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CLIQ-based Quench Protection of a Chain of High-field Superconducting Magnets

E. Ravaioli, V.I. Datskov, G. Kirby, M. Maciejewski, H.H.J. ten Kate, and A.P. Verweij

***Abstract*—Conventional quench protection systems for high magnetic-field superconducting magnets are based on external heaters composed of resistive strips in close contact with the coil, and rely on thermal diffusion across insulation layers of the order of tens of micrometer. The large contact areas between the coil and the heater strips, and the thin insulation between them required for an effective protection constitute a significant risk of electrical breakdown and one of the most common causes of magnet damage. CLIQ technology offers a valid option for a time- and cost-effective repair of magnets with failing heater-based protection systems. In fact, its effective heating mechanism utilizing coupling loss, its robust electrical design, and its fast implementation, as compared to alternative repair options, constitute definite advantages over the conventional technology. In the past years, CLIQ was successfully implemented on various coils in a single-magnet configuration. Now the design of a CLIQ-based protection system integrated in a chain of series-connected magnets is presented. The protection of a chain of superconducting magnets usually is considerably more challenging than the protection of stand-alone magnets due to the increased energy stored in the circuit and the presence of transitory effects. The effectiveness of this new method is demonstrated by means of electro-thermal simulations modeling the transition to the normal state and the temperature evolution in one quenched magnet, and the electrodynamics of the entire magnet chain.**

***Index Terms*—accelerator magnet, circuit modeling, CLIQ, quench protection, superconducting coil.**

I. Introduction

PARTICLE colliders rely on superconducting multi-pole magnets to bend and focus the particle beam in their trajectories. Magnets are often connected in series, hence forming a chain, to feed the same current to all magnets and to reduce the number of power converters and current leads required for operation. As the particle collision energy is proportional to the magnetic field generated by the collider's main dipole magnets, the case of a circuit composed of series-connected, high-field superconducting magnets is of significant interest.

The quench protection of a chain of superconducting magnets usually is considerably more challenging than the protection of stand-alone magnets. The increased energy stored in the circuit makes it more difficult to safely remove the circuit transport current. Furthermore, the electrodynamics of a chain of superconducting magnets requires particular consideration due to the presence of distributed coil-to-ground parasitic capacitance, frequency-dependant impedance of the superconducting magnets, and the very low electrical resistance of the circuit [1]–[3].

Conventional quench protection systems for high magnetic field superconducting coils are often based on quench heaters, which rely on thermal diffusion across insulation layers.

CLIQ (Coupling-Loss Induced Quench) technology, recently developed at CERN, can be more advantageous due to its simple and robust electrical design, to its fast implementation, and to its effective heating mechanism, which relies on coupling loss generated in the conductor [4]–[6]. In the past years, CLIQ was successfully implemented on various coils in a single-magnet configuration, and the transient following a CLIQ discharge convincingly reproduced with electro-magnetic and thermal simulations [6]–[12].

Now the design of a CLIQ-based protection system integrated in a chain of series-connected magnets is presented. The performance of this new method is demonstrated by simultaneously modeling the transition to the normal state and the temperature evolution in one magnet and the overall electrodynamics of the magnet chain by means of TALES (Transient Analysis with Lumped-Elements of Superconductors), a new software developed at CERN for quench-protection and fault-cases studies [4], [13]–[15].

II. Protection of Chains of Superconducting Coils

A brief overview of the most common protection strategies for chains of superconducting magnets is outlined here.

A. By-pass elements

A passive protection method consists in installing a by-pass element across each coil to protect [16]–[18]. Valid by-pass elements include resistors, single diodes, back-to-back diodes, or more complex protection schemes composed of combinations of these [19]. In the case of a quench, the electrical resistance developed in the coil's normal zone forces part of the magnet transport current through the by-pass branch, thus dissipating part of the magnet energy in the by-pass element, thereby also limiting the voltage across the quenched coil.

B. Energy-extraction

The energy stored in the magnet circuit can be discharged into an external energy-extraction system [20]–[22]. The main

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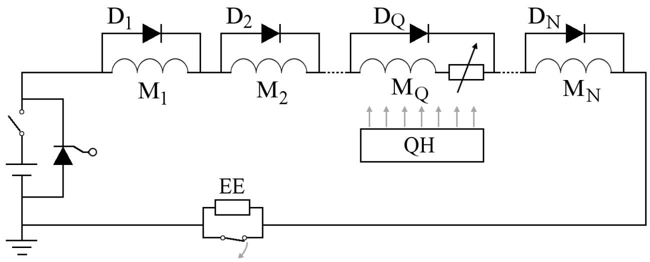

Fig. 1. Schematic of a chain of superconducting magnets ($\mathrm{M_1}$-$\mathrm{M_N}$) protected by quench heaters (QH), by-pass diodes ($\mathrm{D_1}$-$\mathrm{D_N}$), and an energy-extraction system (EE). Only the active protection system of magnet $\mathrm{M_Q}$ is shown.

