ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA202

THE CONTROL SYSTEM OF THE CERN PLATFORM FOR THE TEST OF THE HIGH LUMINOSITY LHC SUPERCONDUCTING MAGNETS

H. Reymond, M. F. Gomez de la Cruz, I. Matasaho, A. Rijllart, CERN, Geneva, Switzerland

Abstract

A new generation of superconducting magnets is being developed, in the framework of the HL-LHC upgrade project. Several laboratories in Europe, USA, Japan and Russia collaborate on this project. One of the tasks assigned to CERN is to conduct the optimization tests and later the series tests, for the MQXFS and MQXF-A/B magnets. A new dedicated test bench has been built at the CERN superconducting magnet test facility (SM18), where these magnets will be evaluated under their operational conditions in the LHC tunnel. To fulfill the test conditions on these high performance magnets, a new high frequency data acquisition system (DAQ) has been designed, associated to a new software used to control two 15 kA power converters. This article presents all the technical aspects of these two major components of the test platform, from the PXIe hardware selection of the DAQ system to the operational applications deployment. The commissioning phase and results of the first measurement campaign are also reported.

INTRODUCTION

In the view to extend the discovery potential of the LHC accelerator, it is foreseen to increase its luminosity by a factor of ten beyond its initial design. To conduct this challenging project, from the preliminary studies up to the installation in the tunnel, expected for 2024/2025, a strong collaboration has been established worldwide. The involved laboratories and industrial partners from Europe, USA, Japan and Russia are joining their efforts through the High Luminosity Large Hadron Collider project (HL-LHC [1]).

This major upgrade leads, among other technological challenge, to the replacement of the Inner-Triplet, Nb-Ti made quadrupole magnets, by a new generation of high field magnets, based on Nb_3Sn conductor. In this framework, CERN has been charged to conduct the optimization tests on the MQXFS [2] (short coil prototypes, see Fig. 1) and later the series test for twenty MQXF.

At CERN, all the superconducting magnet evaluation tests are done in a dedicated test facility, named SM18. However, despite the fact that this facility is well equipped, with state of the art measurement technologies and more than fifteen dedicated cryostats (heavily used during the LHC magnets test campaign), none of them was fitted for these new demanding and upper sized magnets.

In this context, the construction of a new dedicated test area has been initiated in 2015, allowing the presence of a 800 mm large and 11 m long vertical cryostat and a high current power supply (up to 30 kA) and its associated protection circuit. These components are intended to test the magnets at the nominal temperature of 1.9 K with a peak field of 11.4 T at the conductor level.

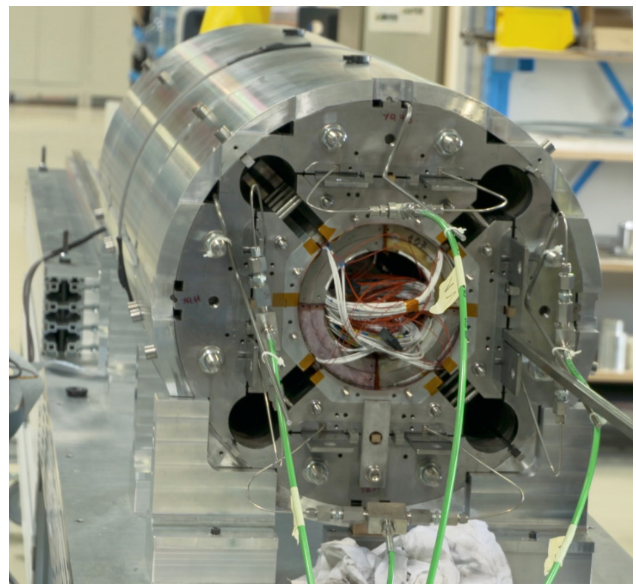

Figure 1: The assembly of the first model of the MQXFS quadrupole magnet.

Thus, in parallel with the assembly and installation of all the mechanical, electrical and cryogenic elements of this test bench (defined as Cluster D), a new data acquisition and power supplies control systems were designed and developed.

THE NEW DATA ACQUISITION SYSTEM

The aim of the DAQ is to record some signals from the magnet under test, mainly coil and quench heater voltages with the current in the circuit. The theoretical design of the DAQ system has been mainly guided by the fact that it was firstly dedicated to a magnet R&D research program. By experience we knew that in this type of project the measurement systems must be oversized in term of channels and treatment capabilities compared to one dedicated to a series measurement. The prototype magnets are much more instrumented, while hosting a big number of voltage taps (vtaps), strain gauges and quench heaters than in the final version of the production magnet. The second main point of the design was related to the high frequency reading ability, up to 200 kHz in our case. This is needed for the general magnet quench analysis but also for the flux jump analysis [3]. This very short instability, a typical behaviour of the Nb_3Sn magnet based conductor needs to be carefully studied during the prototype evaluation.

