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Ambient Temperature Field Measuring System for LHC Superconducting Dipoles

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Abstract - It is foreseen to perform acceptance tests including field measurements of the collared coils assembly of the LHC superconducting dipoles to estimate, at an early production stage, the possible significant deviations from the expected multipole component value of these magnets. A sensitive measuring probe and efficient data acquisition are the consequence of a low magnetizing current necessary to limit the coils heating. This demands a high signals sensitivity and an enhanced signal-to-noise ratio to retrieve the higher multipole component. Moreover, the correlation with the multipoles content of the magnets at cryogenic temperature and nominal excitation current need to be identified before the manufacturing process may continue. The field probe of the mole-type is equipped with three radial rotating search coils, an angular encoder and gravity sensor. It has been designed to slide inside the bore of the dipole coils and to measure the local field at fixed positions. The field analysis resulting in terms of multipole components, field direction and field integrals, measured on four 10 m long, twin-aperture LHC dipole prototypes, will be described together with the performance of the measuring method.

I. INTRODUCTION

The mechanical construction accuracy of LHC superconducting dipole coils, needs to be tested soon after their fabrication process to foresee, at an early production stage, their capability to produce the expected field when operated as superconducting magnets. Hence, it is planned to perform an acceptance test of the collared coils assembly by measuring the field they generate at ambient temperature. This is intended to be a validation of the production quality to avoid, in the event of a test failure, the succeeding complex and costly magnet construction. For this purpose, the harmonic method was devised to identify the possible manufacturing defects by way of any significant deviation from the multipole design values. When this occurs, an inverse field computation analysis would be applied to locate the potential structural causes.

Since the measurements take place with dipole coils at ambient temperature, only a low magnetizing current is allowed in order to limit the coils heating. Thus, the sensitivity to fields lower than .01 T is the main issue of 'warm' field measurements using the harmonic method. Unlike the currently used a.c. techniques, a d.c. excitation and rotating

search coils was preferred for LHC dipoles. This approach is based on the sensitivity and dynamic range of the signal amplifier-integrator of each data acquisition channel and on system noise rejection capabilities. Bucking of the large dipole component is also used, mainly to compensate for search coil common mode error signals.

II. SIGNAL ANALYSIS

Harmonic analysis of signals from d.c. low level fields is a critical issue. In order to achieve the desired resolution and reproducibility the d.c. method takes advantage of discrete frequency transform properties and on-line integration.

When an analog signal from a field pick-up coil is analyzed in the frequency domain, through its spectrum given by a Fourier series, the unavoidable presence of noise is not crucial, provided the noise spectrum is not in the range of the field harmonics to be analyzed. This condition is, generally, verified as the latter are in the lowest frequency range where noise is not expected. Hence, signal and noise components are apart in the resulting spectrum.

However, harmonic analysis is not, usually, performed directly on analog signals, but rather on their digitized counterpart, to make frequency transformations more applicable by computing techniques. Thus, pick-up coil signals must be sampled at regular intervals before being digitized, and, consequently, the resulting samples sequence is no longer represented by a Fourier series. Instead, the discrete Fourier transform is required to determine its band limited discrete frequency content. The DFT only provides an exact transform of the samples sequence which is, generally, an approximation of the analog signal spectrum.

As a consequence of sampling, the DFT spectrum is periodic, with period $f_a = 1/T$, where T is the sampling period. If the maximum frequency present in the analog signal is f_g , then to avoid any overlapping of the spectra, the sampling relation $f_a > 2f_g$ must be verified. If so, field harmonics are precisely retrieved by the Fourier transform, distinct from uncorrelated noise spectrum. When spectra overlapping occurs, frequencies higher than $f_g/2$, the Nyquist frequency, cause aliasing and, so, they induce errors in the main spectrum. The amount of aliasing can be reduced by appropriately increasing the sampling rate. Hence, errors in the main spectrum, due to noise frequencies, can be minimized.

One alternative technique, using anti-aliasing filters before applying the transform, is incompatible with the precision

required by field harmonic analysis, because they produce signal attenuation in their passband and, more important, significant phase distortion.

