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OFFSET CORRECTION IN A DIGITAL INTEGRATOR FOR ROTATING COIL MEASUREMENTS

P. Arpaia[1,2]*, P. Cimmino*[1,2]*, L. De Vito*[2]*, and L. Fiscarelli*[1,2]

[1] European Organization for Nuclear Research (CERN), Geneva, Switzerland, {pasquale.cimmino, lucio.fiscarelli}@cern.ch
[2]University of Sannio, Department of Engineering, {arpaia, devito}@unisannio.it

Abstract: The rotating coil technique is extensively used in high-precision measurements for accelerator magnet testing. One of most relevant error sources is the drift arising from the integrator offset. In this paper, a correction algorithm for the offset drift in digital integrators is presented. Preliminary experimental results for the measurement correction of the main field of a superconducting dipole magnet of the Large Hadron Collider at CERN show the effectiveness for fast rotating coil measurements.

Keywords: Magnetic field measurements, accelerator magnets, signal processing.

1. INTRODUCTION

In particle accelerators, an accurate control of the beam is achieved by imposing constraining tolerances on the magnetic field of the magnets. Clearly, high-quality magnetic measurements are crucial also during all the phases of design, construction, testing, and operation of the accelerator magnets [1].

In magnet testing, inhomogeneous magnetic fields are measured by means of the rotating-coil method. According to Faraday's law, by rotating in a magnetic field, a coil generates a voltage. The voltage signal is integrated by angular steps in order to measure the magnetic flux. The harmonic content of the flux, pondered with sensitivity factors, is related to the distribution of the field in the volume spanned by the coil [2].

Typically, the coil signal is acquired and treated by using a digital integrator with on-line data process capability. Recently, at CERN, a fast digital integrator (FDI) has been developed, in order to satisfy the demanding requirements of testing the superconducting magnets of the Large Hadron Collider (LHC) [3]. By means of an accurate time base and specific integration algorithms provide high performance [3].

The integrator, as well as the other components of the measurement system, has to provide low uncertainty. In particular, dc voltages coming from the transducer (e.g. thermocouple effect) and offset voltage of the analogue front-end of the instrument determine a drift in the integration. If not corrected, this affects the spectrum of the flux and corrupts the field measurement [4].

Some corrections can be applied to mitigate the offset drift. In general, the dc-offset voltage can be estimated immediately before starting the measurement and successively subtracted from the data. This straightforward correction provides good results for short measurements compared to the stability of the offset. In the case of long measurements, the correction becomes useless.

In the particular case of rotating coils, the periodicity of the signal can be also exploited to correct the drift. At a constant speed, the flux points corresponding to the same coil position must be at the same level. This method is ineffective in the very-common case of a magnet powered by a cycling current. The field variation produces a modulation of the coil signal making the periodicity assumption unacceptable.

In this paper, a correction method for the offset drift in digital integrators for long measurements is presented. The proposed procedure, based on an automatic feedback loop, is also effective in the case of data taken on cycled magnets. Due to its low computational complexity, it can be easily performed on-line directly on the instrument processor.

The paper is organized as follows: in Section 2, the procedure for measuring the magnetic flux spectrum is recalled; then, in Section 3, the proposed correction is presented. Finally, in Section 4, preliminary experimental results are reported, showing the method effectiveness in actual flux measurements.

2. FLUX HARMONICS MEASUREMENT

The flux spectrum is measured as the sequence $d\phi(n)$ of digital definite integrals, computed on a fraction of the period of the rotating coil, corresponding to the angle between two successive encoder measurements, by applying, in each period of the coil, the following procedure [1]:

1. The samples $d\phi(n)$ of a coil period are collected in an array;
2. The magnetic flux is obtained by integrating the samples $d\phi(n)$:

$$\phi(n) = \frac{1}{N}\sum_{n=1}^{N} d\phi(n), \tag{1}$$

where N is the number of samples per period.

3. A linear correction for the envelope of the sequence is carried out on the samples by normalizing the samples of the period by the value of the current measured from the coil:

$$\phi_{ec}(n)=\phi(n)\frac{b_m}{an+b} \tag{2}$$

where $an+b$ is the expression of a linear fit of the measured current in the coil, corresponding to the considered period and b_m is the average value of the fit.
4. The Fast Fourier Transform (FFT) of the corrected flux is evaluated, and the ratio of the real parts and imaginary parts of each harmonic, versus the fundamental harmonic is taken.

3. DC OFFSET CORRECTION ALGORITHM

The proposed correction is designed as an automatic feedback loop working on the sequence $d\phi(n)$ of digital integrals (Fig. 1). In an initial step, the control sequence $c(n)$ is set to 0. Therefore, the $d\phi(n)$ sequence is integrated, thus obtaining the flux sequence $\phi(n)$. A specific block measures the dc offset affecting the flux sequence. The measured dc offset $b(n)$ is finally filtered in order to obtain a control sequence $c(n)$ to be subtracted to the $d\phi(n)$ sequence. The feedback filter is a 4-order FIR (Finite Impulse Response) low-pass filter, with a cut-off frequency equal to π/2.

