TRANSIENT MAGNETIC FIELD ANALYSIS FOR THE LOCALIZATION OF ELECTRICAL FAULTS IN SUPERCONDUCTING COLLARED COILS

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Abstract

The follow-up of the construction of superconducting magnets for accelerators requires setting up of powerful diagnostic tools to detect weak electrical points in the superconducting coils at various stages of their fabrication. In particular some electrical short circuits well detectable after collaring of the magnet often disappear after the coil is uncollared for repair; therefore it is preferable to localize this kind of electrical faults before disassembling the magnet.

An R&D work on detection and localization of inter-turn short circuits is being carried out at CERN in view of the series production of the LHC magnets. The diagnostic methods under study include pulse propagation, time domain reflectometry and transient magnetic field analysis. In this paper special emphasis is put on the analysis of the magnetic field distortions created by the short circuits during a pulsed discharge. A model of LHC dipole allowing the simulation of different fault conditions in the coils has been implemented in ROXIE (static case) and in OPERA-2D (transient case). The model has been verified experimentally on a dedicated short dipole magnet equipped with micro-switches to trigger short circuits in different areas of the coils.

1. INTRODUCTION

The pattern of the magnetic field in modern superconducting accelerator magnets is mainly determined by the geometry of the coils. In an ideal case a current of the type $I(\varphi) = I_0 \cos(\varphi)$ distributed around the aperture produces a pure dipole field. For practical reasons multi-layer coils graded with longitudinal wedge-shaped spacers inserted between the conductor blocks approximate this condition (Fig. 1). The LHC dipole coils are composed of two layers connected with each other to form a pole. This paper is focussed on the study of the single aperture superconducting short models for the LHC in view of applying the results of the investigation to the 15-m long double aperture magnets.

Since 1989 a test and evaluation program of short superconducting dipole magnets for the LHC is under way at CERN. It was intensified in 1995 when a production of a new series of 1-m long dipole magnets was launched [1]. The design is based on a dismountable structure allowing easy implementation of variants (Fig.2). The coils are confined in a fixed volume by the collars with a pre-compression sufficient to counteract the electrodynamic forces during magnet excitation. The outer layer of the coils is separated from the collars by 0.5

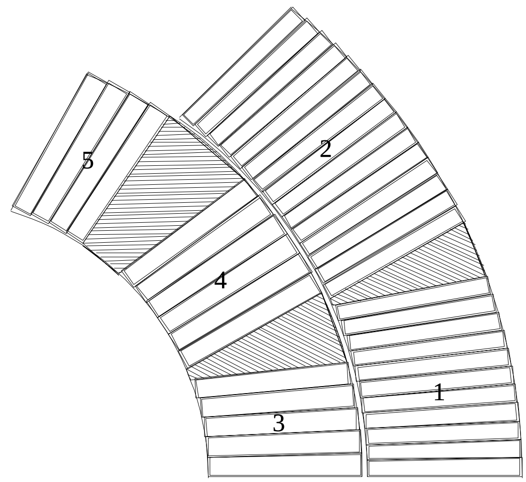

Fig. 1. Quadrant cross section of a 5-block geometry coil; 2 conductor blocks in the outer and 3 in the inner layer

mm of ground insulation and by a 0.7 mm thick austenitic steel protection sheet called collaring shoe. A ferromagnetic yoke is clamped around the collared assembly by an external bolted stainless steel cylinder. The yoke enhances the magnitude of the magnetic field induction inside magnet's aperture and prevents the collars from expanding when submitted to the Lorentz forces exerted on the coils.