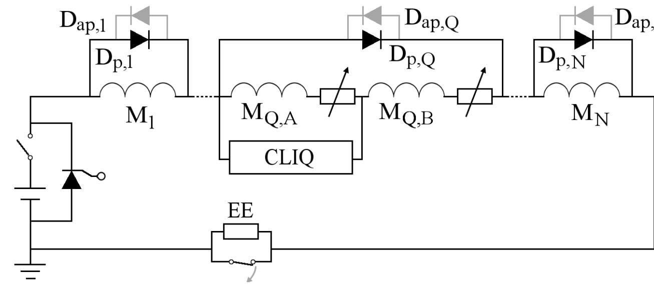

Fig. 2. Schematic of a chain of superconducting magnets ($\mathrm{M_1}$-$\mathrm{M_N}$) protected by CLIQ, by-pass diodes in parallel ($\mathrm{D_{p,1}}$-$\mathrm{D_{p,N}}$) and antiparallel ($\mathrm{D_{ap,1}}$-$\mathrm{D_{ap,N}}$), and an energy-extraction system (EE). Only the CLIQ unit connected to the two sections $\mathrm{M_{Q,A}}$ and $\mathrm{M_{Q,B}}$ of one magnet is shown.

drawback of this method is that the value of the extraction resistor R_{EE} [Ω], and hence the decay time, is limited by the maximum safe voltage in the circuit U_{EE}=$R_{\mathrm{EE}}I$ [V].

C. Quench Heaters

Nowadays highest performance superconducting magnets are protected by active systems relying on active heating of the conductor, hence forcing the discharge of the magnet stored energy with the electrical resistance developed in the coil itself. With respect to an external energy-discharge system, active transfer of the superconductor to the normal state also offers a more uniform profile of the voltages and stress within the coil due to the distribution of inductive and resistive components over the conductor length.

The conventional technology is based on quench heaters, composed of resistive strips in close contact with the coil and relying on thermal diffusion across insulation layers in the order of tens of micrometer [23]–[26]. The large contact areas between the coil and the heater strips, and the thin insulation between them required for an effective protection constitute a significant risk of electrical breakdown and one of the most common causes of magnet damage [27]–[30].

A protection scheme frequently adopted comprises active-heating units and a by-pass element protecting each coil [20], [31]. This solution, shown in Fig. 1, reduces the problem of the protection of the entire chain of N_{M} magnets to the more manageable task of protecting individual shunted coils. In this design, usually only the protection units of the coil where the quench is detected are activated to avoid unnecessarily quenches in the other coils. An energy-extraction system can be added to avoid dissipating the energy of the coils still in the superconducting state in the by-pass element of the quenched coil [20]–[22], [31].

D. Integration of CLIQ in the Chain

CLIQ technology, recently developed at CERN, is an interesting option for the protection of high magnetic-field superconducting magnets [4]–[6]. Its fast and effective heating mechanism, relying on coupling loss generated in the conductor [32], makes it possible to discharge more quickly the magnet current, hence decreasing the coil's hot-spot temperature. Besides, its simple and robust electrical design reduces the expected risk of failures.

A CLIQ system is composed of one or more units featuring a charged capacitor bank and connected to the coil to protect. A very fast transition to the normal state is achieved in the winding pack by discharging the capacitor bank, thus introducing high current-changes in the coil sections, which in turn generates high magnetic-field changes and hence high coupling loss in the strand.

In the past years, CLIQ was successfully tested on various coils in a single-magnet configuration [6]–[12]. Experimental results are in good agreement with the performance predicted by the developed electro-thermal models.

