LHC INNER TRIPLET POWERING STRATEGY

F. Bordry, H. Thiesen, CERN, Geneva, Switzerland

Abstract

In order to achieve a luminosity in excess of 10^{34} $cm^{-2}s^{-1}$ at the Large Hadron Collider (LHC), special high gradient quadrupoles are required for the final focusing triplets. These low-β triplets, located in the four experimental insertions (ATLAS, CMS, ALICE, LHC-B), consist of four wide-aperture superconducting magnets: two outer quadrupoles, Q1 and Q3, with a maximum current of 7 kA and a central one divided into two identical magnets, Q2a and Q2b, with a maximum current of 11.5 kA. To optimise the powering of these mixed quadrupoles, it was decided to use two nested high-current power converters : [8kA, 8V] and [6kA, 8V]. This paper presents the consequence of the interaction between the two galvanically coupled circuits. A control strategy, using two independent, standard, LHC digital controllers, to decouple the two systems is proposed and described. The converter protection during the discharge of the magnet energy due to quenches or interlocks of the magnets are discussed. Simulation and experimental prototypes were used to validate these results.

1 INTRODUCTION

The inner triplet system provides the final focusing of the proton beams before collision at four locations in the LHC machine, the high luminosity interaction regions located at IRs 1 (ATLAS) and 5 (CMS), and the low luminosity interaction regions located at IRs 2 (ALICE) and 8 (LHCb). Each inner triplet consists of 3 quadrupole optical elements and 4 magnets (Q1, Q2a, Q2b, Q3) [1].

The KEK laboratory (Japan) is responsible for the design, manufacture and acceptance testing of the Q1 and Q3 cold masses (MQXA magnet). FERMILAB is responsible for the design, manufacture and acceptance testing of the Q2a and Q2b cold masses (MQXB magnet). FERMILAB is also responsible for the integration of the above cold masses. The inner triplet systems include several other corrector magnets and include one of the superconducting separation dipoles (D1) in the low luminosity interaction regions.

In this paper, only the powering and the protection of the main quadrupole inner triplet magnets are studied.

2 CIRCUIT DESCRIPTION

In 1999, the decision was taken that the inner triplet quadrupole magnets MQXA and MQXB will be “mixed” in the four insertions. The two types of magnets have different design and parameters (Table 1).

To optimise the powering of these mixed quadrupoles, it was decided to use two nested high-current power converters : [8kA, 8V] and [6kA, 8V]. These converters are made with a modular concept using [2kA,8V] current sources in parallel [2]. The [2kA, 8V] subconverter will be used extensively for the LHC machine: more than 700 units will be produced.

Table 1: Inner triplet magnet parameters

	MQXA (Q1, Q3)	MQXB (Q2a, Q2b)
Nominal gradient	205 T/m	205 T/m
Nominal current	6450 A	11390 A
Ultimate current	6960 A	12290 A
Inductance	90.7 mH (=L1/2)	18.5 mH (=L2/2)
Stored energy at nominal current	1890 kJ	1200 kJ

A [±600A, ±10V] trim power converter [3], connected across the Q1 magnet, allows the correction of the difference in the integrated gradients of the Q1 and Q3 magnets. Furthermore, the possibility to change only the gradient of the Q1 magnet will facilitate the β* measurements [4].

The consequence of this economical powering layout is the interaction between the three galvanically coupled circuits.

A schematic of the powering is shown in Figure 1.

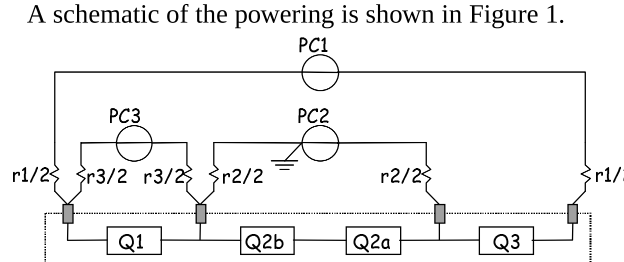


Figure 1: Inner triplet powering scheme

Table 2: Circuit parameters

PC1	[8kA, 8V]
r1	0.6 mΩ
τ1	380 s
PC2	[6kA, 8V]
r2	0.8 mΩ
τ2	50 s
PC3	[±600A, ±10V]
r3	1.4 mΩ
τ3	65 s