The superconducting cable is insulated by one layer of polyimide film followed by a layer of adhesive tape. The external adhesive bonds adjacent turns of the coil. The effective thickness of the cable's insulation is about

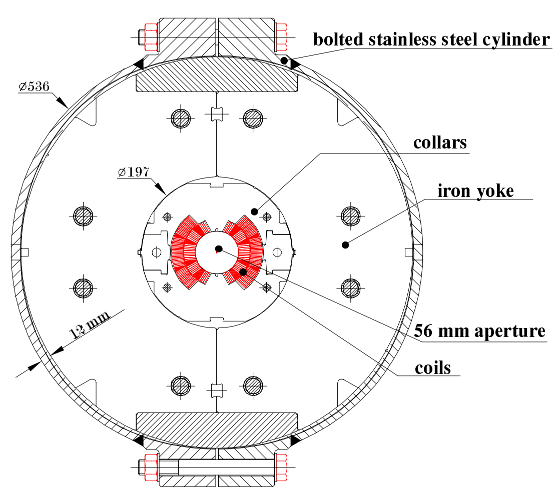

Fig. 2. Cross section of a single aperture dipole magnet

125 μm; i.e. two adjacent turns are separated by about 250 μm of insulation. This dielectric barrier can be damaged during one of the magnet assembly phases, resulting in an inter-turn short circuit. The change in the distribution of the current in the coils of the magnet due to the fault produces a distortion of the magnetic field. This effect is used here for the longitudinal localization of the short circuits by means of transient magnetic field analysis.

2. INTER-TURN SHORT CIRCUITS

Often inter-turn short circuits are well detectable when the magnet is collared. The presence of the fault in the magnet can be diagnosed by means of pulse propagation methods at ambient temperature. A voltage impulse is produced between the terminals of the magnet

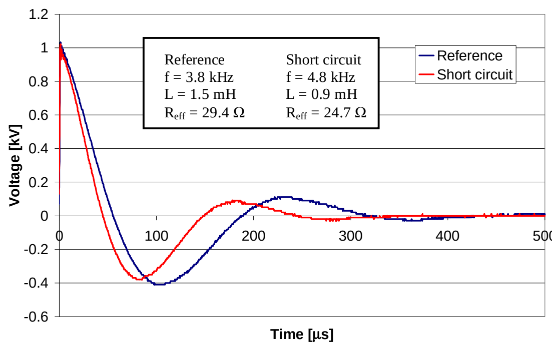

Fig. 3. Discharge curves at 1 kV

by a discharge generator. The coil's response in form of voltage and current oscillations is then registered and analyzed in terms of pseudo period of the oscillations, inductance and effective resistance of the coils. Fig.3 shows the discharge curves acquired on the collared assembly during a test at 1 kV. An equivalent electrical circuit of the magnet under test can be represented as an RLC distributed line excited by a charged capacitor. The oscillations produced during the discharge are gradually damped down by the resistive components of the line, which correspond to the different dissipation processes in the coils and in the surrounding magnet structure.

In case of an inter-turn short circuit, the current is redirected to the neighboring cable turn through the short circuit path. Energy is dissipated additionally at the point of fault. For the propagating impulse the coil appears to be shorter by a length of a cable turn affected by the short circuit. The value of the magnet's inductance decreases, whereas the damping factor and the frequency of the oscillations are increased. The existence of the electrical fault can be thus verified, nevertheless the method does not allow to localize the position of the short circuit. Traditional localization procedures based on resistance and voltage ratio measurements require dismounting of the collars. Often after the collars are removed and the internal prestress in the coils released the short circuit disappears. Time consuming methods involving local controlled pressure increase over small sections of the coils must be employed thereafter to reestablish and localize the short circuit.

3. MAGNET MODELING

3.1 *Multipole expansion of the magnetic field*

The quality of the magnetic field is analyzed in terms of multipole field expansion. According to the design project of the LHC [2], the complex magnetic field induction is expanded as follows:

$$B_y + iB_x = \sum_{n=1}^{\infty} (B_n + iA_n) z^{n-1} \tag{1}$$

Coefficients B_n and A_n indicate normal and skew field multipoles, respectively. In terms of radial and angular field components expansion (1) is equivalent to:

$$\begin{aligned} B_r(r,\theta) &= \sum_{n=1}^{\infty} r^{n-1} (B_n \sin n\theta + A_n \cos n\theta) \\ B_\theta(r,\theta) &= \sum_{n=1}^{\infty} r^{n-1} (B_n \cos n\theta - A_n \sin n\theta) \end{aligned} \tag{2}$$