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA202

The diversity and the signal types to be analysed from such magnet type, induced the need for a synchronized multi-frequencies acquisition system, formerly HF (from 5 to 200 kHz), MF (from 1 to 5 kHz) and LF (up to 1 kHz), all with 16-bit resolution and 1 mv accuracy.

Selection of the hardware platform

Several conclusive experiences with using the PXI [4] platform, in the domain of the process control and data acquisition, comforted us in using this modular instrumentation standard. It is composed of hundreds of cots card references, provided by more than 70 suppliers. The modularity is a strong argument, as the DAQ system will have to run over a period of eight or ten years. This will ensure the possibility to either replace the CPU or some deprecated cards, by more performing devices during the expected life time of the installation.

Since five years the PXIe, an advanced version of the initial standard, has emerged on the market. It offers several improvements, among significantly increased bus bandwidth, additional timing and synchronisation features and extended levels of environmental performance needed in extreme industrial environments.

The fact that the major players in the field like Keysight Technologies™, ADLINK™, MARVIN™, and National Instruments™ are proposing their new products mainly for the PXIe standard has convinced us to adopt it.

Selection of the chassis

Due to the number of differential analogue channels expected for the HF (200) and LF (140), we took in our survey only the 18-slot chassis.

Table 1: PXIe Chassis

PXIe Chassis	Slot	Slot BW	System BW	Timing Slot
PXIe-1075	8 hybrid 8 PXI	1 GB/s	4 GB/s	1
PXIe-1085-12	16 hybrid	4 GB/s	12 GB/s	1
PXIe-1085-24	14 hybrid	8 GB/s	24 GB/s	1
PXIe-1086	16 hybrid	4 GB/s	12 GB/s	1

Our choice focused on the PXIe-1085-12, resulting in a compromise between the system bandwidth, compared to the PXIe-1085-24 and the price, compared to the PXIe-1086. This last one being fitted with a hot-swappable redundant power supply, which adds 25% to the price.

Selection of the CPU

For the CPU, the choice was relatively restrained because we were looking for a powerful one, but having in mind that these industrial components have a very short life cycle. Every four years, the new introduced product line pushes the previous one to be almost obsolete. We selected the PXIe-8840, based on a 2.7 GHz Intel Core i5-4400E chip. The two cores and the 4 GB ram were enough for the tasks to be handled. Other options were, the PXIe-8115 or PXIe-8135, but we judged them approaching their end of life and the brand new PXIe-8080 was too powerful and expensive for our needs.

Selection of the HF cards

The HF card was the most important input card of the DAQ, as it should be able to capture any magnet transient event, with a shortest duration of 5µs. To figure out this point, we made a survey from the X Series [5], which are the most advanced multifunction DAQ cards. We selected only those with 16 bits ADC and 1 MHz as minimum bandwidth.

Table 2: PXIe HF Cards

PXIe Card	AI Diff. SE	Sampling Rate	MUX
PXIe-6341	8 16	500kS/s	Yes
PXIe-6356	8	1.25MS/s	No
PXIe-6358	16	1.25MS/s	No
PXIe-6361	8 16	2MS/s	Yes
PXIe-6363	16 32	2MS/s	Yes
PXIe-6368	16	2MS/s	No

A first iteration in our selection, removed the cards without the simultaneous recording feature (one dedicated ADC per channel), to avoid the effect of the multiplexer settling time. The remaining cards having all a total harmonic distortion of -80 dBFS. The PXIe-6356 was discarded due to its 8 analogue inputs, not compatible with the total of 200 channels needed. We finally retained the PXIe-6358.

Selection of the LF cards

Concerning the medium and low frequency DAQ cards, the offer is plethoric, but here our main concern was the channel density per card. According to the precedent choices we made, 1 CPU and 13 HF cards already filled the 18-slot chassis. As we wanted to keep one slot free for future usage, the 144 LF channels would have to fit in three cards as maximum.

Our survey highlighted the four references presented in Table 3, from which we took (based on the channel density) two PXIe-6365, giving 144 differential channels. A second choice could have been the PXIe-6375, offering 104 differential channels on one card, but with the risk to

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA202

lose this amount of signals in case of failure of this unique card.

