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**FAULT DETECTION AND IDENTIFICATION METHODS
USED FOR THE LHC CRYOMAGNETS AND RELATED CABLING**

D. Bozzini, F. Caspers, V. Chareyre, Y. Duse, T. Kroyer, R. Lopez, A. Poncet, S. Russenschuck

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Several methods for electrical fault location have been developed and tested. As part of the electrical quality assurance program for the LHC, certain wires have to be subjected to a (high) DC voltage for the testing of the insulation. With the time difference of spark-induced electromagnetic signals measured with an oscilloscope, fault localization within ± 10 cm has been achieved. Another method used, and adapted for particular needs, is the synthetic pulse time-domain reflectometry (TDR) with a vector network analyzer (VNA). This instrument has also been applied as a low frequency sweep impedance analyzer in order to measure fractional capacitances of cable assemblies where TDR was not applicable.

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Several methods for electrical fault location have been developed and tested. As part of the electrical quality assurance program for the LHC, certain wires have to be subjected to a (high) DC voltage for the testing of the insulation. With the time difference of spark-induced electromagnetic signals measured with an oscilloscope, fault localization within ± 10 cm has been achieved. Another method used, and adapted for particular needs, is the synthetic pulse time-domain reflectometry (TDR) with a vector network analyzer (VNA). This instrument has also been applied as a low frequency sweep impedance analyzer in order to measure fractional capacitances of cable assemblies where TDR was not applicable.

INTRODUCTION

The LHC accelerator is composed of 1750 superconducting circuits powering individual or series-connected superconducting magnets. The complexities of a superconducting machine, the difficult access to the live parts of the electrical circuits, and the soldered interconnections all housed in a cryogenic environment, have motivated the development of methods for the electrical fault location. This paper lists the major constraints limiting the electrical diagnostic of the LHC superconducting circuits. It gives an overview of three methods developed and successfully tested during the manufacturing and installation of cables and bus-bars. The limitations of the presented methods and the objectives for the future developments are also presented.

ELECTRICAL FAULT LOCATION

The difficulty related to the detection and location of electrical faults mainly depends on the accessibility of the conductors, the inductive and capacitive characteristics of the circuits, and on the length and geometrical layout of the circuit.

Superconducting accelerators are composed of highly inductive magnet elements connected in series and spread over hundreds of meters. In contrast to accelerators with normal conducting magnets, the conductors and bus-bars are not working in an ambient environment. In conventional machines, the accessibility to the circuits at the extremity of each magnet allows to perform electrical diagnostic measurements in a relatively easy and fast way. If necessary, a part of the circuit can be electrically insulated by simply opening the accessible interconnections. In a superconducting accelerator, the conductors, bus-bars and magnets are operated in a cryogenic temperature environment. In the LHC, the

circuits are located in cryogenic distribution lines and the magnet cold masses themselves are housed in cryostats under vacuum [1]. In the continuous cryostat regions, the longest distance covered by a chain of magnets is 2.7 km and the most complex circuit is composed of more than 400 bus-bar segments. In order to obtain the required low resistance, the electrical interconnections of the elements composing a superconducting circuit are soft soldered [2] or ultrasonically welded. Those interconnections cannot be opened, nor accessed, for electrical fault detection. The above described differences between resistive and superconducting accelerators motivated the development of new methods for a precise and systematic detection.

TYPES OF FAULTS

Faults affecting electrical circuits can be of different nature, resulting in different degrees of complexity for their diagnostic. The two main classes are faults detectable at any time (such as an open circuit) and faults appearing only under particular circumstances (such as a short circuit between a conductor and ground appearing when the circuit is high voltage tested). A third type of fault includes all the cases affected by varying environmental parameters such as the variation of the insulating resistance due to changing humidity or temperature. The three methods presented in this paper are applicable for the first two types.

METHOD 1: SPARK-INDUCED ELECTROMAGNETIC SIGNALS

Description of the Fault

During a qualification test at 4 kV (DC) between two conductors of a 638 m long superconducting cable, a voltage break-down at 2.05 kV was observed. To decide whether to replace or locally repair the faulty cable, it was necessary to identify the exact location of the fault.

Methodology

During a voltage break-down in a conductor of length l , a spark-induced electromagnetic signal is generated exactly where the break-down takes place. Two waves will propagate in both directions with a constant signal propagation velocity, denoted v , towards the direction of the extremities of the conductor (denoted A and B). The time difference Δt measured between the two signals arriving at the extremities of the conductor allows calculating the distance l_f of the fault from the extremity A by the simple relation,

$$l_f = \frac{1}{2} \cdot (l - \Delta t \cdot v)$$

Set-up Configuration

A DC voltage source is connected between the two conductors. Two high voltage probes of a 500 MHz digital scope are connected to the extremities A and B of the conductor. Figure 1 shows configuration.