By introducing a reference magnetic field, equal to the main dipole field B_1, and the normal and skew multipole coefficients relative to the main field at a reference radius r_0,

$$a_n = \left.\frac{A_n r^{n-1}}{B_1}\right|_{r=r_0} \qquad b_n = \left.\frac{B_n r^{n-1}}{B_1}\right|_{r=r_0} \tag{3}$$

the radial and angular components of the field can be expressed as:

$$\begin{aligned} B_r(r,\theta) &= B_1 \sum_{n=1}^{\infty} \left(\frac{r}{r_0}\right)^{n-1} (b_n \sin n\theta + a_n \cos n\theta) \\ B_\theta(r,\theta) &= B_1 \sum_{n=1}^{\infty} \left(\frac{r}{r_0}\right)^{n-1} (b_n \cos n\theta - a_n \sin n\theta) \end{aligned} \tag{4}$$

The main normal coefficient of the multipole expansion (b_1) is thus always normalized to 1. Higher harmonic coefficients are given in units of 10^{-4} relative to the dipole B_1.

3.2 *Reference magnet models*

Both static and transient models of the 5-block collared dipole magnet without iron yoke were developed and analyzed using two different CAD programs. In the static model the conductors are excited with I = 20 A direct current. Since the collars are non-magnetic the calculation of the magnetic field harmonics in the static case is based uniquely on the geometry of the coils and the distribution of the current in the conductors.

Transient model simulates the behavior of the magnet during a 1 kV pulsed discharge in which the peak current reaches a value of i_{max} = 20 A. In this case the frequency of the oscillations of the current decaying in the coils, the skin and the eddy current effects in the conductors, copper wedges, collaring shoe and the collars are taken into account during field computations.

3.2.1 Static case

The static model was created with The **R**outine for the **O**ptimization of Magnet **X**-Sections, **I**nverse Problem Solving and **E**nd Region Design (ROXIE) program developed at CERN [3]. Data concerning the characteristics of the superconducting cable for the external and internal layers of the coils are taken directly from the ROXIE database. The program features optimization of the coil geometry as a function of the desired magnetic field pattern. Advanced conductor positioning options, like the alignment of the cables on the inner or outer radius of the given layer, are also available. The conductors are subdivided into the regions corresponding to the number of strands in the cables, i.e. 2 rows of 18 elements for the external layer cable, and 2 rows of 14 elements for the internal one. The current line representing the strand is located in the center of each region. Magnetic field resulting from the coils is calculated directly from the Biot-Savart law (Fig. 4.)

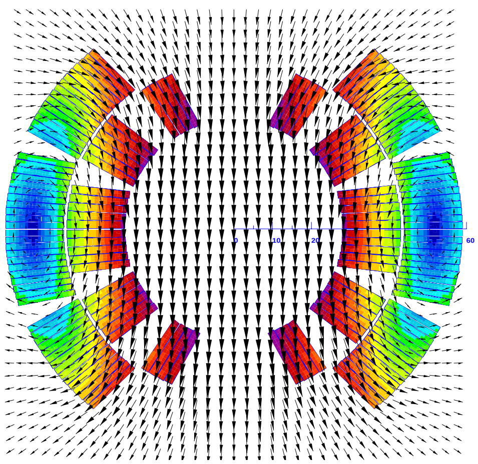

Fig. 4. Magnetic vector field computed with ROXIE

Two cases are considered below. The case with the current grading takes into account the keystoned (trapezoidal) form of the cable's transversal cross section. As a consequence of this shape the strands near the inner perimeter of the cable are closer to each other than the ones near the outer edge. This results in grading of the current density throughout the conductor. The case without grading assumes uniform current density distribution in the cable. The outcome of the harmonic analysis of the radial field component at the reference radius of r_0 = 10 mm is given in Table 1.

Table 1. ROXIE harmonic analysis of the magnetic field

Current grading	B_1 [$\cdot 10^{-4}$ T]	b_3	b_5	b_7
On	-122.8	-0.96	0.032	0.008
Off	-122.2	-0.52	0.017	0.013

Due to the dipole symmetry of the coils neither skew multipole terms nor even-ordered normal multipoles are present in the field expansion. Grading of the current gives a difference of 0.44 units for the sextupole in comparison to the uniform current density case.