Table 3: PXIe LF Cards

PXIe Card	AI Diff. SE	Sample Rate
PXIe-6345	40 80	500kS/s
PXIe-6355	40 80	1MS/s
PXIe-6365	72 144	1MS/s
PXIe-6375	104 208	1MS/s

Design of the DAQ application

The DAQ software has been designed in view to get the most of the capabilities offered by the selected hardware, while taking into account what is expected during a magnet test data recording. The Fig. 2 presents the timeline of a typical magnet test and the distribution of the HF, MF and LF durations.

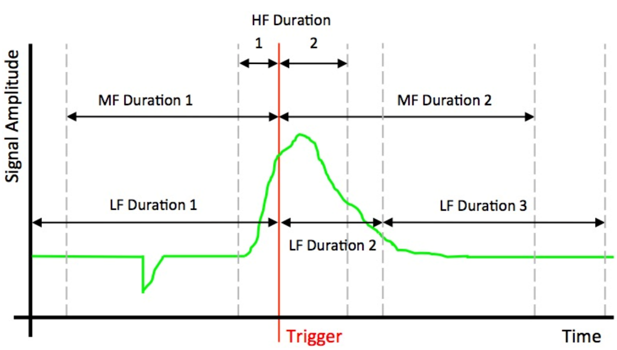

Figure 2: The timeline of a magnet recorded event.

The trigger input signal defines the zero time reference of the three frequency ranges (HF/MF and LF). The magnet signals can be recorded either by an HF or LF card, according to the cabling done from the signals to the PXIe input modules or by both when signals are split. This scheme is a good compromise between the file size of the dataset and the complete overview of the event itself. A design only based on a high frequency recording for the whole event length, would have been too expensive (i.e. local storage needed and programming efforts to manage the data stream to the disk) and not really useful taking into account the signal shape.

The ability to define a high frequency acquisition period around the trigger permits to get all the transient activity of the signals, while the medium and low frequency records give their behaviour on much longer term.

To implement these requests from the specification design toward an operational application, we used the LabVIEW™ graphical programming language.

On the structural point of view, the DAQ application has been made of two modules. One for the graphical user interface (GUI), accessible from the operational Linux consoles, present in the control room and the second running as a Real-Time application, directly on the PXIe CPU.

The GUI gives access to all the DAQ setting functionalities, through two HF/MF and LF (see Fig. 3) dedicated panels. Each of them provides an editor, where the operator can freely define the recording profile. Depending on the PXIe cards available in the chassis, all the related channels can be individually selected.

For the HF/MF configuration panel, a name, a transducer type, a gain/offset and analysis group can be defined. The HF cards can be divided into four groups, with their own acquisition frequency and recording durations. The trigger can be chosen from any of the signal list and its threshold value can also be set.

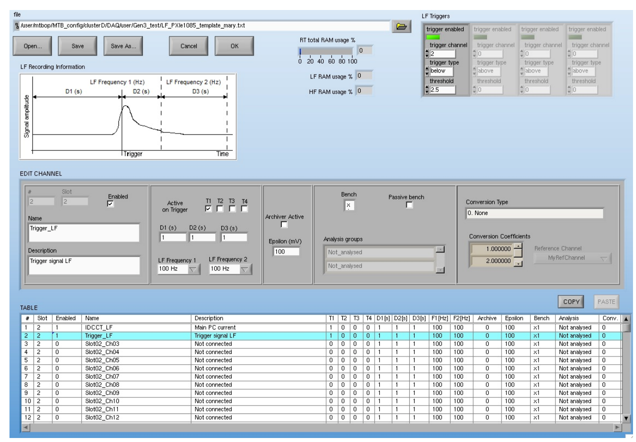

Figure 3: The LF configuration panel.

On the LF side, the properties are the same, but in addition a conversion type with a set of coefficients can be fixed. This permits to the offline analysis tools, to present the data in raw or converted unit (temperature, pressure, …). The triggering capabilities are extended to four signals, which can be detected on a falling/rising edge, over a threshold. Any channel can be attached to one of them. An optional archive mode can also be individually applied to the input channels. Data points are then taken every 10 minutes, or each second on an epsilon change threshold exceeding.

After the recording of a magnet test event, the data files stored locally on the PXIe CPU hard disk are automatically transferred, by a FTP daemon, towards a long-term storage system, where they are made available for the offline analysis tools.