Since the sampling rate is bounded by the multitask computing power of the system processor, notably when on-line integration is performed, spectra aliasing is generally expected. However, the integration lowpass attenuation, is appropriate to filter the multiple spectra. Moreover, a software implemented data averaging, from any number of search coil revolutions, is also provided to increase the attenuation of zero mean noise before applying the DTF.

The system continuous setting of the sampling rate up to 250 sample/s when four integrators are used, allows to retrieve noise frequencies multiple of dipole, up to 100 Hz. If the input signal do contains higher frequencies, then aliasing is expected.

When the dipole field is a 0.5 Hz signal, a typical example, the integrator attenuation past 100 Hz is higher than 50 dB relative to dipole (fig. 1). Hence, filtering of noise higher than the Nyquist frequency is significant, with the result that the discrete signal spectrum is no longer periodic.

Fig. 1 Frequency response of the digital integrator.

Nonetheless, special care is, still, needed to minimize noise in the range where attenuation is not sufficient. In particular, excitation current noise is the most critical because the related field generates noise amplified by the pick-up coils flux derivative. For this reason, d.c. voltage stabilized excitation is preferred to avoid the considerably higher ripple noise of current stabilized supplies, mostly in the critical frequency range. A servo regulation is custom added to compensate for slow current drift due to dipole coils heating.

III. MEASURING SYSTEM

The measuring system consists of a self-contained field sensor probe and a portable equipment for data acquisition and analysis, in order to be easily operated at manufacturing factories.

The field probe is a 'mole-type' device with 42 mm diameter (fig. 2), suited to slide inside the duplicate of the 'cold' bore tubes, inserted into the dipole coil apertures, where it is pulled along to regular longitudinal positions to measure the local field. It is fitted with three radial harmonic search coils coupled to an optical angular incremental encoder, and an electrolytic gravity sensor. Two d.c. motors, for harmonic

Fig. 2 Mole-type probe for ambient temperature field measurements.

coils rotation and for servo regulation of the gravity sensor tilt are, presently, located on a support bench near one dipole end (fig. 3). The rotation transmissions to the pick-up coils, with maximum angular velocity of about 1 turn/s, and to the probe for tilt adjustment, are realized by 1.5 m long modular shaft spacers.

Fig. 3 Layout of measuring bench.

The radial search coils (Fig. 4a) are made up of a 20 wire flat micro-cable wound onto a fiber-glass epoxy reinforced core, and interconnected with an original technique. This technology was specifically developed for LHC dipole measurements (Fig. 4b) [1]. Their length is limited to 750 mm to keep the sag below 0.1 mm and the area is about 1.6 m².

Fig. 4 a) Cross-section of harmonic coils. b) Winding cross-section

Areas and coils alignment match within 10⁻³ by this precise manufacturing process. Their outer measuring radius is 19.3 mm for a bore tube radius of 21.5 mm. This provides a greater sensitivity to higher order harmonics than the smaller probes to be used inside the anticryostat tube for measurements in the superconducting state. The central winding is used for dipole bucking, but no specific area matching or compensation is realized to achieve a high dipole rejection. The rotating structure using three radial coils is appropriate for the mechanical construction, the electrical compensation of common mode noise and for redundancy.

An angular encoder, with nominal resolution of 87 $\mu\text{rad}/\text{point}$ (72000 points/revolution), defines the field sampling angles. Its absolute precision proves to be higher than $\pm 40 \mu\text{rad}/\text{point}$ when it is calibrated against a reference encoder by mean of an automated computer driven bench. To adjust the encoder angular position marker pulse defining the reference axis for field measurements, the probe level orientation is on-line servo regulated to better than $\pm 5 \mu\text{rad}$ for each new position of the probe along the dipole bore tubes. For this purpose, the level controller uses an electrolytic gravity sensor with a range of $\pm 30'$, featuring resolution higher than $\pm 1 \mu\text{rad}$. The ultimate absolute angular reference is given by a dipole magnet, with field direction mechanically adjusted to better than $\pm 10 \mu\text{rad}$. Hence, it is periodically used to validate the calibration of the gravity sensor in order to keep the absolute error of the probe tilt within the given bounds. This procedure is mandatory to comply with the demanded precision of $\pm 100 \mu\text{rad}$ for the dipoles field direction. Any start measuring angle offset is software compensated, since it is impractical to mechanically adjust the search coils orientation, with respect to the dipole field direction, to better than the required precision..

