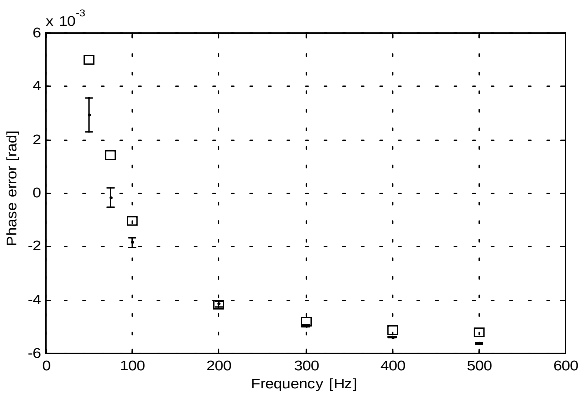

Fig. 9 – Phase error vs. frequency (squares correspond to the orientation of $\theta_0=0$ while points with uncertainty bars correspond to the orientation of $\theta_0=\pi/8$)

The method has been tested also at currents up to 6 kA at 50 Hz feeding the three bus-bars by a three-phase balanced current system. An array oriented at $\theta_0=\pi/8$ has been mounted on phases 2.

Reference current measurement has been provided by a coaxial anti-inductive shunt. The output signals of the shunt has been sent to a 12 bit data acquisition system through a differential channel. Current measurement standard uncertainty has been estimated 0.3% I_n.

The output signal of the circular array has been acquired by the same data acquisition system through a differential channel. Measurement have been made by processing 1024 samples via FFT.

The array has been calibrated following the procedure described above, obtaining $\widetilde{G}=$ $-2.6444\cdot10^{-4}$-i$6.1107\cdot10^{-6}$ [VA^{-1}]. Current and phase errors vs. current r.m.s. value are plotted in figure 10.

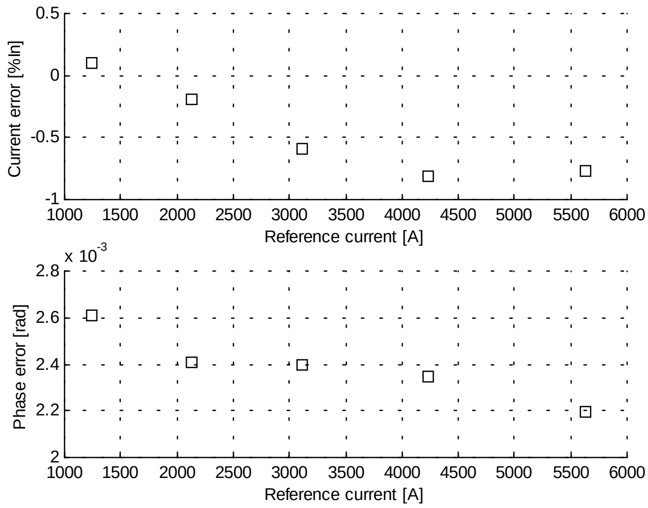

Fig. 10 – Current and phase errors vs. reference current in the case of a three-phase balanced current system flowing in the bus-bars.

5. CONCLUSIONS

In the paper a current transducer based on circular array of magnetic sensors has been applied for ac current measurement in a bus-bar system. A geometric property for cross-talk error compensation has been analytically formulated and experimentally verified. The transducer has been metrologically characterized in a 50-500 Hz frequency range and the effects of nearby bus-bars have been experimentally investigated. A test at high currents has been presented, showing that the transducer belongs to 1% accuracy class.

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