DETECTION AND LOCATION OF ELECTRICAL INSULATION FAULTS ON THE LHC SUPERCONDUCTING CIRCUITS DURING HARDWARE COMMISSIONING

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Abstract

As part of the electrical quality assurance program (ELQA), the insulation of all superconducting circuits of the LHC has to be tested with a d.c. voltage of up to 1.9 kV. Fault location within a ± 3 m range over the total length of 2700 m has been achieved in order to limit the number of interconnection openings for repair. In this paper, the methods, tooling, and procedures for the detection and location of electrical faults will be presented in view of the practical experience gained in the LHC tunnel. Three particular cases of localized faults during LHC hardware commissioning will be discussed.

INTRODUCTION

The LHC accelerator is composed of 1750 superconducting circuits powering individual or series-connected superconducting magnets distributed over lengths ranging from 5 m to 2700 m. The complex operating mode of a superconducting machine, the difficult accessibility to the circuits, the tunnel environment, and the radiation levels after beam commissioning define the constraints for the intervention time and the methods for diagnostic. Within the ELQA activities [1] a dedicated programme for electrical fault location has been established during the hardware commissioning (HC) phase in order to gain maximum experience for the operation of the LHC machine. This paper describes three types of insulation faults detected and localized during HC on the main circuits, i.e., the main dipole (MB) and the main quadrupole (MQ) circuits. The boundaries of the developed methods are presented together with the open issues to be considered for the future development of diagnostic tools.

ELECTRICAL ENVIRONMENT

The LHC superconducting circuits are housed in helium tight enclosures surrounded by a continuous cryostat. The access to the circuits is possible only at the extremities of the powering sectors, where the current-leads are installed, and via the diagnostic voltage pick-ups that are routed to the outside by a dedicated instrumentation feedthrough system [2] installed on each cryo-magnet. The two mentioned access points are the only way to get in contact with the circuits without the opening of the cryostat and the helium enclosure.

Another important parameter for a precise fault location along a circuit spreading hundreds of meters is the routing of the conductors linking the series-connected magnets. As the ohmic resistance of the conductors is very low, the routing through the cryo-magnets and the lengths of the circuit branches have to be precisely known or determined. The relevant parameters required for the fault location in the main magnet circuits are given in Table 1.

Table 1: Parameters of the MB and MQ circuits used for the location of an insulation fault

Parameter	Unit	MB	MQ
Coils in series		154	47
Signal pick-ups per magnet		12	16
Powering sector length	m	~2700	~2700
Distance between 2 magnets in series	m	~45	~108
Circuit resistance at 300 K	Ω	~950	~41
Coil resistance at 300 K	Ω	~6	~0.8
Conductor linear resistance at 300 K	$\Omega.m^{-1}$	$0.6\cdot10^{-4}$	$1.0\cdot10^{-4}$

ELECTRICAL INSULATION FAULTS

Detection of Insulation Faults

The electrical insulation of each circuit is tested by applying a d.c. voltage versus ground and versus the other circuits [3]. This test reveals any insulation fault and gives preliminary information about the fault nature.

Types of Faults

Two types of insulation faults encountered during the HC phase can be distinguished. The first consists on a solid short to ground. The resistance fault to ground or to another circuit is low and remains observable. The second type is a short occurring only when applying a voltage above a certain threshold. This type of fault manifests itself in two different scenarios. If the test is repeated, the breakdown appears at the same voltage level as at the previous test. In the second scenario the voltage breakdown degrades the insulation, thus creating a short to ground detectable without applying a voltage.

Test Conditions

The state of the machine at which an insulation fault is detected is important as it determines the procedure to apply for its location. The temperature T of the circuits is the key parameter, as the resistance of the circuit is a highly nonlinear function of T. Each circuit undergoes a series of electrical tests at different machine states. The insulation qualification is performed at 300 K before starting the cool down, and then repeated at cryogenic conditions below 2 K, prior to the powering tests. During the cool down and warm up, the insulation of circuits is monitored by applying 50 V d.c.

1: SHORT-CIRCUIT TO GROUND AT ROOM TEMPERATURE

Description of the Fault

During the electrical insulation tests at 300 K, a voltage breakdown at 1.3 kV d.c. occurred on the MB circuit. The repetition of the test provoked a second discharge at 300 V with the appearance of a solid short to ground. In order to repair the fault before the cool down of the sector, it was necessary to precisely localize the fault.