3.2.2 Transient case

The geometry of the coils defined in ROXIE served as a reference for the transient model implemented in OPERA-2D [4]. In addition to the conductor blocks the model includes the copper wedges, the collaring shoe, and the collars (Fig. 5). OPERA-2D uses FEM approach to solve the electromagnetic problem and calculate the redistribution of the currents due to the eddy current effects.

The effective conductivity of the collars was adjusted in the model in order to fine-tune the computational results to the experimental data acquired by measuring the peak field induction inside magnet's aperture and around the collars. For setting the correct value of the conductivity of the cables an additional test was carried out to evaluate the magnitude of the eddy current effects. Separate layers of the coils were excited one at a time to analyze the screening effects. Matching between the model and the experiment was achieved by assigning to the conductors the conductivity values measured with 1 A direct current, i.e. $3.63 \cdot 10^7$ S/m for the inner layer cable, and $3.23 \cdot 10^7$ S/m for the outer layer cable.

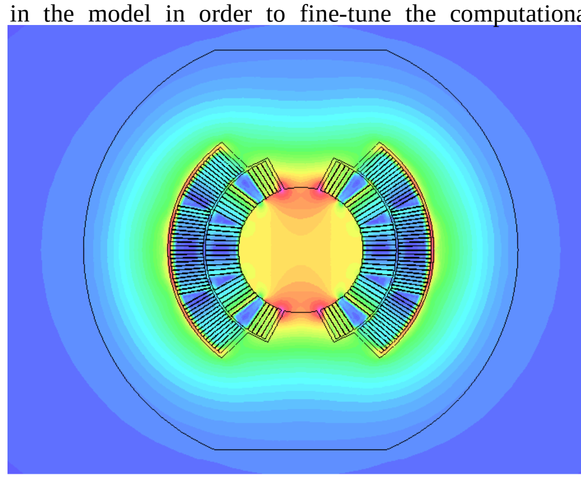

Fig. 5. OPERA-2D transient model

Relative multipole coefficients obtained during harmonic analysis of the magnetic field are of the order of 10^{-4} and their computation requires high accuracy. The validity of the results relies on the precise definition of the coil geometry and correct implementation of the current density distribution into the model. Therefore the optimized OPERA-2D model was verified in the static case to check the convergence of the results with the ROXIE reference model.

Table 2. Comparison of static models at r_0 = 10 mm

Static Case	B_1 [$\cdot 10^{-4}$ T]	b_3	b_5	b_7
ROXIE	-122.2	-0.52	0.017	0.013
OPERA-2D	-119.3	-0.55	0.020	0.013

Table 2 shows that the model implemented in OPERA-2D and analyzed in the static case corresponds to the ROXIE analysis without current grading. The results of the harmonic analysis for the transient case are listed in Table 3.

Table 3. OPERA-2D transient field analysis

Transient Case	B_1 [$\cdot 10^{-4}$ T]	b_3	b_5	b_7
10 mm	-74	-201	20.1	0.04

The effect of the eddy currents induced in the transient case deteriorates significantly the quality of the field and attenuates the main dipole component in comparison to the static case.

4. SHORT CIRCUIT INDUCED FIELD DISTORTIONS

In case of short circuit the current follows a path different from the nominal one. Fig. 6 depicts schematically an inter-turn short circuit occurring between turns 30 and 31 of the magnet. The current is redirected at the point of fault through the short circuit path. In the cross-section preceding the fault (X-section 1) the current flows in conductor 30 but not in 31. It returns in opposite direction carried by conductor 154 only. In the cross-section behind the short-circuit (X-section 2) conductor 30 is deprived of current.