THE POWERING CONTROL SYSTEM

As designed for the LHC magnet series measurement campaign, the SM18 is fitted with 6 clusters (A to F) of two magnet test benches. Each cluster has its own 15 kA

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA202

power converter (PC) and all the needed protection and DAQ systems. To optimise the use of the equipment it has been decided to move the power converter of the unused cluster F to cluster D and to connect them in parallel. This provides the 30 kA output current requested for the evaluation of the MQXF magnets.

The existing power controllers

From the technical point of view, these power converters are controlled from a Function Generator Controller [6], version 2.00 (FGC2). This embedded microcontroller-based computer performs all the actions requested, from the state control to the digital current regulation loop, allowing the full execution of the tasks expected at the powering level.

The FGC2 devices used in SM18 are the same as those in the LHC, controlling the powering of the dipole and quadrupole magnets over the 27 km of the accelerator. To achieve this, they are connected to a WorldFIP real-time fieldbus [7], which is then managed by a set of gateway front-end computers (FEC).

This same topology has been deployed in SM18, where several power converters from 60 A to 15 kA, can be controlled individually to execute any current cycle on the magnets connected on their respective cluster.

The remote control of the PC is done by sending commands through the network to the gateway FEC, associated with the unique identifier of the device to control. The string message formatted as "Device/Property#Value" is then broadcasted over the fieldbus and executed by the FGC2 that matches the message ID.

The new power converters control application

An application to operate the SM18 power converters was already in use, but was not fitted to control simultaneously two of them. This triggered the need for a new development, for which we also used LabVIEW^{TM}. Its graphical capabilities have been used to create the GUI (see Fig. 4), presenting the FGC2 status, the commands sent and received and finally the behaviour of the high power stage, for the both converters.

On the code layer, several tasks have been developed to manage the user actions from the GUI, to establish the communication with the devices and to gather all the data to be displayed for the bench operation.

The communication and subscription dedicated task gathers more than forty status signals from each PC and FGC2, which are then presented on the front panel. From these, the operator checks the "faults" and "warnings" indicators, before to switch-on the high power stage of the converters.

A specific powering start-up sequence has been developed in collaboration with the power converter experts and integrated in the control application. During this critical phase, a set of commands is sent simultaneously to both FGC2 controllers. The aim is to start the PC, firstly in voltage regulation mode. Then after several periods of five seconds, where the *POWER* application manages the proper execution of the sequence between the two converters, the regulation mode is turned to current. A succession of SET and GET commands allows the PC to get finally their expected state. Some embedded electronics ensures local execution of the regulation by using the DC current transformer (DCCT) output signals and Vref / Iref set points.

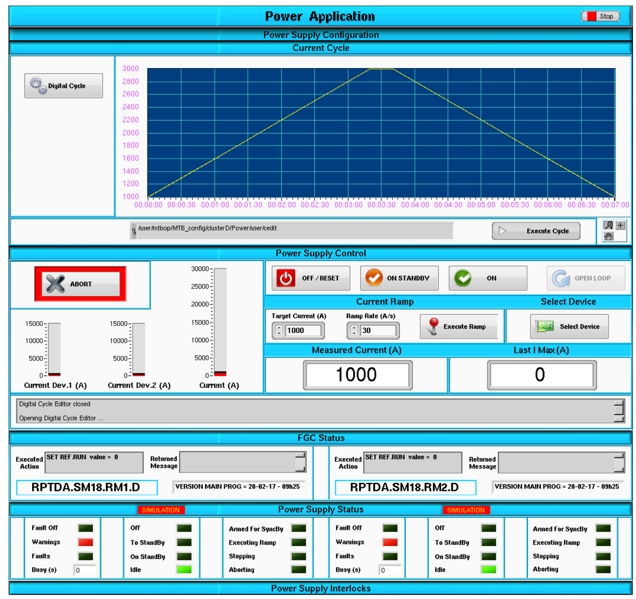

Figure 4: The main panel of the *POWER* application.

Once in idle mode the power converters are ready to execute the ramp or current cycles needed to test the magnet on the bench. For this the developed application is fitted with a complete current cycle editor. It gives the possibility to create a new or to adapt an existing current profile saved as text file. The cycle is assembled by a set of individual segments of either plateau (with proper duration and current values) or ramp (defined by the start current, end current and ramp rate values).