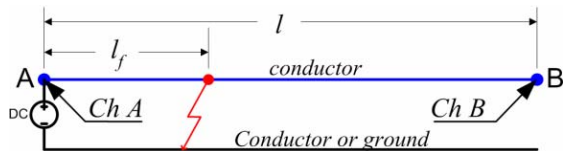


Figure 1: Setup for time difference measurement of spark-induced electromagnetic signals.

The scope will trigger on Channel A in a single mode detection configuration. The detection level is fixed at 5 V (AC). Once the trigger is armed the voltage level is increased up to the break-down level. The spark-induced signal picked up by Channel A launches the recording of the two channels.

Measurement Analysis

The calculation of the distance l_f requires knowing the exact signal propagation velocity of the tested wire. The propagation velocity of a signal in a shielded conductor depends on the linear impedance of the conductor. For superconducting wires and cables for a particular application, these values are unknown, and the impedance might be erratic due to the absence of a shielding and due to a variation in the environmental parameters. Two different approaches have been tested to measure the propagation velocity. The first is the laboratory measurement of a type-test conductor. The second consists of measuring it on a conductor with an exact known length installed in a real working environment. Table 1 gives the propagation velocity measured for two types of superconducting wires by using the two approaches.

Table 1: Signal propagation velocity in superconducting wires (c denoting the speed of light).

Wire type	Wire description	Working environment	Length [m]	Velocity of propagation [m/s]
1	6 kA s-c wire, 7 Cu strands, 13 NbTi strands	Laboratory test	4.61	0.58-c
		Real working environment	4.06	0.68-c
2	Single copper wire AWG 26, 19 strands	Laboratory test	6.00	0.65-c
		Real working environment	6.80	0.67-c

The accuracy obtained in determining the distance of the fault on conductors with a maximum length of 638 m is within ± 5 mm per meter. Fig. 2 shows the read-out of the two signals of the tested wire of type 1. The measured time difference of 3355 ns gives a fault distance of 25.1 m from point A, which was confirmed by the measurement of the fault distance after the dismantling of the cable.

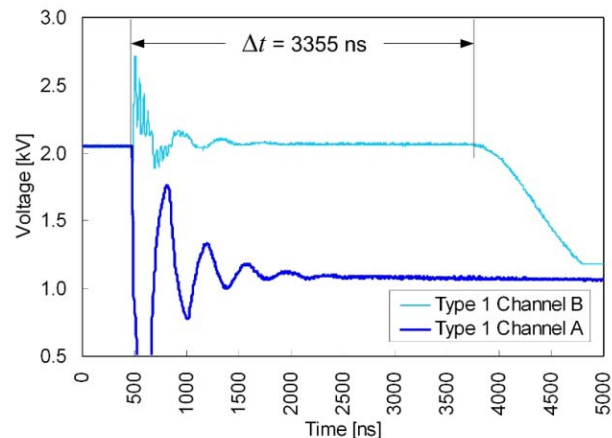


Figure 2: Record of spark-induced waves at both extremities of a type 1 wire.

METHOD 2: TIME-DOMAIN REFLECTOMETRY

Description of the Fault

During the qualification tests of superconducting magnets, several hard faults (open circuits and short circuits) have been detected on a type 1 wire which powers a superconducting coil. The fault presented in this case is a short to ground. The exact location of the fault position determines the type and complexity of intervention for repair.

Methodology

Time-domain reflectometry is a well known method for hard faults localization [3]. A short low voltage pulse is injected in a wire. Depending on the change of impedance along the wire, the pulse (or a part of it) is reflected. The time delay between the incident and reflected signal, the magnitude and polarity of the reflected signal and the propagation velocity, allow the location of the impedance change and the nature of the fault. From a practical point of view, due to the superposition of the multiple reflections generated by the pulse, the diagnostic is done by comparing the resulting wave caused by a faulty wire with a reference wire placed in the same environment.

Set Up Configuration

Two different configurations have been tested. The first is based on a synthetic pulse time-domain reflectometry by means of a VNA (HP8753). The complex data set of S-parameters taken at a number of equidistantly spaced frequencies can be transformed into the time domain. The advantage of taking measurements in the frequency domain are a better signal to noise ratio as compared to direct time domain measurements, and a pulse shape that can be tailored to specific needs. The results obtained with the VNA have been confirmed with measurements taken with an industrial TDR of type MEGGER 2000/2P.