A. dc offset measurement block

The dc offset measurement method operates on the flux sequence $\phi(n)$. Assuming the envelope of $\phi(n)$ approximated by a straight line over two periods, two lines can be identified, representing the upper and the lower envelope, respectively.

Therefore, the average $I(n)$ of the flux samples over each semi-period is evaluated. Then, the lines representing the upper and the lower envelopes of the $I(n)$ sequence are obtained for each semi-period. The offset at the semi-period k is given by the value of the average line at k, as shown in Fig. 2.

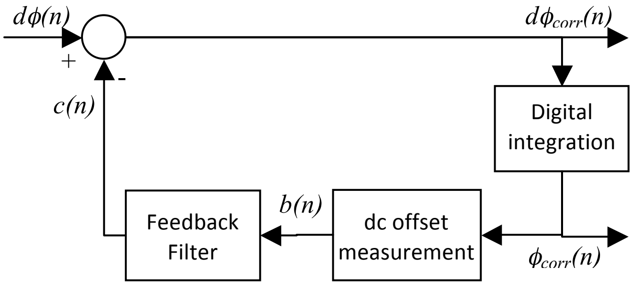

Fig.1. Block scheme of the dc offset correction loop.

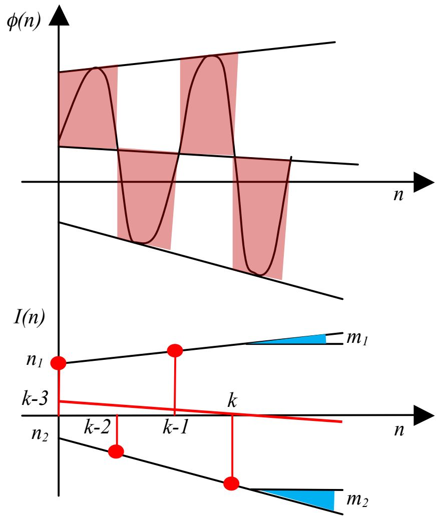

Fig. 2. The dc offset measurement procedure. The average $I(n)$ of the flux samples over each semi-period is evaluated. Then, the lines representing the upper and the lower envelopes of the $I(n)$ sequence are obtained for each semi-period. The offset at the semi-period k is given by the value of the average line at the semi-period k.

Given $I(k)$, $I(k-1)$, $I(k-2)$ and $I(k-3)$, the values of the average sequence $I(n)$ obtained in the last four semi-periods, the parameters of the upper and lower envelope lines are given by:

$$m_1=\frac{I(k-1)-I(k-3)}{2} \tag{1}$$

$$m_2=\frac{I(k)-I(k-2)}{2} \tag{2}$$

$$n_1=I(k-3) \tag{3}$$

$$n_2=I(k-2)-m_2. \tag{4}$$

The parameters of the average line between the upper and the lower envelope are given by:

$$m_3=\frac{m_1+m_2}{2} \tag{5}$$

$$n_3=\frac{n_1+n_2}{2}. \tag{6}$$

Therefore, the dc offset measurement is given by:

$$b=4m_3+n_3. \tag{7}$$

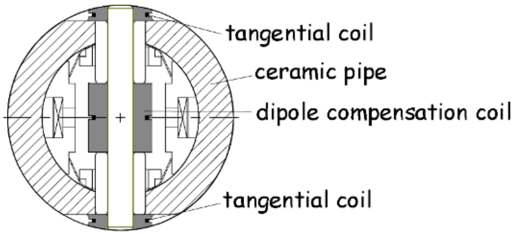

Fig. 3. Coil shaft cross section [5].

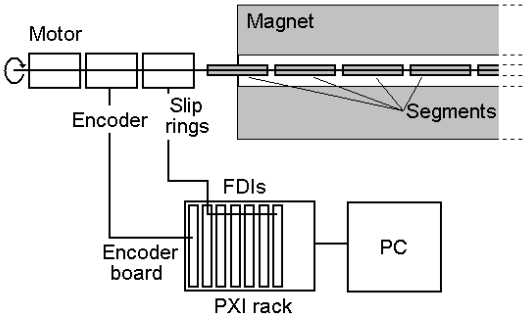

Fig. 4. Rotating coil measurement system for LHC main dipoles [6].

