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**Impact of the Voltage Transients after a Fast Power Abort
on the Quench Detection System in the LHC Main Dipole Chain**

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Abstract

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Each energy-extraction unit is composed of redundant electromechanical breakers, which are opened to force the current through an extraction resistor. When a switch is opened arcing occurs in the switch and a voltage of up to 1 kV builds up across the extraction resistor with a typical ramp rate of about 80 kV/s. The subsequent voltage transient propagates through the chain of 154 dipoles and superposes on the voltage waves caused by the switch-off of the power converter. The resulting effect caused intermittent triggering of the quench protection systems along with heater firings in the magnets when the transient occurred during a ramp of the current.

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Index Terms—Accelerators, LHC, quench protection, superconductors

I. INTRODUCTION

THE Large Hadron Collider (LHC) contains 8 main dipole circuits, each one composed of 154 superconducting twin-aperture dipole magnets [1]. Each dipole has an inductance L_{mag} at nominal field of 98.7 mH, so the total inductance of each circuit is 15.2 H and its total stored energy is 1.1 GJ at a nominal current of 11850 A. Nevertheless, the

maximum operating current is presently limited to 6000 A [2].

Each circuit (see Fig. 1) is powered by a 13 kA power converter (PC). The PC is by-passed by a crowbar which conducts the current when the PC is switched-off. At the output of the PC an LC filter is present with a nominal inductance (L_{filter}) and capacitance (C_{filter}) of 250 μ H and 100 mF respectively. Initially the capacitive branches of the filter had an equivalent resistance of 3.37 m Ω . The measured frequency in each of the 8 dipole circuits is 28.5 Hz, although the resonance frequency calculated with the nominal values of the filter is $f_{filter} = 1/(2\pi \cdot \sqrt{L_{filter} \cdot C_{filter}}) \approx 31.8$ Hz.

The protection of each dipole in case of a quench is ensured by the magnet Quench Protection System (QPS) [3]-[5]. This included initially only quench detectors for each magnet (iQPS) [3]. This system measures the voltage difference between the two apertures (A_{pA} , A_{pB}) of a dipole (ΔU_{ap}). This turned out not to be sufficient, and a second system was installed (nQPS) [4]-[5]. The nQPS compares the voltage across each dipole with the voltage of two electrically adjacent dipoles (ΔU_{mag}). If one of the two systems measures a difference beyond the threshold for more than the discrimination time, it triggers the firing of the quench heaters.

The protection system is complemented by cold by-pass diodes (D) and two separate energy extraction units [6]. Each is composed of redundant electromechanical switches (SW) and a 148 m Ω extraction resistor (R_{EE}) in order to quickly discharge the circuit and thus protect the by-pass diodes and the busbars. In parallel to each dipole a 100 Ω resistor (R_P) is present for smoothing transient voltage oscillations.

During the first years of LHC operation it was observed that the voltage transients generated after the PC switch-off and the switch openings can result in spurious triggering of the QPS.

Several improvements to the circuit and its QPS have been adopted in order to minimize the false triggering hence improve the circuit availability.

II. FAST POWER ABORT

In case of a quench or in case of PC-related problems, a Fast Power Abort (FPA) is triggered. It consists in the switch-off of the PC and the opening of the two extraction switches. The current of the circuit is forced to pass through the two extraction resistors and decays with a time constant of 51 s.

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Fig. 1. Schematic of the LHC main dipole circuit. On the right side, a detailed schematic of a dipole is shown.

The transient following a FPA is characterized by voltage waves generated at the output of the PC and across the switches, and propagating through the dipole chain.

The wave developed at the PC is characterized by the frequency f_{filter} . Its amplitude increases with increasing PC output voltage, given by $V_{PC,0} \approx R_{circuit} \cdot I_0 + L_{mag} \cdot dI_0/dt$, where $R_{circuit}$ is the resistance of the non-superconducting components of the circuit ($\approx 1 \text{ m}\Omega$) and I_0 is the current flowing in the circuit. $V_{PC,0}$ mainly depends on dI_0/dt since the resistive contribution is almost negligible.

Any voltage wave travelling along the circuit propagates through a dipole in a time which can be approximated as $t_{dipole} \approx \sqrt{L_{mag} \cdot C_{ground}} \approx 170 \mu\text{s}$, where C_{ground} is the capacitance to ground of each dipole ($\approx 300 \text{ nF}$) [7].

III. ADOPTED IMPROVEMENTS TO THE QPS

In February and March 2010, unacceptable spurious triggering of the QPS was observed when a FPA was requested while the circuit was ramping up or down at the nominal ramp-rate of 10 A/s. The circuit was thoroughly analyzed with PSpice® [8]-[9] to assess the impact of different modifications to the configuration of the circuit and the QPS.

