EEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2013
This manuscript was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044023, (2014).

A new hybrid protection system for high-field superconducting magnets

E Ravaioli[1,2], V I Datskov[1], G Kirby[1], H H J ten Kate[1,2], and A P Verweij[1]
[1]CERN, Geneva, Switzerland [2]University of Twente, Enschede, The Netherlands

Email: Emmanuele.Ravaioli@cern.ch

Abstract

The new generation of high-field superconducting accelerator magnets poses a challenge concerning the protection of the magnet coil in the case of a quench. The very high stored energy per unit volume requires a fast and efficient quench heating system in order to avoid damage due to overheating. A new protection system for superconducting magnets is presented, comprising a combination of a novel Coupling-Loss Induced Quench (CLIQ) system and conventional quench heaters. CLIQ can provoke a very fast transition to the normal state in coil windings by introducing coupling loss and thus heat in the coil's conductor. The advantage of the hybrid protection system is a global transition, resulting in a much faster current decay, a significantly lower hot-spot temperature, and a more homogeneous temperature distribution in the magnet's coil.

1. Introduction

The very high stored energy per unit volume in new-generation high-field superconducting accelerator magnets presents a serious risk to its safety in the case of a quench. If the coil has to absorb the magnet stored energy, a very fast quench heating system is required that can quickly transfer a large portion of the coil winding pack to the normal state, thereby shortening as much as possible the discharge of the transport current.

Conventional quench protection systems, such as energy extraction, quench heaters, and by-pass diodes or resistors [1-4], have drawbacks and limitations. An energy-extraction system is costly and the value of its resistor is limited the maximum safe voltage in the circuit. Quench heaters rely on thermal diffusion through insulation layers, usually a slow process, and increase the risk of electrical failures.

A new Coupling-Loss Induced Quench (CLIQ) protection system was recently developed and tested at CERN [5]. This quench protection method is based on rapidly changing the local magnetic field in a superconducting coil and thereby introducing coupling loss and thus heat in the conductor. The heat introduced by the CLIQ is generated directly in the copper matrix of the superconducting strands and can initiate a fast transition to the normal state due to the enhancement of the local temperature to a level far beyond the current sharing temperature.

A new hybrid system consisting of the novel CLIQ system and conventional quench heaters (QHs) is presented here. Due to the synergy between the two methods, this innovative system further improves the performance of the protection system by inducing a much more global superconducting to normal state transition and thereby reducing the hot-spot temperature. In fact, the two systems are more efficient in heating up different regions of the magnet: the quench heaters are easier to attach to the outer layers of a coil, whereas CLIQ can introduce losses effectively in the inner high-magnetic-field regions.

2. The Hybrid Protection System

The Coupling-Loss Induced Quench (CLIQ) protection system, as presented for the first time in [5], is schematized in Fig. 1. It is composed of a capacitor bank C, a floating voltage supply S, two additional resistive current leads CL1 and CL2 connecting the system to the magnet, a thyristor TH, and a reverse diode D. The CLIQ design is based on a protection scheme already proposed in [6-7] but now with the addition of the recently patented reverse diode [8], which is essential to significantly improve the system's performance. The capacitor bank is charged by S with a voltage U_0. Upon quench detection, the thyristor is activated resulting in a current I_C to be discharged through CL2. The presence of the reverse diode allows continuous oscillations of I_C. The resulting change in the transport current of the two coils I_1 and I_2 changes the local magnetic field within the two coils L_1 and L_2, which in turn introduces inter-filament and inter-strand coupling losses [9]. Such high losses are sufficient to initiate the transition to the normal state of large portions of the coil winding pack by heating up the conductor.

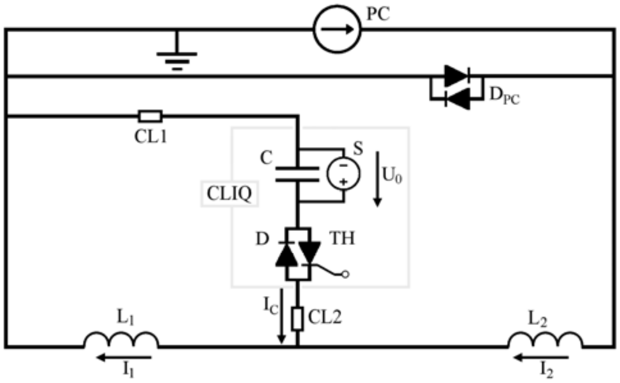

Figure 1. Schematic of the new Coupling-Loss Induced Quench (CLIQ) system implemented in the magnet test.

