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Modeling of the Voltage Waves in the LHC Main Dipole Circuits

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The phase velocity of the waves travelling along the chain changes due to the inhomogeneous AC behavior of the dipoles. Furthermore, complex phenomena of reflection and superposition are present in the circuit. For these reasons analytical calculations are not sufficient for properly analyzing the circuit behavior after a fast power abort.

The transients following the switch-off of the power converter and the opening of the switches are analyzed by means of a complete electrical model, developed with the Cadence® suite (PSpice® based). The model comprises all the electrical components of the circuit, additional components simulating the dipole AC behavior, and the ground lines of the circuit including its parasitic capacitances.

The simulation results are presented in order to illustrate the behavior of the circuit and to assess its performance under different operating conditions. The comparison between measurement data and simulations shows a very good agreement.

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Index Terms—Circuit modeling, 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 (see Fig. 1) [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].

In case of a quench or in case of problems related to the power converter (PC), a Fast Power Abort (FPA) is triggered. It consists in the switch-off of the PC ($t=0$), the opening of the extraction switch SW1 in the middle of the chain ($t=350$ ms), and the opening of the switch SW2 at the end of the chain ($t=600$ ms). The current of the circuit is then forced to pass through the two extraction resistors (R_{EE}) and decays with a time constant of 51 s.

The transient following a FPA is characterized by voltage waves generated at the output of the PC and across the switches, and travelling along the dipole chain. The propagation of this exponentially decaying wave along a lumped transmission line can be described by

$$U(t, n) = A \cdot \exp(-t / \tau) \cdot \cos(\omega t - \sum_{i=1}^n \theta_i), \quad (1)$$

where A is the wave amplitude [V], τ is its decay time constant [s], ω is its angular frequency [rad/s], θ_i is the phase shift induced by element i [rad], and n is the position along the line of the element. In a string of dipole magnets each of the N_{ap} dipole apertures induces a different θ_i on the incoming wave. The wave phase-velocity $v_i = \omega / \theta_i$ is thus changing along the chain. Furthermore, since the wave is slowly-damped and the period of the wave is comparable to the time needed to make a complete loop of the chain $t_{chain} = \sum_{i=1, N_{ap}} (\theta_i / \omega)$, additional phenomena of reflection and superposition occur. In such a scenario, analytical considerations are not sufficient for analyzing accurately the voltage transients following a FPA.

This paper presents a complete PSpice[®] electrical model which simulates the behavior of the circuit and allows exploring its performance in a wide range of operational conditions. All the simulation results presented in this paper refer to the present circuit configuration, featuring a delayed opening of SW1 and SW2, an additional resistance of the PC filter, and the presence of snubber capacitors across the switches [3].

The simulation results are in good agreement with the data measured during dedicated tests. The presented model is important in order to analyze the circuit and minimize the spurious triggering of the Quench Protection System after a FPA, occurring when the voltage difference between two electrically adjacent dipoles (ΔU_{mag}) or between two apertures of a dipole (ΔU_{ap}) becomes larger than the protection threshold.

II. MODELING OF THE CIRCUIT

The circuit model comprises detailed sub-models of all the relevant electrical components, namely the PC, the dipoles, the energy-extraction systems, and the ground lines. Nonetheless, in this paper only the components that have the largest impact on the behavior of the circuit are presented. The detailed description of the model can be found in [4].

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Fig. 1. Schematic of the LHC main dipole circuit

The circuit is powered by a 13 kA PC, 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, thus having a theoretical resonance frequency of $f_{filter} = 1/(2\pi \cdot \sqrt{L_{filter} \cdot C_{filter}}) \approx 31.8$ Hz. In the circuit model, the values of L_{filter} and C_{filter} are set to 285 μ H and 110 mF respectively in order to obtain a better fit with the measured f_{filter} of about 28.5 Hz in each of the 8 dipole circuits. The resistance of the capacitive branches of the filter R_{filter} was initially 3.4 m Ω , but was recently changed to 10.1 m Ω [3].

The protection of each dipole (M001-M154) in case of a quench is ensured by two individual Quench Protection Systems [5]-[6], cold by-pass diodes, and quench heaters. Two separate energy-extraction units [7] are present in order to quickly discharge the circuit and thus protect the by-pass diodes and the busbars. Each unit is composed of redundant electromechanical switches (SW), a 148 m Ω extraction resistor (R_{EE}), and 53 mF snubber capacitors (C_{SN}) in parallel [8]. In parallel to each dipole a 100 Ω resistor (R_p) is present for smoothing transient voltage oscillations.