Three improvements to the QPS were implemented in 2010 and 2011. Firstly, the addition of a delay between the PC switch-off and the extraction-switch openings, aiming at separating in time the effects of the different waves. Secondly, the increase of the resistance of the filter at the output of the PC (R_{filter}), aiming at increasing the damping of any wave travelling in the circuit. Thirdly, the installation of snubber capacitors (C_{SN} cf. Fig. 1) across the extraction switches, aiming at smoothing the transients occurring after the switch openings. Table I resumes the different circuit configurations discussed in the following sections.

TABLE 1 ADOPTED CIRCUIT CONFIGURATIONS

Configuration	Delay between PC switch-off and switch openings	Additional R_{filter}	Snubber capacitors
C1	No	No	No
C2	Yes	No	No
C3	Yes	Yes	Yes

A. Delay between the PC switch-off and the SW openings

In order to avoid the superposition of the waves generated by the PC switch-off and by the two switch openings, it was decided to separate in time the three events. The new configuration (C2), adopted in March 2011, features the

opening of the switch in the middle of the chain (SW1) 350 ms after the PC switch-off, and the opening of the switch at the end of the chain (SW2) 250 ms later. The adopted delays are much smaller than the time constant of the circuit (51s).

Figure 2 shows the measured voltage over the sixth magnet of the chain (U_{mag} of M006 cf. Fig. 1) after a FPA while the current was constant at 6 kA for the three different configurations shown in Table I. Before the FPA ($t < 0$), U_{mag} is about zero as no inductive component is present and $R_{circuit}$ is negligible. In configuration 1 (see Fig. 2-C1) the PC switch-off and the switch openings occur at the same time ($t=0$), resulting in a transient damped in less than 100 ms. Once the two extraction switches are opened, the voltage drop across each dipole is $-2R_{EE} \cdot I_0 / n_{dipoles} \approx -11.5 \text{ V}$, where $n_{dipoles}$ is the number of dipoles. Configuration 2 and 3 (see Fig. 2-C2 and 2-C3) clearly show the delayed opening of the switches, resulting in an intermediate U_{mag} of $-R_{EE} \cdot I_0 / n_{dipoles}$ ($350 \text{ ms} < t < 600 \text{ ms}$).

Fig. 2. U_{mag} of M006 during a FPA at $I_0=6 \text{ kA}$, $dI_0/dt=0 \text{ A/s}$. Configuration 1 (C1), Configuration 2 (C2), and Configuration 3 (C3).

The complex transients followed by U_{mag} of each dipole depend on its electrical position along the chain and on its AC characteristics, such as eddy currents and parasitic capacitances. The superposition of the three voltage transients can locally cause large ΔU_{mag} and trigger the nQPS.

While the delay between PC switch-off and switch openings is always beneficial, the delay between the two switch openings actually cause an increase in the value of U_{mag} , since the waves generated across SW1 and SW2 cancel each other when occurring simultaneously. Nevertheless, if superposition with the wave generated at the PC output is not present, ΔU_{mag}

remains below the nQPS threshold as the waves propagate uniformly along the chain. The delay between the switch openings is useful in order to study separately the effects of the three voltage transients.

B. Increase of the resistance of the filter at the PC output

The wave generated at the switch-off of the PC is caused by the energy exchange between the capacitive and inductive branches of the filter at the output of the PC.

The amplitude of this wave depends on $V_{PC,0}$, which in first approximation depends linearly on the ramp-rate of the circuit. Figure 3 shows U_{mag} of M006 during a FPA when $I_0=2$ kA and $dI_0/dt=10$ A/s. When $t<0$, $U_{mag}=L_{mag} \cdot dI_0/dt \approx 1$ V. At $t=0$ the PC is switched-off and the oscillations start.

The frequency of the wave depends on the electrical parameters of the filter at the output of the PC, as shown in section I.

The damping of the oscillations mainly depends on the inductance and resistance of the branches of the PC and its filter, and not on the characteristics of the dipole chain.

Additional resistors were added to the PC filter in February 2011, thus increasing R_{filter} from 3.37 to 10.1 m Ω . The effects of this modification are clearly visible in Fig. 3-C3. The wave frequency, which is completely determined by L_{filter} and C_{filter} , remains unchanged. After about 200 ms after the PC switch-off, the filter is completely discharged and the oscillations induced at the PC output have entirely died out. The delay set between the PC switch-off and the opening of SW1 seems appropriate for decoupling their effects.

Fig. 3. U_{mag} of M006 during a FPA at $I_0=2$ kA, $dI_0/dt=10$ A/s. Configuration 2 (C2) and Configuration 3 (C3).