When launching the current cycle, the file is opened and the data are read and threated by two loops running in parallel in the application code. Each loop is charged to check the status of one FGC2 controller and to send to it the loaded cycle, with the current values divided by two. A last command is then transmitted to authorize the two FGC2 to execute the cycle. Throughout the cycle completion that can run from few seconds up to several hours, the selected one and those two running cycles are displayed on a graph, with a refreshing period of one second.

THE COMMISSIONING OF THE NEW TEST PLATFORM

The commissioning of the new test platform has been done in two stages. The first one was mainly dedicated to the cryostat and the general services used on the test bench. This campaign has been done during one full week, by testing a new prototype of 30 kA superconducting current leads. At this moment the

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA202

POWER application was not fully available neither all the current balancing and regulation electronics. The powering tests were then remotely controlled by an expert from the field, using a low level tool to send manually the FGC2 commands to the two power converters.

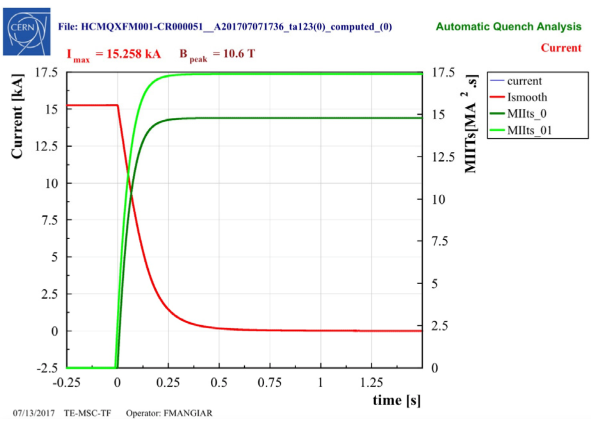

Figure 5: First quench of the MQXFS-5 magnet.

For the second phase, a MQXFS (short prototype magnet) has been installed on the bench. The *POWER* and the DAQ applications were integrated in the toolbar of the Common Console Manager (CCM), the operational application used to access to the variety of monitoring tools and software needed for the execution of the tests.

After an initial phase of tuning in the FGC2 parameters and the start-up sequence in the *POWER* application, this last one has proven its ability to control the two 15 kA power converters. The tests realised over two weeks aimed at validating all the magnet protection systems and to verify the powering capabilities of the bench. The current delivered to the magnet under test has been gradually increased, taking into account the fact that the magnet itself was a new one. Its physical integrity and its training cycle history was a constant concern for the responsible of the magnet evaluation.

After only five days of tests the first quench of the MQXFS-5 superconducting magnet, occurred at 15258 A (see Fig. 5) has fully satisfied all the involved members.

Other tests have been conducted on this magnet in the following days, leading to a quench current of 18093 A, giving a magnetic field of 12.51 T, above the 11.4 T expected at the magnet design phase.

CONCLUSIONS AND PERSPECTIVES

The need for a test bench to evaluate a new generation of superconducting magnets in the framework of the HL-LHC project initiated several R&D activities. We handled those related to the data acquisition system and to the remote control of two 15 kA power converters. After a survey, the PXIe platform has been selected for the DAQ system and a dedicated application has been developed in LabVIEW™. This graphical programming language has also been used to design new software to pilot synchronously two 15 kA power converters, from the control room of the test area. These three components have been fully assessed during the commissioning phase of the new test bench. They have proven to be well adapted to the actual needs, with several possibility of extension.

A new timing system is actually under development to allow synchronizing the data from the DAQ with other specific measurement benches, which should be added in the future, like magnetic measurements. The *POWER* application will be reused as a base for the development of a future operational tool, designated to remotely control up to nine power converters, within the framework of the CERN GSI-FAIR project [8].

REFERENCES

[1] http://hilumilhc.web.cern.ch/
[2] P. Ferracin *et al*, "Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC", FERMILAB-PUB-16-048-TD
[3] M. Marchevsky *et al*, "Magnetic Quench Antenna for the MQXF quadrupoles", FERMILAB-CONF-17-048-TD
[4] http://www.pxisa.org/About/Architecture
[5] http://www.ni.com/product-documentation/9376/en/
[6] D. Calcoen, Q. King, P.F. Semanaz, "Evolution of the CERN Power Converter Function Generator / Controller for Operation in Fast Cycling Accelerators", ICALEPCS 2011, WEPMN026
[7] R. Brun, R. Rausch, C. H. Sicard, "Using Worldfip for Synchronisation and Time Stamping in the LHC Accelerator", ICALEPCS 2001, TUAP072
[8] J. H. Derking *et al*, IOP Conf. Ser.: Mater. Sci. Eng. 101 012104