Characterization of Deformed Magnets from External Magnetic Measurements

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***Abstract*—Due to the unavoidable construction tolerances and imperfections in the assembly of coils, the actual magnetic field of manufactured magnets usually differs from the design one. Depending on the consistency and the profile of the field error, a number of problems may arise, especially in high performance devices, such as NMR magnets or thermonuclear fusion devices. Typical quality insurance procedures can hardly reveal possible Winding Packs (WP) deformations. In this digest an assessment of limits and possibilities of WP deformation analysis by means of external field measurement is discussed, while in the full paper also the related reconstruction procedure will be discussed.**

***Index Terms*—Magnetic analysis, Superconducting magnets, Inverse Problems.**

I. Introduction

An assessment of the impact of manufacturing and assembly tolerances is generally required in the testing phase of electromagnetic devices, especially for the most expensive ones, to verify if design performance is guaranteed also for real devices, and, in addition, to evaluate the actual requirements of possible correction systems. In the following, attention will be paid to high field superconducting magnets for Fusion Technology as ITER Toroidal Field Coils (TFC); however quite similar considerations can be applied to any high-performance magnets, such as background field magnets for Nuclear Magnetic Resonance.

Typical quality insurance procedures involve a first survey in the warehouse where magnets were manufactured, performed using laser tracking to accurately define the external geometry of each coil, but these cannot reveal possible Winding Packs (WP) deformations. A viable alternative could be to detect the characteristics of the WP inside the case by means of magnetic measurements. This hopefully will provide a possibility to learn at earlier stages of the fabrication phases the future impact on magnetic field, and then to allow the implementation of corrective measures during installation phases. External field measurements have been extensively used to characterize current redistribution in superconducting cables, in Nuclear Magnetic Resonance and in accelerator magnets [1-4].

Unfortunately, the variations of magnetic field (the "field error") due conductor deformations are expected to be quite small and easily hidden by background noise or other effects (such as eddy currents or imprecise knowledge of iron presence), and these limitations do pose narrow limits to the actual practicability of this approach. As a consequence, a careful preliminary feasibility study is required to assess the actual possibility of detecting with magnetic measurements small deviations of conductors from nominal geometry.

As a first point, the choice of the best suited measurement procedure must be performed. Since the WP, in the case of TFC, is realized using steel holders, eddy currents induced in these parts could adversely impact the measurement accuracy. On the other hand, static fields are typically measured using "point-wise" probes, highly sensitive to local field variations, and great care must be given in the probe positioning system.

A second issue pertains the use of differential probes, taking advantage of possible nominal field symmetries, that get lost due to symmetry-breaking WP deformations, or measuring field map gradients rather than the map itself, filtering out "large scale" details of the field map. However, these probes are even more sensitive to alignment errors, and great care must be taken in their manufacturing and assembly.

Different solutions will be considered in the papers, and advantages and drawbacks will be highlighted. In this digest a preliminary assessment for the characterization of ITER TFC-like magnets will be presented, showing advantages and drawbacks of different approaches in terms of measurement accuracy and effectiveness. In the full paper, also the possible use of AC sources will be addressed, and some hints for WP characterization will be discussed.

II. Modeling of the System

In the hypothesis of DC power supplies, the relationship between sources (the current in the WP conductors) and measurements (the field measured by probes) is described by the magnetostatic equation. The interest here is on the effect of very small deformations of source currents. It is consequently reasonable to assume that the magnetization of the iron present in the measurement hall is not perturbed significantly by these deformations, and it can be computed (or measured) using the nominal configuration of WP, and possibly filtered out. The system model is then given by a set of linear equations relating the current in WP conductors and the measured fields:

$$m_k = \mathbf{g}_k\left(\underline{p}\right) I_{WP} + m_k^{Fe} \quad k = 1,2,\ldots.N_m \tag{1}$$

where m_k is the k-th measurement, $\mathbf{g}_k$ is the k-th measurements vector due a unit current, I_{WP} is the current in the WP series-connected conductors, m_k^{Fe} is the contribution of iron to the k-th measurement, and N_m is the number of measurements. The degrees of freedom (DOF) in the model are contained in the array $\underline{p}$, describing the deformed geometry of the WP, and such unknowns affect the coefficients $\mathbf{g}_k$. Since measurements are taken at room temperature, it will be assumed that no current redistribution occurs among strands in the cables.

The relationship among parameters and matrix coefficients are non-linear. Their evaluation can be effectively done by minimization of a suitable error function. This will be addressed in the full paper. The aim of this digest is just to assess the reliability of known terms m_k in the system. An estimation of the effect on measurement accuracy was already discussed in [4]. In this digest, a comparison of possible probes choice and measurement points' location is presented.