Measurement Analysis

VNA and industrial TDR measurements are plotted in Figures 3 and 4, respectively. Each plot contains the trace of the reference-wire signal and the faulty-wire signal.

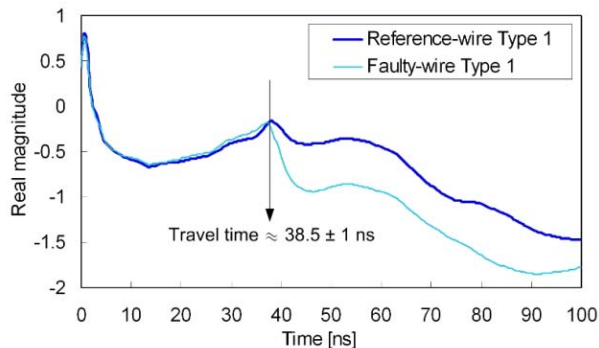


Figure 3: Measurements based on a synthetic pulse time-domain reflectometry by means of a VNA.

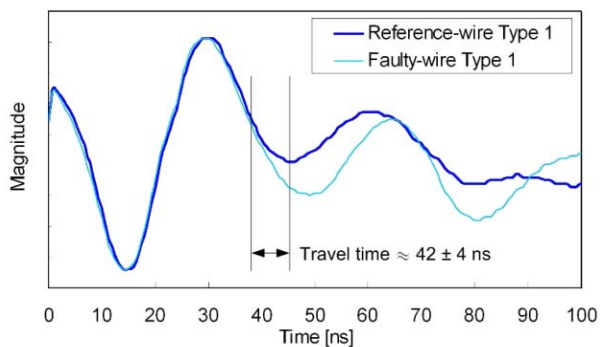


Figure 4: Measurements done with an industrial TDR.

Both configurations are successfully applied to determine the exact location of the fault. The possibility to generate short rectangular pulses with the VNA allows measuring with a high accuracy the time delay, therefore the fault distance can be calculated within ± 10 cm. The industrial TDR has a pulse width of 7 ns with a resolution of 1 ns. Fig. 4 shows that the change of form of the two waves is less accurate on this type of plot. The accuracy obtained with this conventional TDR is within ± 40 cm.

METHOD 3: MEASUREMENT OF FRACTIONAL CAPACITANCES

Description of the Fault

An open circuit fault has been detected on wires of type 2 of a length of 10 m installed inside a magnet cold mass. For this type of hard fault location, method 2 could be applied, but in this case a different method based on the fractional measurement of capacitances is presented.

Methodology

As shown in Figure 5, an open circuit is composed of two portions of circuit of lengths l_1 , l_2 and capacitances C_1 , C_2 measured versus ground. This method allows determining the location of the fault by measuring the capacitances of each portion by pointing to terminals A

and B, with respect to ground. This method is applicable if the wires are in the same environment; routing path and the dielectric characteristic are the same. Under this assumption, the calculated ratio $C_1 / (C_1 + C_2)$ corresponds to the ratio of $l_1 / (l_1 + l_2)$. A cross check is done by measuring the total capacitance C_{tot} with A and B connected in common mode.

Set up Configuration

A VNA, used as a diagnostic, tool can be converted into a swept frequency impedance meter up to about 10 MHz. This mode of operation is in particular useful for wiring faults which cannot easily be pinpointed by conventional or synthetic pulse TDR (e.g. if there are lumped capacitors in the wire loop to be tested).

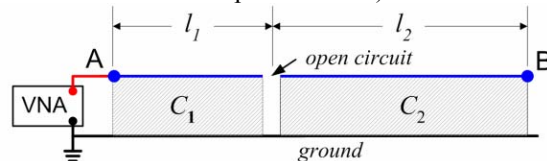


Figure 5: Fractional capacity measurement of portion l_1 .

LIMITATIONS OF THE METHODS

While testing with Method 1 a circuit having a high capacitance versus ground, the use of a DC voltage source charging the capacitances might be risky. At the breakdown the stored energy will be discharged through the fault, increasing the level of the damage. For TDR methods, the lumped capacitors and inductances in the wire loop will change the linear impedance. The location of faults on loops with impedances changes cannot be done with the presented methods.

CONCLUSION

Methods for diagnostics of non hard faults without entering in the domain of destructive tests should be investigated. Improvements are envisaged to avoid this problem by developing a static high voltage short test pulse generator that will limit the energy applied to the circuit. Methods 2 and 3 are used on a regular basis, but they are limited to the detection of hard faults affecting portion of circuits with invariable linear impedance and a known velocity propagation of the signal. Faults showing degradation of the insulation in the range of 100 Ω up to 100 K Ω cannot be detected by these methods

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