4. EXPERIMENTAL RESULTS

The proposed correction method has been implemented in MATLAB and experimental tests have been carried out on the absolute and compensated signals typical of the rotating coils technique [4]. In particular, the main field of a LHC main dipole superconducting magnet is measured by a Fast Digital Integrator (FDI) acquiring the absolute signal of the central coil sketched in the shaft cross-section of Fig. 3. Another FDI measures the compensated signal obtained by connecting a tangential and the central coils in opposition in order to cancel the main component and enhance the signal-to-noise ratio [5]. The measuring shafts are rotated at 1 turn per second by a motor unit, including an angular encoder and slip rings for the coil signals (Fig. 4).

The magnetic flux is measured between 512 angular positions per turn. A PC controls the measurement bench and stores the integrated coil data.

In Figs. 5a and 5b, the measured sequence of the magnetic flux is reported before and after the correction for both the compensated and uncompensated coil configurations, respectively.

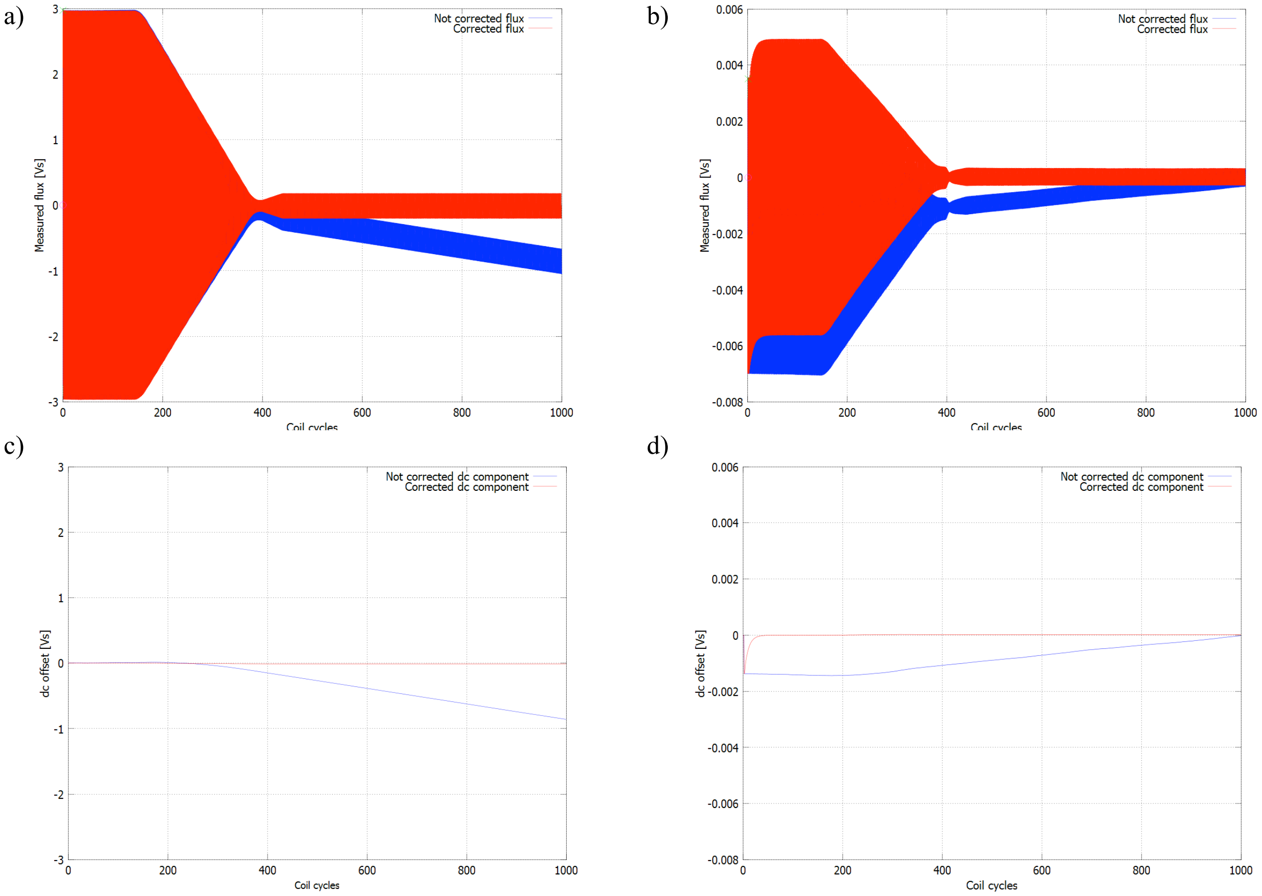

Fig. 5. Magnetic flux before and after correction for absolute (a) and compensated (b) configuration; measured dc component for absolute (c) and compensated (d) configuration.