Current "sticks" (i.e. straight filamentary currents of limited extend) have been used to discretize the complex shapes of possibly deformed TFC [4]. The number of sticks used to represent each conductor in WP is chosen on the basis of the precision needs.

III. Assessment of Reconstruction Procedure

In this section, in order to present an example of the assessment procedure, ideal coil geometry is assumed as a circular massive coil with major radius of 7 m and a trapezoidal section with 0.7 m major and 0.5 minor sides (see Fig. 1). The WP is composed of 120 conductors, placed as in Fig. 1. The conductors are series connected, and fed with a 200 A DC current. The effect of 5 mm "radial" shift of WP inside the case, not uniform along the coil, but leading to a "hellipticization" is considered as a test case. Field measurements are performed using Hall probes, with 0.1% accuracy on Full scale reading, assumed in all cases as twice the maximum value of "reference" signal (that is, the signal in the nominal case).

Three possible measurement techniques are considered. The first one is the "absolute" measurement: probes readings are proportional to field component along the measurement direction (in this case, tangential to the WP side, as reported in Fig. 1). The second one is a "gradiometric" approach, measuring radial derivative of tangential field component. Finally, the third approach is a "differential" one: probes measure the difference of field components along measurement direction on two points, symmetrically placed across the WP (Fig. 1).

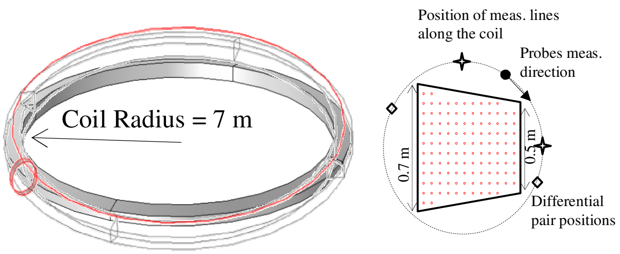

Fig. 1 – Left: Layout of the nominal (wireframe) and deformed (solid) coil. The deformation is amplified for clarity. The traces of measurement line are also partly reported. Right: Layout of Winding Pack, with probes positions.

The effect of the deformation were measured along a circumference 0.6 m away from the nominal WP centre, at the cross section reported in Fig. 1, and on two lines along the coil surface (one is reported in Fig. 1, above the coil, the second one is on the coil plane, outside the coil case). Results for the three measurement approaches, compared to noise level, are reported in Fig. 2 for the circumference around the WP and in Fig. 3 for the two lines above (up) and aside (bottom) the coil.

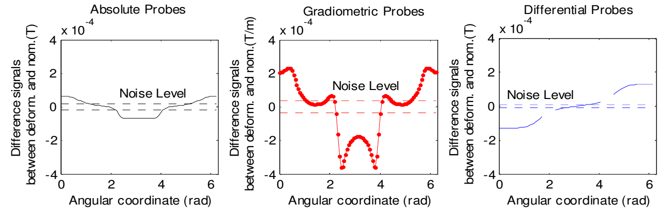

Fig. 2 – Difference of measurements between nominal and deformed configuration around the WP for the three measurement approaches.

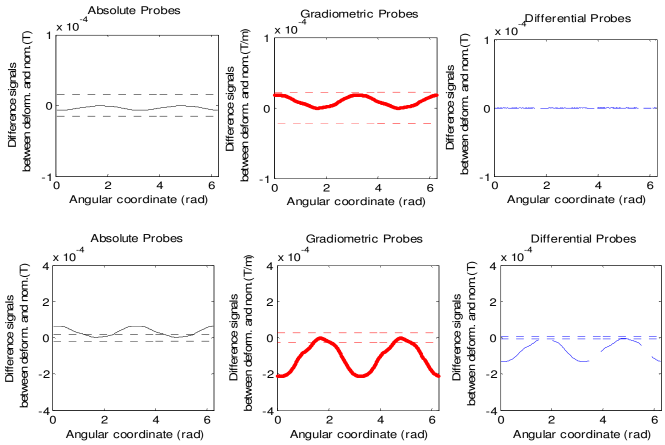

Fig. 3 – Difference of measurements between nominal and deformed configuration above the coil (up) and aside the coil (bottom) for the three measurement approaches.

IV. Conclusions

The mathematical formulation to describe the problem is fully satisfying and the numerical procedure to face with its solution is suitable to the requirement; therefore, depending on the actual characteristics of the hall and of the measurement system, in principle, the method could be applied to try measuring deformations of WP from external magnetic measurements. On the other hand, a measurement can be considered reliable only if its value is much higher than the collective effect of all measurement errors, as suggested by precautionary principle. This makes the choice of measurements quite critical in presence of uncertainties in the position and alignment of probes and noise.

In the paper, a possible procedure to estimate WP deformations using (noisy) measurements will also be assessed.

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