3 CONTROL STRATEGY

3.1 Circuit coupling

Taking into account the two main circuits, the state equations of the circuit are:

$$dX/dt = A.\ X + BU$$

with $X = \begin{bmatrix} i1 \\ i2 \end{bmatrix} \qquad U = \begin{bmatrix} v1 \\ v2 \end{bmatrix}$

and

$$A = \begin{bmatrix} \frac{-r1}{L1} & \frac{r2}{L1} \\ \frac{r1}{L1} & -r2\cdot\left(\frac{1}{L1}+\frac{1}{L2}\right) \end{bmatrix} \qquad B = \begin{bmatrix} \frac{1}{L1} & \frac{-1}{L1} \\ \frac{-1}{L1} & \frac{1}{L1}+\frac{1}{L2} \end{bmatrix}$$

From these equations, it is clear that there is inductive coupling between the two circuits: a variation in one voltage reference produces variations in both magnet currents. This system is a MIMO system (Multi Input Multi Output). This interaction leads to magnet current errors during transients. Simulations show that these errors are in the order of 10ppm at the start of the LHC ramp, which is comparable to the required reproducibility (±10 ppm) for the inner triplet converters [5].

3.2 Decoupling principle

To transform a MIMO system into two SISO (Single Input Single Output) systems, two matrices D and K are introduced to get a new system with diagonal state matrices:

$$dX/dt = (A + B.K)\ X + (B.D)\ W = Ad\ X + Bd\ W$$

The matrices Ad and Bd are chosen as follow:

$$Ad = \begin{bmatrix} -\frac{r1}{L1+L2} & 0 \\ 0 & -\frac{r2}{L2} \end{bmatrix} \qquad Bd = \begin{bmatrix} \frac{1}{L1+L2} & 0 \\ 0 & \frac{1}{L2} \end{bmatrix}$$

then

$$K = B^{-1}\ .\ (Ad - A)\ ; \qquad D = B^{-1}\ .\ Bd$$

3.3 Decoupling implementation

For LHC power converters, the high-precision current loop is a digital loop implemented in a dedicated digital controller [6]. The K and D decoupling matrices could be implemented either in digital or in analogue hardware. To simplify and standardise the control software, it was decided to use independent, standard, LHC digital controllers for the inner triplet systems. Then, the decoupling matrices are implemented on an analogue card located in one of the three converters (Figure 2).

For simplification, the presentation of the decoupling strategy was done with a system of order 2. For the inner triplet systems, the same development is done for the three-coupled circuits; the analogue decoupling card is receiving the three voltage references from the three DSPs and the three measured currents (DCCT measurements).

3.4 Results

The decoupling principle has been tested on two warm magnets with two [±600A, ±10V] converters according to the Figure 3.

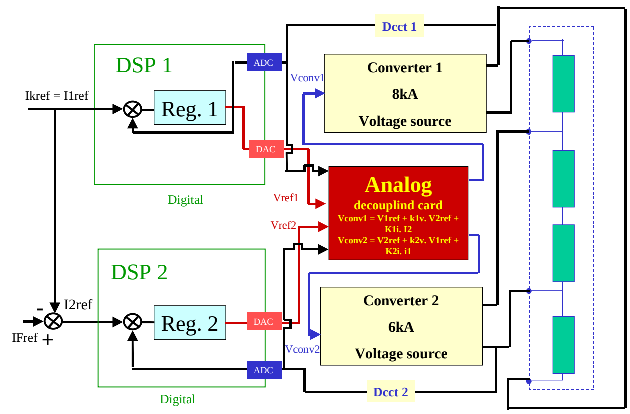


Figure 2: Inner triplet powering decoupling

Table 3: Circuit parameters

L1	r1	L2	R2	rc
15 mH	4.9 mΩ	15 mH	3.89 mΩ	1.59 mΩ

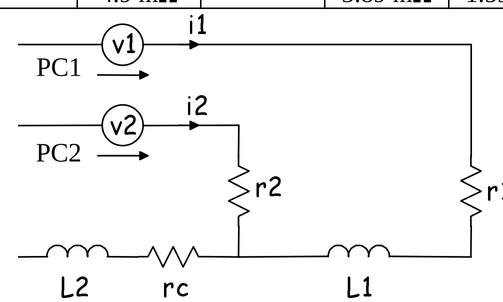
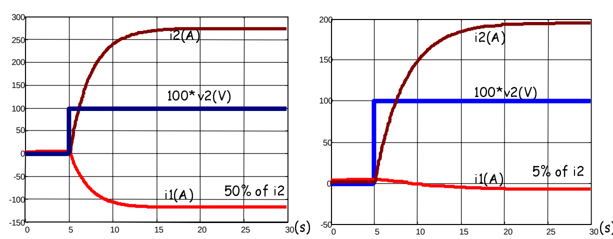


Figure 3: Experimental set-up

Figure 4 shows the error on the I1current when a step voltage of one volt is applied to the PC2 inner converter; the voltage reference to PC1 is constant (30mV). In spite of a large perturbation, the error on the current I1 is small in the case of decoupling (less than 5% of I2 instead of more than 50%).



a) without decoupling b) with decoupling

Figure 4: Experimental results

These results are obtained with parameter variations on the resistance and inductance values in the order of 10%.