With limited modifications to the circuit design, CLIQ can be successfully implemented for protecting magnets which are part of a chain. As an example, in Fig. 2 the integration of CLIQ in a chain of magnets by-passed by diodes is shown. The only modification with respect to the quench protection design presented in Fig. 1 is the implementation of CLIQ instead of quench heaters and the presence of additional antiparallel diodes ($\mathrm{D_{ap,1}}$-$\mathrm{D_{ap,N}}$) across each magnet protected by a CLIQ system. The antiparallel diodes are required to provide a return path for the current introduced by CLIQ, hence avoiding the introduction of significant current changes in the other magnets of the chain. Since they only carry a short pulsed current, limited heat deposition is expected in these components. Alternative designs featuring parallel resistors instead of diodes are also possible [33].

III. CLIQ in the LHC Chain of Dipole Magnets

As a case study, the design of a CLIQ system protecting one magnet of an LHC chain of 154 dipole magnets is presented and discussed [12].

A. LHC Chain of Dipole Magnets

The LHC comprises eight octants, each featuring a chain of N_{M}=154 superconducting twin-aperture dipole magnets ($\mathrm{M_1}$-$\mathrm{M_N}$) [1], [34]–[39]. Each dipole magnet has a self-inductance L_{M} of 98 mH at a nominal current of I_0=11850 A, resulting in a total self-inductance of each circuit 15.1 H and a total stored energy of 1.1 GJ at nominal field.

Each circuit is powered by a 13 kA power converter, by-passed by a crowbar, which conducts the current when the converter is switched off. In the case of a quench, the protection of each magnet [20], [31] is assured by two individual quench detection systems [40]–[42], cold by-pass diodes, and quench heaters [23]–[26], [37]. The circuit includes two separate energy extraction units, one located close to the power converter and one in the middle of the chain [21], [22]. They quickly discharge the circuit current and therefore protect the by-pass diodes and the busbars. Each unit is composed of redundant electro-mechanical switches, a 74 mΩ extraction resistor, and 53 mF snubber capacitors in parallel [43]. In parallel to each dipole magnet, a 100 Ω resistor is installed for smoothing transient voltage oscillations.

In the case of quench detection or in the case of problems related to the power converter, the converter is switched off and the two energy-extraction switches are opened. The circuit current is then forced to flow through the two extraction resistors and decays with a time constant of $\tau_{\mathrm{EE}} \approx N_{\mathrm{M}} L_{\mathrm{M}} / (2 R_{\mathrm{EE}}) \approx 102$ s.

B. Electro-dynamic Model of an LHC Main Dipole Magnet

Linear models are not sufficient for accurately analyzing and predicting the voltage transients occurring in a chain of superconducting magnets due to the presence of coil-to-ground parasitic capacitances, coupling currents, magnetization effects, and eddy currents, which make the magnet behavior not ideally inductive.

The equivalent lumped-element circuit proposed in [2], [3], [44] is used to model the behavior of an LHC dipole magnet at different frequencies. After validation under various operating conditions, it is now adopted as the standard tool for the simulation of electro-dynamic transients occurring in the eight LHC dipole magnet chains [2], [3].

C. CLIQ System for an LHC Main Dipole Magnet

The LHC main dipole magnet is composed of two identical 14 meter long, two-layer, cos-θ dipole apertures, assembled in a common iron yoke structure and electrically connected in series [34]–[38]. A CLIQ system composed of two units was recently tested on this coil in stand-alone configuration in the CERN magnet test facility [12]. The same 2-CLIQ configuration is assumed here, obtained by connecting two units at the joints between the poles and apertures.

To avoid conduction after activating the energy-extraction system, the opening voltage of the antiparallel diode (see $\mathrm{D}_{\mathrm{ap,Q}}$ in Fig. 2) has to be sufficiently high. Since after activating the energy-extraction system the voltage developed across each magnet of the chain is $-2R_{\mathrm{EE}} I_0 / N_{\mathrm{M}} \approx 11$ V, the opening voltage has to be higher than this value to avoid damage. Alternatively, various diodes can be connected in series to obtain the required opening voltage. In this case, a value of 20 V is proposed.

D. Simulation of a CLIQ in the Chain of LHC Dipole Magnets

The electro-magnetic and thermal transients occurring in one magnet, and the electro-dynamic transients occurring in the entire circuit during and after a CLIQ discharge are simulated using TALES [4], [13]–[15]. The model couples the