Methodology and Measuring Technique

The method consists of determining the ohmic resistances between the two circuit extremities and the fault. The measurement is done by powering the circuit in closed loop mode with a d.c. current source working in floating mode with respect to ground. As shown in Fig. 1, the voltage drop U_A at the extremity A versus ground is equal to the voltage drop measured between the point A and the fault. Symmetrically, the voltage U_B at the extremity B gives the resistance of the fault from point B. The ratio U_A / U_B allows determining the fault with an accuracy of ± 50 m along the sector. Subsequently, the same type of measurement is done locally at the circuit branches where the fault is expected. This set-up allows to the precise measurement of the voltage difference between adjacent voltage pick-ups and to compute the linear resistance of the conductor. Knowing the routing of the circuit element and their resistance, it is possible to determine the distance of the fault from the neighbouring voltage pick-ups.

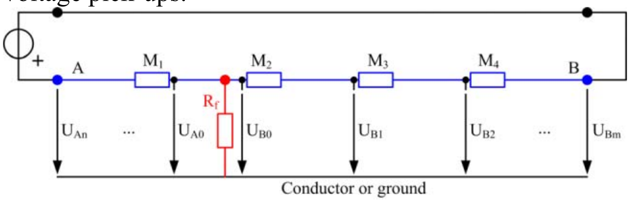

Figure 1: Fault location based on voltage ratio technique.

Measurements Analysis

The faulty region has been localized in the area of two MB magnets powered in series. Locally, the fault has been precisely localized on a conductor at 1.4 m from the neighbouring voltage pick-up. The investigation after the opening of one single interconnection confirmed the position of the fault. The conductor was actually squeezed on a metallic part and the polyimide insulation damaged.

2: EARTH FAULT DUE TO THERMAL CONTRACTIONS

Description of the Fault

During the cool down phase, at an average temperature of 130 K along the powering sector, an MQ circuit has been detected to be in contact with ground. While continuing the cool-down towards 2 K the short suddenly disappeared at around 90 K. The temporary fault to ground has been provoked by the differential thermal contractions between the metallic helium enclosure and the conductors of that circuit. The fault location was done while keeping the powering sector at an average temperature of 120 K where the fault was present.

Methodology

The method follows the one described in the previous section. However, in this case the temperature in the helium enclosures varies along cooling sub-sectors of about 108 m by up to ± 60 K. The resistance of the conductors varies accordingly. Thanks to the available voltage pick-ups and the temperature sensors in the sub-sector, the voltage drops per unit length can be determined as a function of the temperature.

Measurement Analysis

For the measurement of the partial resistances, the MB circuit is used as reference, as it has the higher number of voltage pick-ups per sub-sector. The voltage drops are measured when impressing a d.c. current to the circuit. Knowing the conductor cross-section ratio between the reference circuit MB and the faulty circuit MQ, the expected voltage drops over accessible voltage pick-ups of the MQ circuit are calculated. Fig. 2 shows the parameters of the MQ circuit and the computation of the fault location using the values U_A and U_B. The fault has been computed to be localized at around 15.4 m from the closest reference or at around 45 m from the nearest MQ pick-up in point B. The accuracy is ± 3 m and it is predominantly due to the uncertainty of the temperature gradient between two pick-ups. During the repair, the fault has been confirmed to be at a distance of 30 cm from the computed location. The insulation of the conductor was ripped off due to the friction conductor against metal.

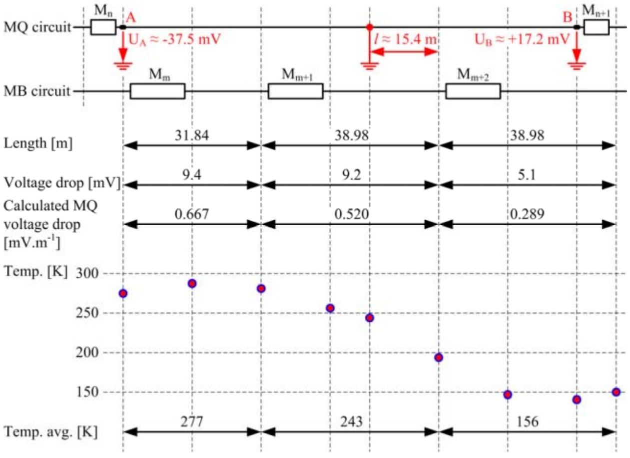

Figure 2: Diagnostic of a short circuit to ground in a sub-sector whose temperature is non-homogenous.

3: HIGH VOLTAGE BREAKDOWN AT CRYOGENIC CONDITIONS

Description of the Fault

During the MB electrical insulation test at cryogenic conditions, a voltage breakdown occurred at 1.4 kV d.c., the nominal value for the successful qualification being at

1.9 kV. The first breakdown did not create any solid short to ground.