A computer based control system performs data acquisition and processing to analyze field multipoles, field angle relative to gravity and field multipole integrals.

The hardware is based on VME industrial standard. It is designed to be easily customized to different measuring conditions. Its graphic interface is specifically user oriented to simplify the operation at industry. It also provides on-line access to all measured and computed data by way of the built-in graphic display capabilities. The system software core for data acquisition is the concurrent (multitask), real-time digital integration of four voltage signals, currently from three single coils and one dipole compensated signal. The advantage of four simultaneous acquisitions is evident when data from different search coils are compared. Custom designed integrator, based on voltage-to-frequency conversion, features an input dynamics of 120 dB. Integrators are individually servo adjusted for electronic drift and the flux signals are earth field compensated. On-line integration is very convenient to perform field measurements insensitive to variations of search coil angular velocity. A software modular and multitask design allows to freely increase the number of simultaneous integrators used, compatibly with the limit

sampling time of about 1 ms for each integrator. Signal integration over any number of revolutions of the harmonic coils, can be set to improve random noise rejection. When a single revolution is used, few seconds are required for the measurements and the related computations for one bore position of the probe, with simple actions required to the user. Custom selection of the number of voltage samples per revolution up to 512, provides adequate sampling capabilities. The software, also, provides fine adjustment of search coil angular acceleration and velocity which, together with the excitation setting, allows to optimize the acquisition channels input signal. Presently, the probe longitudinal positioning is the only manual operation required.

IV. PROTOTYPE DIPOLE FIELD MEASUREMENTS

Ambient temperature field measurements of the prototype collared coils at industry, were planned to help identify any potential correlation with their counterpart measurements of the prototype magnets in the superconducting state. However, they were, temporarily, replaced by 'warm' measurements of 10 m prototype dipole magnets during their reception tests.

A d.c. excitation current in the 13-15 A range was used to generate dipole fields of about .009 T to .01 T.

The results concerning odd harmonic normal and skew components are confirmed by several complementary measurements. In particular, the multipoles set from compensated and single coils, match closely up to 15th order [2].

Thus, the primary interest of dipole bucking is to reduce common mode noise and to allow higher signal amplification to enhance the measurement precision and reproducibility.

The comparative analysis of data from radially opposite coils and the compensated coil, proved essential to help identify systematic errors due to uncorrelated system noise and distortions from spurious fields. It, also, allows a more reliable estimation of the overall measurement quality.

Comprehensive data from both apertures of the tested magnets are compared for the same harmonic order in fig. 5.

Typical single and compensated coil flux signal for harmonics up to 15th, when the dipole field is about .01 T, are shown (Table 1), together with the associated absolute errors. Flux values range from 16 mV's for the dipole to 0.18 μV 's for harmonic 15th, with a dipole voltage signal of about 50 mV. A signal integration dynamics of about 100 dB is,

Fig. 5 Examples of measured harmonic modules on four LHC prototype dipoles.

therefore, needed. The errors represent the reproducibility of

n	INPUT FLUX (V.s)		INPUT FLUX ERRORS (V.s)		NORMALIZED HARMONIC ERRORS @ 10 mm	
	Bucking	Single	Bucking	Single	Bucking	Single
	Cn	Cn	Cn	Cn	Cn	Cn
1	1.6E-02	1.6E-02	6.3E-07	6.3E-07		
2	6.4E-06	5.7E-06	5.0E-08	4.0E-08	1.3E-06	7.5E-06
3	8.5E-06	8.9E-06	6.6E-09	3.7E-08	2.1E-07	1.5E-06
4	2.3E-06	2.3E-06	6.0E-09	5.6E-08	1.1E-07	1.4E-06
5	1.9E-06	2.0E-06	5.2E-09	4.9E-08	7.5E-08	8.6E-07
6	4.2E-07	3.9E-07	5.8E-09	5.1E-08	4.8E-08	5.2E-07
7	3.4E-06	3.4E-06	5.7E-09	5.8E-08	2.3E-08	2.7E-07
8	6.0E-07	6.1E-07	5.5E-09	4.4E-08	1.4E-08	1.7E-07
9	1.1E-06	1.1E-06	5.1E-09	5.1E-08	7.9E-09	8.1E-08
10	3.3E-07	3.2E-07	7.2E-09	5.4E-08	3.4E-09	5.4E-08
11	7.5E-07	7.6E-07	6.6E-09	5.8E-08	3.0E-09	2.6E-08
12	8.3E-08	8.5E-08	6.2E-09	5.1E-08	1.6E-09	1.6E-08
13	7.5E-08	6.9E-08	7.8E-09	5.0E-08	1.1E-09	8.4E-09
14	9.2E-08	1.0E-07	4.5E-09	6.2E-08	5.2E-10	5.6E-09
15	1.8E-07	1.9E-07	5.5E-09	3.4E-08	2.6E-10	2.0E-09