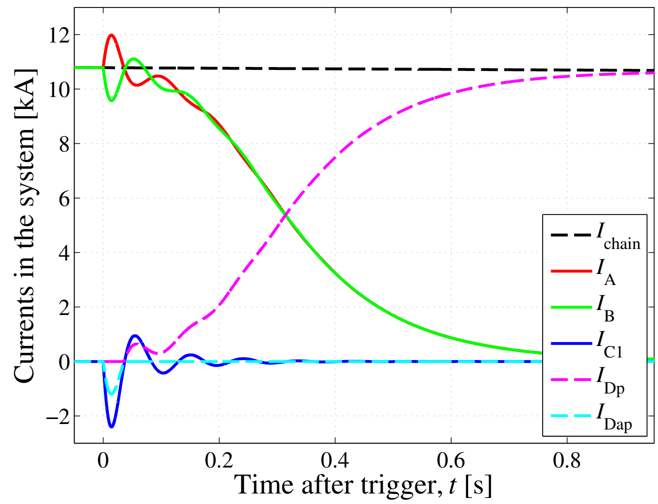

Fig. 3. CLIQ-based protection of an LHC dipole magnet, part of a chain of 154 magnets. Simulated currents in the magnet circuit I_{chain}, in the two coil sections I_{A} and I_{B}, through one CLIQ unit I_{C1}, and in the by-pass diodes I_{Dp} and I_{Dap}, versus time, after triggering a 2-CLIQ, 60 mF, 600 V system [4].

equivalent lumped-element network of one magnet, developed with the method described in [13], with the transmission line model presented in [2]. The interaction between the voltage transient developed after triggering CLIQ and the voltage waves generated at the output of the power supply and across the energy-extraction units is studied under various operating conditions.

The case of a CLIQ discharge in the 39-th series-connected magnet (M039), roughly equidistant from the power supply and the energy-extraction unit in the middle of the chain, is presented here. In order to assess the impact of the transient caused by CLIQ on the magnets of the chain, it is considered here that CLIQ is activated well after the power converter switching-off and energy-extraction triggering.

The simulated currents flowing in the various system components are shown in Fig. 3. At t=0, a 2-CLIQ, 60 mF, 600 V system is triggered and a 2.4 kA, 13 Hz current I_{C1} [A] is introduced by each of the two CLIQ units connected to the coil. During the first current pulse, about half of the current introduced, corresponding to $I_{\mathrm{Dap}} = I_{\mathrm{A}} - I_0$, flows through the antiparallel diode. The oscillations of the currents flowing in the coil sections I_{A} [A] and I_{B} [A] are sufficient to generate high inter-filament coupling loss in the superconductor and transfer to the normal state a large fraction of the winding pack in a few tens of millisecond. The electrical resistance of the coil's normal zone develops a high resistive voltage. As the voltage across the magnet cannot increase above the parallel-diode opening voltage of 6 V, a high negative inductive voltage is generated in the magnet, i.e. its current is rapidly discharged. The current flowing in the rest of the chain I_{chain} [A] is discharged with a much longer time constant, $\tau_{\mathrm{EE}} \approx 102$ s, as explained in section III-A. Thus, an increasing fraction of current is diverted to the parallel diode. About one second after triggering CLIQ, the current flowing through the quenched magnet is roughly zero, and the circuit current is

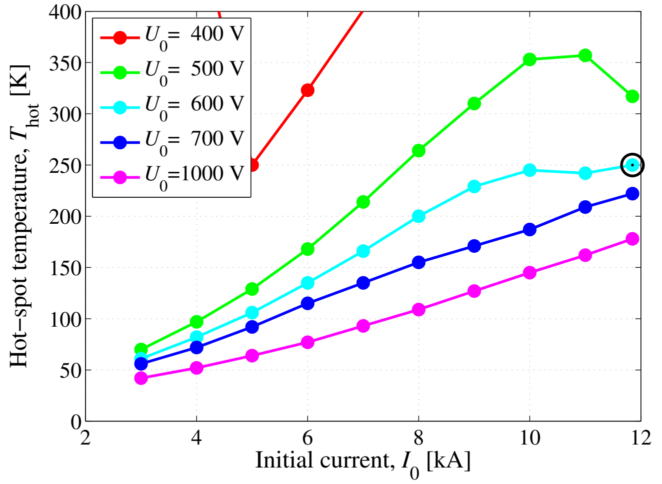

Fig. 4. Simulated coil's hot-spot temperature versus initial current, as a function of CLIQ charging voltage U_0, after triggering a 2-CLIQ 60 mF system. The black circle refers to the simulation shown in Fig. 3 [4].