4 POWER CONVERTER PROTECTION

The two 1-quadrant converters are built with free-wheel diodes. The 4-quadrant converter is protected by two back-to-back thyristors. These free-wheel devices are normally rated to the maximum current of the converters and their cooling is designed according to the time constant of the circuit. However special attention should be exercised in case of nested converters.

4.1 Power converter fault

If a fault occurs in one of the three converters, the others are shut down immediately. The magnet currents free wheel through Dpc1, Dpc2 and Th1a. The time constants of these decaying currents are long (Figure 6). To withstand these discharges, the Dpc1, Dpc2 and Th1a devices are water-cooled by independant circuits. If a lack of water is detected in the Dpc1 cooling circuit, the four magnets will be quenched by firing the quench-heater power supplies.

4.2 Magnet quench

For the converter protection, the worst case is the quench of Q2a or Q2b. In this case, as soon as the i2 current through the inner converter is equal to zero, a high overvoltage (up to 3kV) is applied across the PC2 converter. To avoid this destructive overvoltage, it is necessary to add some semiconductor devices to give a low impedance path for the Q1 and Q3 magnet currents. A first solution is to add a thyristor in anti-parallel with the PC2 converter. This thyristor should be designed to carry the maximum current of Q1,3 magnets (7kA). A second solution is to connect an extra 7kA diode (D3) across Q3 magnet (Figure 5). This solution does not require any firing circuit. Figure 7 shows the simulated evolution of the three power converter currents and voltages after Q2 magnet quench. The Th1a thyristor must be rated to withstand 7kA current in spite of its location in a 600A converter. The cooling of these semiconductors is not a crucial point as all the inner triplet magnets are quenched by quench heaters as soon as a quench is detected on any magnet. It should be noted that if the PC3 converter could be a 1-quadrant converter, the Th1a thyristor could be replaced by a 7kA diode and Th1b could be removed. The protection then becomes purely passive.

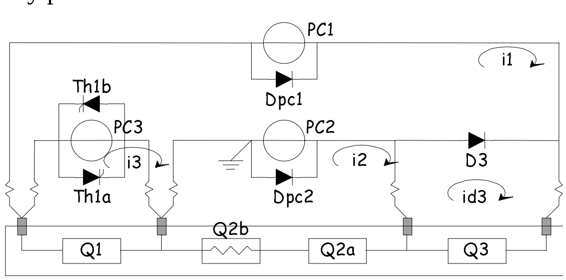


Figure 5: Inner triplet powering protection

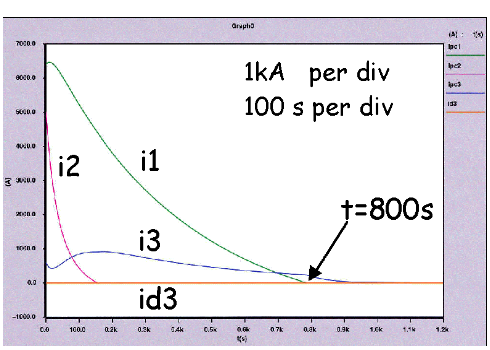


Figure 6: Simulated current waveforms during the converter shut-down

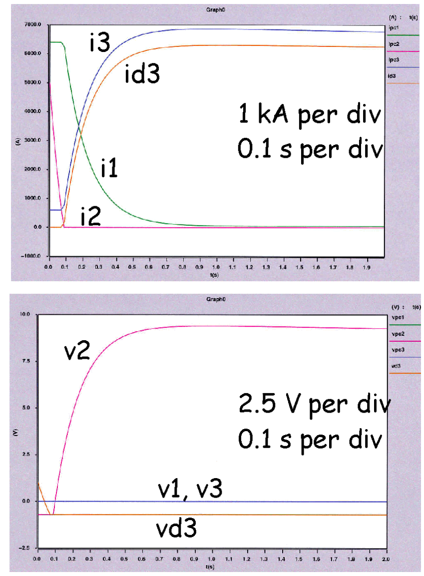


Figure 7: Simulated waveforms after Q2 quench

5 CONCLUSION

As a result of the tests completed to date, the control of the nested power converters seems to fulfil all the performance requirements of the LHC inner triplet system. The inner triplet converters are standard LHC converters but dedicated protection devices are required. The protection of the converters in the case of an earth fault on the circuits should be studied. Before the first commissioning of the inner triplet during the LHC sector test, more tests on superconducting magnet models should confirm these results and allow finalising the converter interlocks.

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