LHC DIPOLE MAGNET SPLICE RESISTANCE FROM SM18 DATA MINING

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Abstract

The splice incident which happened during commissioning of the LHC on the 19th of September 2008 caused damage to several magnets and adjacent equipment. This raised not only the question of how it happened, but also about the state of all other splices. The inter magnet splices were immediately studied and new measurements recorded, but the internal magnet splices were still a concern. At the Chamonix meeting in January 2009, the CERN management decided to create a working group to analyse quench data of the magnet acceptance tests in an attempt to find indications for bad splices in the main dipoles. This resulted in a data-mining project that took about one year to complete. This presentation describes how the data was stored, extracted and analysed reusing existing LabVIEW™ based tools. We also present the encountered difficulties and the importance of combining measured data with operator notes in the logbook.

INTRODUCTION

After the melting of a busbar interconnect splice in sector 34 in September 2008 during hardware commissioning, a special campaign was initiated to find bad splices by calorimetric and quench protection system (QPS) measurements [1]. These measurements were made in sectors 12, 56, 67, 78 and 81. The sectors 23, 34 and 45 were not measured, due to the fact that they were not cold at the time of the campaign.

No bad splices were found within the detection limits of 20 nΩ, but two bad magnet splices of about 100 and 50 nΩ were found inside the dipole magnets (MBBI334 and MBBI303). When these magnets were opened 'hardly soldered' splices were indeed found between poles and apertures.

The Chamonix Workshop (January, 2009) therefore gave a recommendation to look back in the magnet test facility (SM18) data and try to find indications for bad splices looking at the old provoked quench test data.

A working group was formed with members from the Technologies, Engineering and Physics departments to make this analysis [2]. It was decided to study with priority the magnets in sectors 23, 34 and 45, for which the least precise measurements existed, as they were not cold at the time of the campaign. It was also decided to study only the main dipoles. The main quadrupoles were connected in quite a different way in SM18 than in the LHC, thus making the joint measurements very uncertain.

During the tests, after repair of the damaged magnets of Sector 34, a dedicated measurement was put in place to measure the magnet splice resistance. These measurements were compared with the quench test data and it was found that the error could easily be 20 nΩ (nominal about 0.3 nΩ), similar to the error in the calorimetric measurements made in LHC.

AVAILABLE DATA FROM THE SM18 MAGNET TESTS

Hall SM18 is the test facility used during the 4 years campaign dedicated to LHC magnets reception and validation.

The data recorded during the magnet acceptance tests primarily contained the electrical insulation of the coils and heaters and at the maximum field strength [3]. A second objective was to determine the field quality through magnetic measurements. No specific splice resistance test was performed.

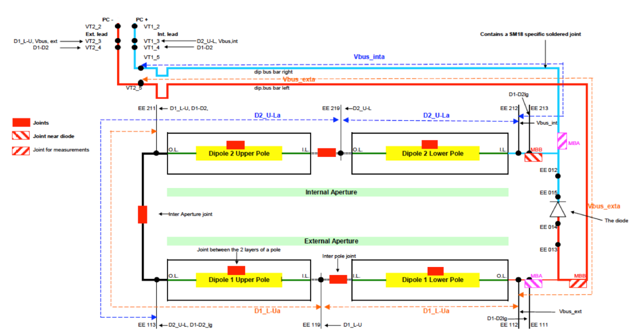

Figure 1: Electrical connections and splices of a LHC dipole.

Nevertheless the quench recorder system, used during these qualification tests, allowed acquiring and archiving hundreds of voltage signals, before and after the quench. These measurements were taken over several sections of the magnet circuit, through the existing voltage taps (see Fig. 1) inside and around the dipole. It is not possible to directly measure the voltage at a specific splice due to the positioning of the voltage taps. The data only allows for the comparison of voltage values in different segments of the magnet for constant currents: any abnormally high value in the difference of measured voltages is an indication of a relatively large resistance in the splices. The method is applicable in the assumption that the probability of having two or more large resistances in the same dipole, whose effects cancel each other perfectly, is very low.

We list here (see Fig. 2) the voltage differences used in order to infer the quality of the two inter-poles, the inter-aperture and the diode splice resistances.

$$V_{D1\_L-Ua} = V_{D1\_L-U} - V_{bus\_Ext}$$
$$V_{D2\_U-La} = V_{D2\_U-L} - V_{bus\_Int}$$
$$V_{D1-D2a} = V_{D1-D2} - V_{bus\_Ext} + V_{supra\_Ext\_lead} - V_{clamp\_Ext} + V_{bus\_int} - V_{supra\_Int\_lead} + V_{clamp\_Int}$$
$$V_{bus\_Inta} = V_{bus\_Int} - V_{supra\_Int\_lead}$$
$$V_{bus\_Exta} = V_{bus\_Ext} - V_{supra\_Ext\_lead}$$
$$V_{Diodesplice} = \begin{Bmatrix} V_{bus\_Exta} & \text{for MBA dipoles} \\ V_{bus\_Inta} & \text{for MBB dipoles} \end{Bmatrix}$$

Figure 2: Voltages used for the splice analysis.