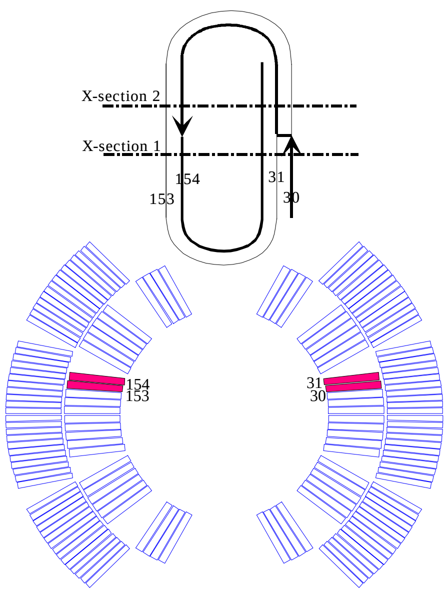

Fig. 6. Schematic representetion of an inter-turn shor-circuit

Table 4. Short circuit analysis at 10 mm

Normal	Reference	X-section 1	X-section 2
B_1	$-74\cdot10^{-4}$ T	$-59\cdot10^{-4}$ T	$-59\cdot10^{-4}$ T
b_2	0	3.3	0
b_3	-201.0	-257.9	-260.0
b_4	0	0.9	0
b_5	20.1	23.1	22.7
b_6	0	0.2	0
b_7	0.04	-0.06	-0.11

Skew	Reference	X-section1	X-section 2
a_1	0	6.4	0
a_2	0	37.1	33.1
a_3	0	1.2	0
a_4	0	5.5	5.2
a_5	0	0	0
a_6	0	0.7	0.7
a_7	0	-0.03	0

Table 4 illustrates how the short circuit affects the multipoles of the magnetic field in comparison to the reference field in this particular example. In cross section 1 the distribution of the current on both sides of the coil is asymmetric due to the fault. As a result measurable normal multipoles of even orders like quadrupole (b_2), octupole (b_4), and skew field harmonics (a_n) with high value of skew quadrupole (a_2) are developed. These field harmonics normally are not present in a dipole magnet without electrical faults. In cross section 2 the current distribution becomes symmetric again; even orders of the normal multipoles and odd orders of the skew harmonics vanish from the field pattern. This effect can be used for the longitudinal localization of the point of fault.

5. EXPERIMENTAL SET-UP

5.1 Detection method

The development of the field harmonics during a pulsed discharge can be detected by a system of pick-up coils (Fig.7). The detection method takes advantage of the vector field geometry characteristic for the even order multipoles. When the coils are positioned on the median plane in the center of the aperture the pulsed magnetic field will induce the same voltage in the coils C1 and C3

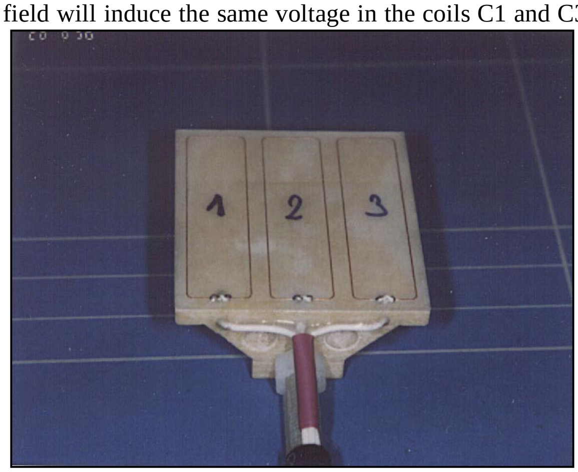

Fig. 7. Printed circuit pick-up coils

if the even orders of the normal field harmonics are not present in the field pattern. Otherwise, if the even-ordered harmonics are developed, a difference in the voltage induction between the two coils will be observed. The contribution of the even order multipoles cancels out in the central coil. Since higher order odd multipoles are negligible close to the center of the aperture, coil C2 picks up mainly the dipole field.

5.2 Instrumentation

One of the MBSMS dipole magnets was equipped with micro-relays soldered on the internal layers in two clusters centered around the cross section in the middle of the magnet, and 280 mm away from the head region of the coil (Fig. 8). The relays, excited with 12 V DC one at a time, create short circuits between adjacent cable turns in well-defined positions. Pulsed current is supplied from a discharge generator by releasing the energy