The problem of modeling the frequency-dependent behavior of a superconducting magnet has been frequently faced in the past [9]-[12]. The behavior of a magnet is not completely inductive due to the presence of magnetization effects, eddy currents, and coil-to-ground parasitic capacitances.

An equivalent electrical circuit (see Fig. 2) is adopted in order to model the behavior of a dipole at different frequencies [10]. The model is composed of two apertures connected in series, whose equivalent impedance is

$$z_a(s) = \frac{sL \left(1 + \frac{s}{R_a / (k(1-k)L)} \right)}{\left(1 + \frac{s}{R_a / (kL)} \right) \left(1 + R_a \frac{C}{4} s + (1-k)L \frac{C}{4} s^2 \right)} \quad (2)$$

for $a=1,2$, where $s=\sigma+j\omega$. $L=49$ mH and $C=150$ nF are physical properties which represent the inductance of an aperture and its coil-to-ground parasitic capacitance respectively, whereas k and R_a are two parameters which model the effects of the eddy currents induced in its coils. For most dipole magnets a good correlation between experimental data and simulations is obtained for $k=0.75$ and $R_{1,2}=10$ Ω . However, some magnets seem to have a different AC behavior in the 2 apertures. In this case the R_a values of one of the apertures is modified to 7 $\Omega < R_a < 10$ Ω .

Fig. 2. Adopted model of a dipole.

Fig. 3 shows the frequency response of the aperture model calculated using (2) for two different values of R_a . The aperture suffering larger eddy currents has a smaller impedance for ω between 100 and 2000 rad/s, and induces a different phase shift for ω above 10 rad/s.

Fig. 3. Frequency response of a dipole aperture calculated with (2). a. Standard aperture ($R_a=10$ Ω) b. Aperture with larger eddy currents ($R_a=7$ Ω). The frequency ω_{filter} is highlighted with circles.

III. SIMULATION RESULTS

This section presents the most relevant simulation results, namely the voltage at the PC output, the voltage across each dipole and the voltage difference between its two apertures.

A. Voltage at the output of the power converter

When the PC is switched off, the voltage at its output (V_{PC}) starts oscillating at the resonance frequency of the filter f_{filter} . The amplitude of the oscillations depends on the initial voltage $V_{PC,0} = R_{circuit} \cdot I_0 + N_{mag} \cdot L_{mag} \cdot dI_0/dt$, where $R_{circuit}$ is the resistance of the non-superconducting components of the circuit (≈ 1 m Ω), N_{mag} is the number of dipoles in the chain, and I_0 is the current flowing in the circuit at the moment of the FPA. $V_{PC,0}$ strongly depends on dI_0/dt and equals about 157 V at

nominal current and ramp-rate. Fig. 4 shows the simulated V_{PC} for three cases, namely a FPA at constant nominal current 6 kA and two FPAs at 2 and 6 kA while ramping at nominal $dI_0/dt=10$ A/s.

The damping of the wave generated at the output of the PC depends on the inductance and resistance of the branches of the PC and its filter, and not on the characteristics of the dipole chain.

Fig. 4. Simulated voltage at the output of the PC during a FPA. a. $I_0=2$ kA, $dI_0/dt=10$ A/s b. $I_0=6$ kA, $dI_0/dt=10$ A/s c. $I_0=6$ kA, $dI_0/dt=0$ A/s.

B. Voltage across the dipoles

After a FPA is triggered, the waves generated at the PC output and across the extraction switches propagate through the dipole chain and as a consequence the voltage across each dipole (U_{mag}) undergoes three separate voltage transients.

As an example, Fig. 5 shows the voltage across M026 during the transient following a FPA at 2 kA, while ramping up at 10 A/s. For $t < 0$, $U_{mag} = L_{mag} \cdot dI_0/dt \approx 1$ V. At $t=0$ the PC is switched off and U_{mag} oscillates at a frequency f_{filter} .

Fig. 5. U_{mag} of M026 during a FPA at $I_0=2$ kA, $dI_0/dt=10$ A/s. a. Measurement b. Simulation.

The voltage transients following each switch opening are smooth due to the presence of snubber capacitors across the switches. After the opening of SW1, the voltage over each dipole equals $U_{mag} = -R_{EE} \cdot I_0 / N_{mag} \approx -1.9$ V, since the voltage drop

across R_{EE1} is divided equally among each magnet. Similarly, after the opening of SW2, $U_{mag} = -2 \cdot R_{EE} \cdot I_0 / N_{mag} \approx -3.8$ V. Comparison between the curves in Fig. 5 shows that measured and simulated U_{mag} are in good agreement.