Data Selection

The most suitable tests for our analysis were those with a long constant current at different current levels. These are present in the quench heater test at 1.5, 3, 12 and 13 kA. They have sometimes a very short constant current part, due to the fact that the operator triggered the recording manually when the current reached the desired value. The constant current recordings vary between 2 and 15 seconds at a sampling rate of 5 kHz (see Fig. 3).

The data taken at 12 and 13 kA have a recording at constant current before and after the trigger, but due to the uncertainty of the amplitude of the offset in the voltage signals, one needs a reference at lower or zero current for comparison.

Constraints of the Measurement Electronics

The electronics used for the amplification of the voltage tap signals consists of two parts connected in series: an isolation amplifier and a variable gain operational amplifier.

This last one can amplify or attenuate the signal depending on the gain setting that is adjustable with a rotary switch. The gain value for each channel has to be manually entered into a configuration database as there is no electronic read-out.

It also has a potentiometer to adjust the zero offset, which is done manually at the start of each measurement campaign.

These manual operations generate some risks, in terms of exactitude of the database content but also for the measured signals.

ANALYSIS METHODS AND TOOLS

High Frequency Data

Our first method determined the resistance of the splices, shown in Figure 3, using the voltage signals over the measured magnet current. For each magnet analysed, these values have been read from high current (around 12 kA) and low current (3 and 1.5 kA) data. Then formulas were applied to return only differential voltages of inter-pole, inter-aperture, internal bus and external bus splices. Afterwards a best-fit interpolation was done on the curves U = f (I) for the selected signals to obtain splice resistance of the related connections. We will refer to this as the fit method. It assumed that the offset is stable in time and is thus very sensitive to any offset drift. As this drift was a concern, a second method has been applied to improve the accuracy of the results.

Most of the magnets have their measurement sequence executed over several days. This leads to potential sources of offset mainly due to electronics drift over time and SM18 hall temperature variations.

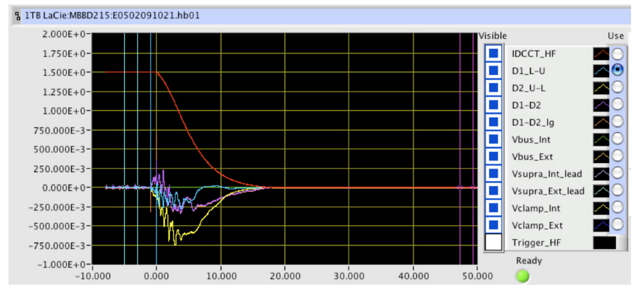

Figure 3: Magnet current and voltage signals from a 1.5 kA SM18 data file.

We assumed that offsets were constant on the voltage signals in the short time span before and after the quench, we have used the SM18 data to compensate the offsets. The resistance was then calculated in a differential way, subtracting these two voltages over the current before the quench.

The limitation of this method was that only the 1.5 kA measurements were usable, because the data taken at higher currents did not include the needed stabilized signals. Even for some quenches at 1.5 kA, signals did not always stabilize well, due to the dynamic behavior of the magnetic field and could not be used.

Another problem we found was that in about 10% of the measurements the gain for the signals V_{bus_Int} and V_{bus_Ext} was systematically too high by a factor of 400. By reading the operation logbook, it has been possible to correct these measurements. This eliminated several otherwise suspect magnets.

Low Frequency Data

After the success of the offset compensation method applied to measurements at 1.5 kA, we tried to see whether a similar method could be applied to high current data based on the low frequency signal sampling. In a short interval around the quench, the sampling frequency is 1 kHz. Outside of this interval signals are recorded when their values change by a certain minimum amount, else only once in 10 minutes, resulting in very few points. Unlike at 5 kHz sampling, offsets are compensated by the measurement electronics used for the low frequency sampling. We tried to see whether these data could be used for offset correction of the data at 12 kA. Unfortunately this was not possible, as there were too few data points in the interval following the quench.

Noise Characteristics

The voltage signals studied typically have a 1 mV noise amplitude peak-to-peak, which is much more than the DC values relevant for 10-100 nΩ resistances.

Early in the analysis we looked at frequency spectra of some signals to check if systematic features in the noise could influence the DC measurements. This turned out to be not the case. Typically there was a strong 400 Hz (and harmonics) contribution in the spectra, explained by the regulating frequency of the power converters, but no noise which could influence the DC value derived from averaging the signals measured at 5 kHz sampling frequency.

Analysis Tools

To cope with the large number of files to be processed (for 1530 measured magnets we had 23000 files) we have developed a tool for automatic data extraction and analysis.