Methodology and Measuring Technique

The location technique for this type of faults is based on the measurement of the velocity of propagation of the spark-induced signal generated by the voltage breakdown [4]. The measurement of the time difference between signals propagating from the fault origin along the conductors allows determining the location of the fault. On large circuits and in presence of a series of highly inductive magnets, a first rough location of the fault is undertaken. As shown in Fig. 3, two or more fast digital oscilloscopes acquire the propagating waves at the extremities of selected magnets. The relatively long time delay of the signal propagation along a coil allows determining the direction of the signal. Each oscilloscope triggers without a common synchronization when the wave is propagating along the magnet. The temporary sequence of the signals acquired allows determining if the fault arrived from the left or right side of the measuring point. Based on a Golden Section Search (subdividing the search in two areas of 0.4 and 0.6 times the original length) the faulty area is localized.

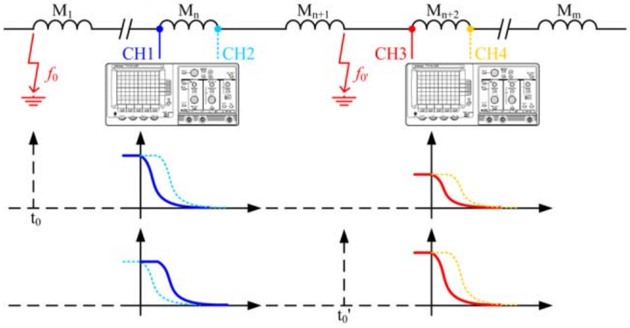

Figure 3: Approximate location of spark-induced signals.

High Precision Location of Fault

Once the faulty area has been found a more precise location of the fault can be done only by comparing traces of nearby voltage pick-ups. Fig. 4 shows the set-up used locally and Fig. 5 presents the read-out of the four signals. Signal on channel 2 is in advance with respect to all other signals. Channels 2 and 3 are acquiring two pick-ups physically soldered at the same location. The signal measured on channel 2 is clearly in advance thus the fault is located along the 3 m long instrumentation wire of the pick-up. However the exact position cannot be determined since the cut-off time of the two signals is not evident to define. The accuracy is estimated to be ± 1 m. During the repair the fault was found along the pointed wire which was damaged at the output of a capillary tube.

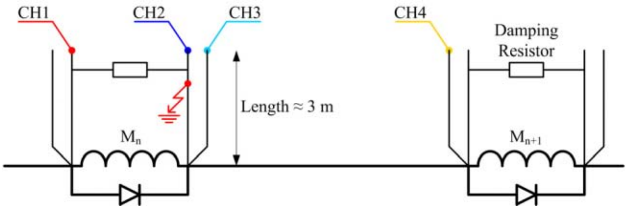

Figure 4: Local set-up for time difference measurements.

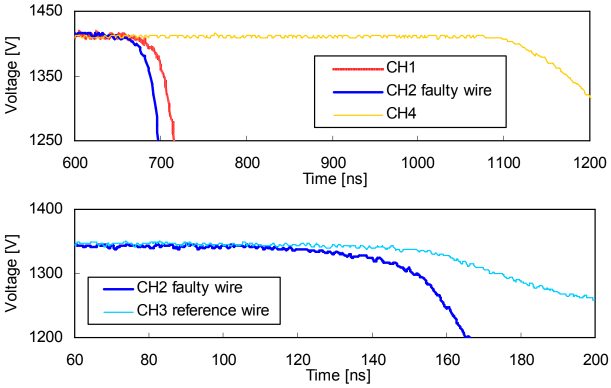

Figure 5: Records of spark-induced signals.

PRACTICAL EXPERIENCE

Beyond the technical aspect on how to treat such electrical faults, two other important factors are the duration and the resources required for such interventions. The application of the voltage ratio method on long and complex circuits requires free access to the machine for three people during 8 working hours. Additional 8 hours are needed for processing and analyzing the measurements taken and to check the relevant integration drawings. For the location of a fault in an environment with varying temperature, 8 additional hours are necessary for temperature measurements and the gauging of the measurements. In summary up to 24 hours are needed for the diagnostic and location of a voltage breakdown fault.

CONCLUSION

The three methods presented have been successfully applied for the location of electrical faults detected during the hardware commissioning phase of the LHC machine. These methods have proven to work in case of solid short circuits and breakdowns under a d.c. voltage. In case of highly resistive faults to ground these methods cannot be applied. A solid short appearing when the circuits are in their superconducting state has not yet been experienced. Time domain reflectometry would be in this case the best method but has to be validated under realistic conditions.

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