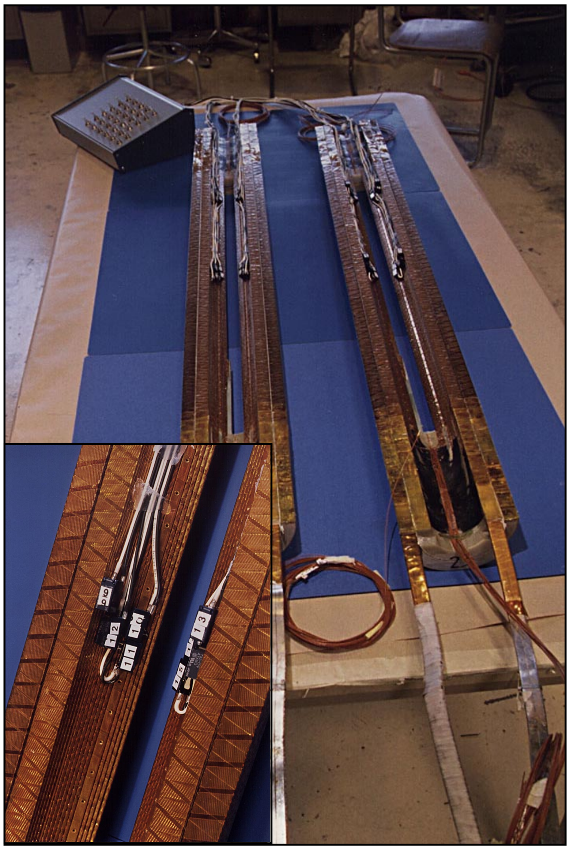

Fig. 8. Coils equipped with micro-switches

accumulated in a 1μF capacitor, charged at 1 kV, into the magnet. The voltage induced in the pick-up coils is measured during the discharge and integrated thereafter to obtain the time evolution of the magnetic field induction. The pick-up coil platform slides on two vetronite rods aligned inside the aperture of the magnet. The entire detection system can be rotated inside the magnet for the measurement of skew fields.

5.3 Results

Experimental results concerning the short circuit discussed in previous section (Fig. 6) are presented in Fig. 9. A measurable difference between the peak field inductions indicated by the coils C1 and C3, higher than the one predicted with the model, was registered in the

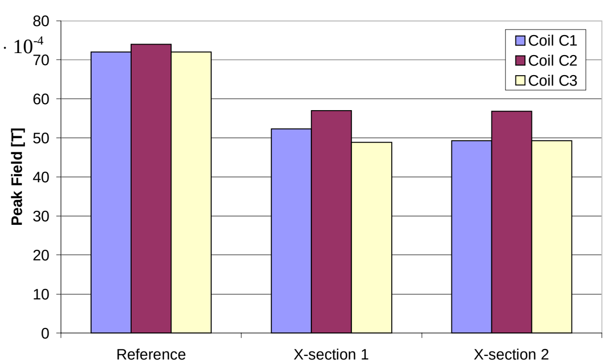

Fig. 9. Pick-up coil indications

area preceding the position of the short circuit (X-section 1). The induction difference vanished immediately, as expected, when the outer edge of the pick-up platform was moved behind the point of fault (X-section 2).

Indications of the central coil (C2) reflect further attenuation of the dipole field under fault conditions. As a consequence of the current redistribution and increased frequency of the current oscillations the field-screening effects in the magnet are enhanced and a degradation of the dipole field occurs. Increased difference between the indications of the coil C2 and the remaining coils of the pick-up system in comparison to the reference signals are attributed to the influence of the large negative normal sextupole predicted in the model. The magnitude of the sextupole at 10 mm is enhanced by 30% due to the short circuit.

6. CONCLUSIONS

Transient magnetic field distortions created by electrical faults in superconducting collared coils were analyzed in view of the localization of inter-turn short circuits. The detection method was based on the study of the development of the field harmonics induced by current redistribution. The experimental procedure has been simulated with OPERA-2D and tested on a dedicated dipole magnet equipped with micro-relays capable of activating artificial short circuits in the internal layer of the coils.

The longitudinal position of the short circuits was successfully established for all of the installed micro-switches with the precision of a few millimeters. An abrupt change of the normal even-ordered magnetic field harmonics was observed in the proximity of electrical faults. The magnet pole affected by the short circuit was also identified in each case. The possibility of an exact azimuthal localization of the inter-turn short circuits is under study.

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