It was designed as follows: A configuration file stored the list of the data types to use for the analysis. The tool automatically opened the files, determined the stable current plateaus and extracted the relevant voltages. Then it performed a linear fit through all the points to evaluate the resistance from the slope. Distribution plots were displayed by the application for each calculated voltage, which gave an overview of the resistances for a complete sector.

RESULTS

The Data Sample

Each dipole magnet tested in SM18 has been measured under several conditions to study its performance. Nevertheless, by only measuring those magnets that contained a long enough stable plateau in current and voltage could provide results that can be used for the resistance calculation. In addition, the linear fit method was only applied to measurements taken within a few hours of each other to avoid introducing errors due to change of conditions (drift in electronics, temperature...).

The measurement system has a 16-bit accuracy over ±10V, which gives 0.3 mV of precision. The amplifier gain was x5 on the D1 and D2 channels. The analysis used current data from 1.5 kA to 12 kA. From this we could calculate that 1 bit corresponded to 5 nΩ at 12 kA. Due to averaging over several hundred points the resolution was improved to 0.5 nΩ.

The distribution showed that the FWHM of the inter-pole resistance was ~10 nΩ. The RMS of the inter-pole resistance per magnet was 0.5 nΩ and 1 nΩ, as expected from the resolution, however this does not take into account systematic effects such as offset drift.

In the course of the analysis we found that the data set corresponding to magnets belonging to sector 78 gave particularly bad results: 33 of the 154 magnets could not be qualified at all. In depth investigation of the data showed that in most cases, even if a current plateau had been reached it was not long enough to allow all voltage signals to stabilize. As sector 78 was filled with the first magnets, we assume that the measurement procedures and tools in SM18 were not yet well tuned and that therefore the measurement conditions were not easily comparable with the other sectors.

The complete available data set was used to crosscheck the quality of the analysis tool, in particular when the individual bench behaviors were analysed. But to get results quickly, we only performed a complete study of the resistances for those magnets from sectors that had not been measured with more accurate methods, i.e. sectors 23, 34, and 45. However, to verify the reliability of our results we performed a detailed analysis of sector 67, which had more precise QPS measurements.

Analysis of the Bench Stability

The SM18 magnet test facility consists of 12 benches arranged in 6 clusters of two, sharing the same racks of DAQ electronics [4]. After analysing the data using the linear fit method, we noticed that the amount of magnets with suspect values on one of their inter-pole splice was strongly dependent on the bench it was measured on and on the date of the measurement. We therefore performed a study in order to characterize the benches (and/or their electronics).

For this we focused on two resistances, R11 and R14, which entirely belonged to the bench, as well as the clamps connecting the dipoles to the bench. We observed that:

- Data taken for the same magnet during different periods of time or on different benches could not be combined.
- The characteristics of two benches over time were unstable.

In the course of this analysis we detected several measurements indicating bench resistances substantially higher than 100 nΩ: besides being unusable for the purpose of the determination of the dipole resistances, these measurements pointed to an error in the electronics, as they could not be physically true. Indeed, in several occasions, the gain factor was wrongly entered into the configuration files associated to the data.

Comparison of Offsets

A total of 152 usable measurements at 1.5 kA were available for the magnets that showed a high resistance in the fit method. Many of the 1.5 kA measurements made on two benches gave high values for D2_U-L.

Excluding these two “bad” benches in the offset compensation method left only a few magnets with R(D2)> 25 nΩ .

A crosscheck of the best-fit and offset compensation methods has been done using all magnets measured on one good bench. These measurements showed particularly good signals. The result was that the offset method worked very well once the gain correction was applied.

Analysis Summary

Overall there were five magnets flagged for high resistance in one or several of the D1, D2, or Diode splices. One of the five magnets was known to have a bad D2 splice; the results of the other magnets were explained by non-stabilized signals. Without gain correction, four more magnets with (very) high resistance would have been flagged.

The measurements of D2 on the two “bad” benches showed signals that were not stabilized before the end of the recording. Thus we excluded these two benches for analysis of D2 with the offset compensation method.

The number of suspicious magnets resulting from the combination of both methods turned out small enough for detailed further manual analysis.

In addition, sixteen magnets could not be properly evaluated due to the poor quality or missing data**.**

Another faulty magnet, which was found with QPS measurements, could not be identified unambiguously with the SM18 data, as the problematic splice was the inter-aperture one.

No other magnets were identified as having a splice resistance higher than 25 nΩ on the inter-pole or diode splices.

CONCLUSION

During this data-mining campaign aimed at finding bad magnet splices, more than 23000 magnet performance measurements were scrutinized. This has been made possible by developing a specific analysis tool, based on an existing LabVIEW™ data viewer. Adding automated pattern and signal extraction and writing analytical algorithms permitted to get an overview of the splice resistance of four LHC sectors. From this, five magnets having high internal splice resistance have been flagged.

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