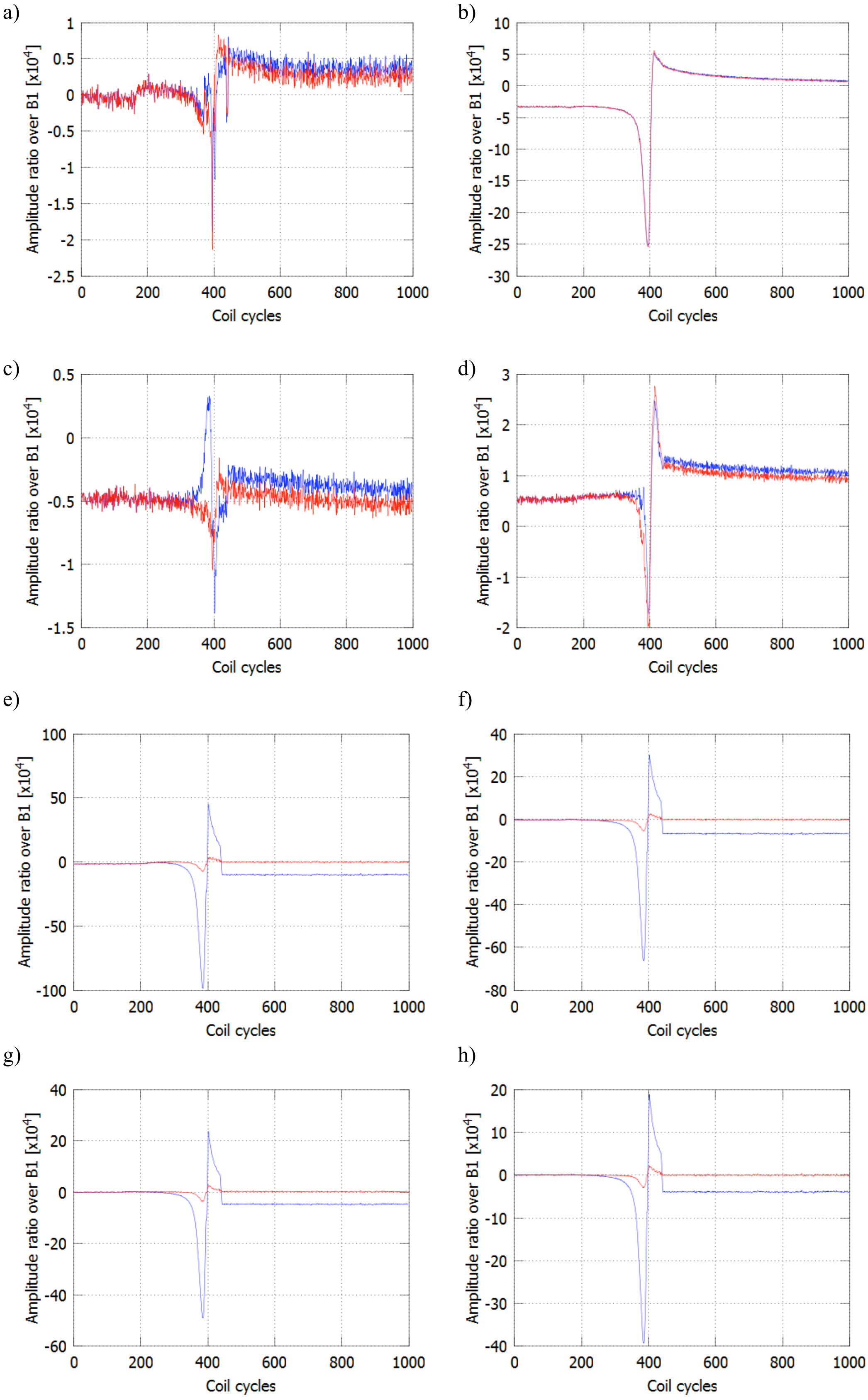

Fig. 6. Measurements of the harmonics for an acquired uncompensated signal, without (blue line) and with (red line) offset correction: real parts of 2nd (a), 3rd (b), 4th (c) and 5th (d) harmonic; imaginary parts of 2nd (e), 3rd (f), 4th (g) and 5th (h) harmonic

The current cycle in the magnet is composed by a plateau at 11850 A, a descending ramp to 500 A, an ascending ramp up to 760 A, and a plateau at 760 A.

The method is able to cancel out completely the dc offset, even when it has not a linear trend and a cycling current modulates the flux (Figs. 5c and 5d).

In Figs. 6, the measurements of the 2nd, 3rd, 4th, and 5th harmonics are reported, in the case of an uncompensated signal, without (blue line) and with (red line) the dc offset correction. A small difference can be appreciated in the real part, while a considerable correction is made in the imaginary part. In any case, the harmonics are brought to a more regular behavior by means of the offset correction method.

5. CONCLUSIONS

In this paper, a dc offset correction method to improve long-duration magnetic flux harmonic measurements in a rotating coil scenario, has been presented.

Preliminary experimental tests show the capability of the method of correcting the dc offset introduced by the measurement system and giving a noticeable contribution to the harmonic measurements of the magnetic flux.

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