The voltage wave generated at the PC output influences each dipole differently, depending on its position and on its AC behavior. Fig. 6 illustrates the maximum and minimum values of U_{mag} during the transient following the PC switch-off ($20 \text{ ms} < t < 350 \text{ ms}$). The asymmetric distribution of the maximum values of U_{mag} can be explained considering the propagation of the wave during its first oscillation. The time needed for propagating through an aperture for $R_a \gg 1000 \Omega$ is approximated by $t_{ap} \approx \sqrt{L \cdot C} \approx 85 \mu\text{s}$ [12], and thus the wave length, representing the number of apertures crossed in a wave period, is $\lambda = 2 \cdot \pi / \theta = 1 / (f_{filter} \cdot t_{ap}) \approx 409$. Hence the first $\lambda \cdot N_{ap} \approx 101$ apertures of the chain (M001-M050) experience a superposition of the wave and reach a larger maximum value of U_{mag} . On the other hand, the wave reaches its minimum after a semi-period, when it crosses aperture $\lambda/2 \approx 204$ (M102).

Fig. 6. Maximum and minimum $U_{mag,PC}$ ($20 \text{ ms} < t < 350 \text{ ms}$) at $I_0=2$ kA, $dI_0/dt=10$ A/s. a. Measurement b. Simulation.

C. Voltage difference between the two apertures of the dipoles

Any wave propagating through the dipole chain is shifted by a different phase angle θ_i by each aperture, depending on the frequency of the incoming wave and on the AC behavior of the aperture. The wave generated after the PC switch-off is characterized by a fixed angular frequency $\omega_{filter} = 2 \cdot \pi \cdot f_{filter} \approx 179 \text{ rad/s}$. If the two apertures of a dipole have a similar behavior at ω_{filter} , the voltage drop over them is similar and ΔU_{ap} remains in the order of a few tens of mV after a FPA. On the contrary, ΔU_{ap} of dipoles with highly different AC behavior in one aperture undergoes large oscillations. The behavior of such dipoles is simulated by setting $R_1 \neq R_2$ in the model of their apertures. Fig. 3 shows the impact of the variation of R_a on the frequency response of an aperture at ω_{filter} .

Fig. 7 and 8 show the comparison between the measured and simulated ΔU_{ap} of M033 and M130 (both having a large difference between R_1 and R_2) during two different phases of the transient following a FPA at 2 kA, ramping up at 10 A/s.

The data were recorded by the QPS during an actual FPA and were sampled with a frequency of 200 Hz. Measurements of ΔU_{ap} with a higher sampling frequency are not available.

Fig. 7. ΔU_{ap} of M033 after the PC switch-off at $I_0=2$ kA, $dI_0/dt=10$ A/s. a. Measurement b. Simulation.

Fig. 8. ΔU_{ap} of M130 after the opening of SW1 and SW2 at $I_0=2$ kA, $dI_0/dt=10$ A/s. a. Measurement b. Simulation.

Fig. 9. Peak-peak ΔU_{ap} of each dipole of the chain after PC switch-off ($0 < t < 350$ ms) at $I_0=2$ kA, $dI_0/dt=10$ A/s. a. Measurement b. Simulation.

Fig. 9 shows the peak-peak ($\max \Delta U_{ap,PC} - \min \Delta U_{ap,PC}$) values reached by ΔU_{ap} of each dipole after the PC switch-off ($0 < t < 350$ ms). The distribution of dipoles with $R_1 \neq R_2$ is in very good agreement with the measured voltages only using R_i as a free parameter.

IV. CONCLUSIONS

When a Fast Power Abort is triggered in the LHC main dipole circuit, complex voltage transients are generated at the power-converter output and across the energy-extraction switches. The resulting waves propagate through the magnet chain and influence the voltage across the dipoles and their apertures, thus risking triggering the magnet Quench Protection System and firing the quench heaters.

The inhomogeneous AC behavior of the dipole apertures and the combined effects of reflection and superposition of the voltage waves make the analytical analysis of the circuit insufficient for accurately understand its behavior.

A PSpice[®] model of the LHC main dipole chain, including detailed models of the dipoles, power converter, extraction switches, and ground lines, has been developed. The AC behavior of the apertures is simulated by means of free parameters which model the eddy currents induced in their coils.

The comparison between measured data and simulation results shows that the model successfully reproduces any relevant feature of the circuit behavior after a Fast Power Abort.

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