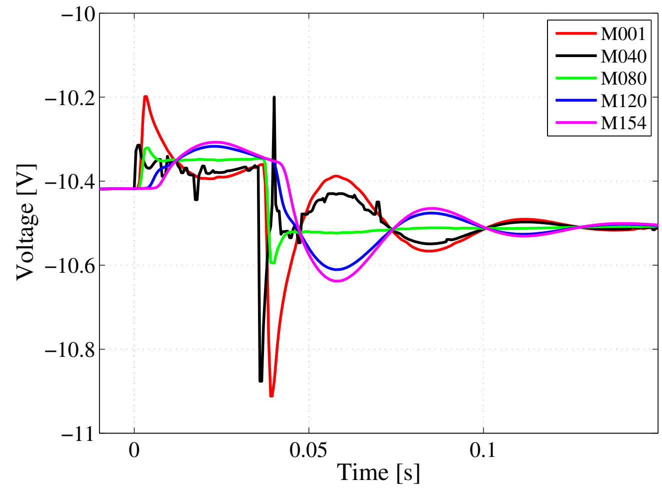

Fig. 5. CLIQ-based protection of an LHC dipole magnet, part of a chain of 154 magnets. Simulated voltage across five selected magnets along the chain, versus time, after triggering the CLIQ unit connected to magnet M039 [4].

completely transferred to the parallel diode, i.e. $I_{\mathrm{Dp}}{\approx}I_{\mathrm{chain}}$.

The simulated hot-spot temperature T_{hot} [K] as a function of the initial transport current is shown in Fig. 4 for values of CLIQ charging voltage in the range 400 to 1000 V. A CLIQ system charged at 400 V is not sufficient to protect this full-size coil, and a 500 V system can barely maintain the coil's hot-spot temperature around the value of 350 K. For a charging voltage of 600 V, a significant improvement is achieved, resulting in a maximum hot-spot temperature of about 250 K over the entire range of operating current. Increasing CLIQ charging voltage up to 1 kV allows a further reduction of T_{hot} to about 180 K.

Triggering a CLIQ unit connected to one magnet develops a voltage wave which propagates along the chain. Analyzing the impact of this wave on the circuit behavior and on the quench detection system is mandatory. The simulated voltages developed across five selected magnets in different positions of the circuit after triggering CLIQ, for the transient shown in Fig. 3, are plotted in Fig. 5. The electrical perturbations introduced across the magnets of the chain have a maximum peak of a few hundred millivolt, significantly lower than the transients caused by switching-off the power converter or opening an energy-extraction switch [1], [2]. The voltage differences between apertures are also small as compared to the quench detection threshold of 100 mV.

This result can be easily explained when considering that the amplitude of any voltage wave developed across a magnet is limited by the back-to-back by-pass diodes. In the considered case, the voltage across the quenched magnet is comprised between -20 V and 6 V, corresponding to the diode opening voltages indicated in section III-C, and therefore the peak amplitude of a wave generated across a magnet is 26 V. This value is significantly lower than the initial voltage across the power converter of up to 165 V, or across an extraction switch, up to 800 V [1], [2]. Thus, the perturbations generated after a CLIQ discharge are about one order of magnitude smaller than those after the power converter switching-off and the switch openings.

In conclusion, the integration of a CLIQ-based protection system in the LHC chain of dipole magnets shows very good performance in terms of maximum coil's hot-spot temperature after a quench, and not significantly interferes with the LHC quench detection system.

IV. Conclusion

CLIQ technology can be applied not only on stand-alone magnets, but also in chains of superconducting magnets. For this application, back-to-back by-pass diodes are installed across each magnet. CLIQ can be implemented either on all magnets of the chain, as the main quench protection system; or on one or more magnets of the chain, as a time- and cost-effective repair option for coils with broken quench heaters.

The study of the voltage transient developed after triggering CLIQ and propagating along the circuit has to be included in the design phase. This analysis can be carried out by means of an equivalent electro-dynamic model of the chain, which includes frequency-dependent effects.

The LHC main dipole chain is presented as a case study. The proposed CLIQ design maintains the coil's hot-spot temperature below safe limits over the entire range of operating currents, and does not induce spurious triggering in the present LHC quench detection system. In fact, the perturbations developed across the other magnets of the chain after activating a CLIQ unit connected to one magnet show a peak of a few hundred millivolt, which is one order of magnitude lower than the transients after the power converter switching-off and switch openings.

A CLIQ-based solution for the quench protection of a chain of superconducting magnets is analyzed and ready to be implemented. Its advantages in terms of energy-deposition velocity and electrical robustness make CLIQ the first choice for a quench protection system of the next generation of chains of high magnetic field accelerator magnet.

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