Table 1 Measuring system resolution and reproducibility.

the measuring system for each multipole, and correspond to the inherent absolute system noise. By inspection, this noise is essentially constant for all harmonics and amounts to about $6 \cdot 10^{-9}$ V.s for the compensated coil, on average a factor of 20 lower than harmonic 15th module.

Errors on normalized data are, also, presented to quantify the measuring system reproducibility at standard 10 mm radius. Error values on normalized data are a factor 10^{-1} to 10^{-2} below the expected dipole harmonic random errors. This latter result suggests that field multipoles would be retrieved with significant reproducibility and resolution margins.

A global analysis of even multipoles data from the prototype magnets tested, do reveals that their patterns are uncorrelated. This outcome excludes significant data biasing due to the presence of systematic measuring errors. The two-in-one magnet design, together with the iron yoke, are factors that influence the presence of these harmonics.

Field direction difference between the two apertures is a very critical parameter of LHC dipoles because of the two-in-one design. On average this deviation is below 1 mrad, with a maximum absolute peak value of about 3 mrad for three tested prototypes and about 6 mrad for one magnet. Large absolute direction variations are, therefore, common to both apertures. This result could imply that the field direction errors are largely induced by the mechanical operations of coils collaring and iron yoke installation. The direction results from search coils positive and negative rotation (fig. 6), reveal a measuring precision of about $\pm 20 \mu\text{rad}$ which is adequately below the demanded $\pm 100 \mu\text{rad}$.

Fig. 6 Field direction difference between positive and negative search coil rotation.

MAGNET	BORE	CURRENT (A)	BL (Tm * E4)	BL / I (Tm * E4 / A)	MAGNETIC LENGTH (m)
1	1	13	821.43	63.19	9.276
	2	13	-816.84	-62.83	-9.224
2	1	13.5	848.46	62.85	9.296
	2	13.5	-847.97	-62.81	-9.291
3	1	15	947.05	63.14	9.299
	2	15	-946.91	-63.13	-9.298
4	1	15	946.15	63.08	9.299
	2	15	-947.85	-63.19	-9.315

Table 2 Integral values of prototype magnets.

Magnet integral values are summarized in Table 2. Together with the computed multipoles field integral, they are of primary interest when compared with the equivalent data derived at nominal current, for the definition of the correlation between field quality at ambient temperature and superconducting state.

V. CONCLUSIONS

The quality controls of LHC dipole coils immediately after their construction, require specific ambient temperature tests at industry. A measuring system was, primarily, designed to perform 'warm' measurements of the field they generate at this manufacturing stage. In accordance with the results, the progress of the magnet assembly may be affected by the way the retrieved multipole content and the field direction correlate with the field in the superconducting state.

The harmonic method used to perform these measurements, was implemented by using static test field and rotating search coils. This method proves to operate efficiently and to be very flexible. Besides, the results achieved, with mandatory low field of about .01 T, show that the dipole natural odd harmonic components are identified by either single coils and compensated coil with close precision up to the 15th order. Even harmonic variable values measured along both apertures, are validated by several complementary measurements. Yet, their intrinsic nature still needs further specific analysis when more coils and magnets field data will be available. For measurement of collared coils, the twin-aperture effect on even harmonics can, eventually, be canceled by energizing only one coil in turn. Field direction is readily measured with an accuracy substantially higher than the required $\pm 100 \mu\text{rad}$.

The general-purpose design of the measuring system makes its utilization not exclusively restricted to LHC dipoles. Indeed, it can, easily, adapt to different mechanical and field configurations, to retrieve field multipole contents, using low magnetizing current, with a considerable degree of reproducibility.

REFERENCE

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