Figure 4 illustrates ΔU_{ap} of M004 after the PC switch-off during the same event shown in Fig. 3. When $t<0$, $\Delta U_{mag} \approx 0$ since the inductance of the two apertures is equal. When $t=0$ the wave generated after the PC switch-off travels through the dipole and causes an unbalanced voltage drop across the two apertures due to their unmatched AC behavior.

Figure 4-C3 shows that the additional R_{filter} effectively lowers the peak values reached by ΔU_{ap} during the transient and increases the damping of the voltage perturbation.

Fig. 4 ΔU_{ap} of M004 at the PC switch-off at $I_0=2$ kA, $dI_0/dt=10$ A/s. Configuration 2 (C2) and Configuration 3 (C3).

C. Snubber capacitors across the extraction switches

During switch openings, arcing occurs in the switch and a voltage of up to 1 kV builds up across the extraction resistor with a typical ramp rate of about 80 kV/s. The subsequent voltage transient propagates through the magnet chain and causes a difference in the voltage measured both across neighboring dipoles and across the two apertures of each dipole.

In order to reduce the arcing and to smooth the voltage transient, 53 mF snubber capacitors have been installed in parallel to each switch in February 2011 [10].

The strong oscillations of U_{mag} induced by the presence of the arcing (see Fig. 2-C2 and 3-C2) are not present after the installation of the snubbers (see Fig. 2-C3 and 3-C3).

Figure 5 illustrates the minimum values reached by U_{mag} of the dipoles of the chain during the events shown in Fig. 2-C2 and 2-C3. The effective smoothing of the transient in U_{mag} after the installation of the snubbers is evident. The values of ΔU_{mag} are reduced accordingly, thus lowering the probability of a spurious triggering of the nQPS.

Fig. 5. Minimum values of U_{mag} of each dipole of the chain at the two switch openings at $I_0=6$ kA, $dI_0/dt=0$ A/s. a. Configuration 2, SW1 b. Configuration 2, SW2 c. Configuration 3, SW1 d. Configuration 3, SW2.

The positive impact of the installation of the snubber capacitors is even more important for the iQPS. The voltage waves generated across the switches cause an unbalanced voltage drop over the two apertures of each dipole. For the dipoles with different AC behavior between the apertures this can cause ΔU_{ap} to overcome the threshold of the iQPS. In Fig. 6 the measured ΔU_{ap} of one such dipole after the opening of SW1 at nominal current is shown. ΔU_{ap} reaches a large negative peak slightly above the ± 100 mV threshold of the iQPS. It is naturally desirable to keep a certain margin with respect to the threshold in order not to fire the quench heaters in case of a FPA. The presence of the snubbers significantly reduces ΔU_{ap} (see Fig. 6-C3) which remains safely below the threshold during the whole event.

Fig. 6. ΔU_{ap} of M079 at the opening of SW1 at $I_0=6$ kA, $dI_0/dt=0$ A/s. Configuration 2 (C2) and Configuration 3 (C3).

Fig. 7. Absolute maximum value of ΔU_{ap} of each dipole of the chain at the opening of SW1 and SW2 at $I_0=6$ kA, $dI_0/dt=0$ A/s. Configuration 2 (C2) and Configuration 3 (C3).

Figure 7 shows the absolute maximum value reached by ΔU_{ap} of each dipole during the two events shown in Fig. 6. Without snubbers ΔU_{ap} of many dipoles is above the iQPS threshold, whereas with the snubbers, ΔU_{ap} is below 100 mV for all dipoles. It can be concluded that the installation of the

snubber capacitors across the extraction switches effectively reduces the oscillations generated at the switch opening and helps preventing undesired iQPS triggering.

IV. CONCLUSIONS

The LHC main dipole circuit suffered initially from spurious quench heater firing due to voltage waves after a Fast Power Abort. Three improvements to the circuit and its Quench Protection Systems have been implemented in order to reduce the amplitude of the voltage waves after a Fast Power Abort hence minimize the spurious triggering of the Quench Protection Systems.

Firstly, a delay between the power-converter switch-off and the two openings of the energy-extraction switches was introduced. This modification avoided the superposition between the waves generated at the output of the power converter and those generated across the extraction resistors.

Secondly, additional resistors were mounted in the capacitive branches of the filter at the output of the power converter mainly in order to increase the damping of the voltage transients.

Thirdly, snubber capacitors were installed in parallel to the extraction switches for reducing the arcing and smoothing the voltage transients after switch openings.

The results show that the adopted measures effectively reduce the impact of the voltage transients following a Fast Power Abort on the main dipole circuits and significantly decreased the number of spurious triggering of the Quench Protection Systems.

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