It can be shown that during the first instant after the triggering of CLIQ the two parallel mutual inductors L_1 and L_2, the discharging capacitance C, and the sum of the resistances of the normal-conducting connections in the circuit R_{eq} form a series RLC circuit [10]. The time evolution of the voltage across C and its current I_C are described by

$$U_C(t) = U_0 \cdot \exp(-\alpha t) \cdot \left[\cos(\omega t) + \frac{\alpha}{\omega}\sin(\omega t)\right], \text{ and} \qquad (1)$$

$$I_C(t) = C\frac{dU_C(t)}{dt} = -CU_0 \cdot \frac{\omega^2 + \alpha^2}{\omega} \cdot \exp(-\alpha t) \cdot \sin(\omega t), \qquad (2)$$

where $\omega = 1\big/\sqrt{L_{eq} \cdot C}$ and $\alpha = R_{eq}/(2L_{eq})$. The equivalent inductance L_{eq} can be approximated as the impedance of two mutually coupled inductors electrically in parallel, $L_{eq} = (L_1 \cdot L_2 - M_{12}^2)/(L_1 + L_2 + 2M_{12})$. Nevertheless, the actual L_{eq} decreases with increasing frequency due to dynamic effects linked to coupling currents, which change the amount of magnetic flux linked to the superconducting coils.

The current I_C is pushed with opposite direction through $L_1$and L_2, and the resulting oscillations in their transport currents I_1 and I_2, respectively introduce a change in the local magnetic field. A detailed explanation of the electromagnetic transients occurring in a superconducting cable subjected to a magnetic-field change can be found in [9-10].

Known theory states that the inter-filament and inter-strand coupling losses per unit volume are proportional to the square of the magnetic-field change, which in first approximation depend linearly on the square of the current change. Thus, when considering for simplicity the case of a low-resistance circuit (R_{eq}≈0, i.e. α≈0) and deriving (2), it can be concluded that the total heat deposited by the CLIQ activation depends on the square of U_0/L_{eq}. This result explicitly shows the physical limit of CLIQ: the heat that can be delivered to a large-size coil is ultimately limited by the maximum safe voltage to ground in the circuit. The impact of the capacitor size C on the system behaviour is more complex to analyse since it depends on the characteristic time constant of the coupling currents and on the value of the resistance R_{eq} [10, 5].

The heat introduced by a CLIQ discharge is mainly located in the inner region of a magnet where the high magnetic-field change causes the introduction of relatively high coupling losses. On the contrary, conventional quench heaters (QHs) are usually attached to the outer layer of a coil, where they are easier to mount and glue with less risk for electrical breakdown; and thus they primarily diffuse heat in the outer region of the coil. For this reason, CLIQ is well suited to be combined with quench heaters in a highly efficient hybrid protection system, which can initiate a quick and global transition to the normal state in very large portions of the coil winding pack, hence reducing the conductor hot-spot temperature reached in the coil after a quench.

3. Protection of a Quadrupole Magnet Using the Hybrid System

The hybrid quench protection system was tested on a 1.65 m long, 8.4 mH, Nb-Ti superconductor based quadrupole magnet [11] in the CERN magnet test facility. In Table I the main parameters of the magnet are summarized.

The performance of the hybrid system is compared to a single stand-alone CLIQ and conventional quench heaters tested on the same magnet in the same test set-up [5]. Furthermore, the optimization of the CLIQ system and its combination with the quench heaters are studied by means of a 2D lumped-element dynamic electro-thermal model developed using Cadence© PSpice. As an example, Figure 2 shows a comparison between the currents measured in the circuit after a CLIQ discharge with initial current I_0=9 kA, U_0=500 V, and C=28.2 mF and the corresponding simulation results.

TABLE I
MAIN PARAMETERS OF THE TESTED QUADRUPOLE MAGNET

Parameter	Value
Nominal current, I	12800 A
Peak magnetic field, B_p	7.8 T
Stored Energy, E	0.64 MJ
Magnetic length, l_m	1.65 m
Self-inductance at I<6 kA, L_m	8.40 mH
Self-inductance at I=12.8 kA, L_{mm}	7.85 mH
Operating temperature, T	1.9 K

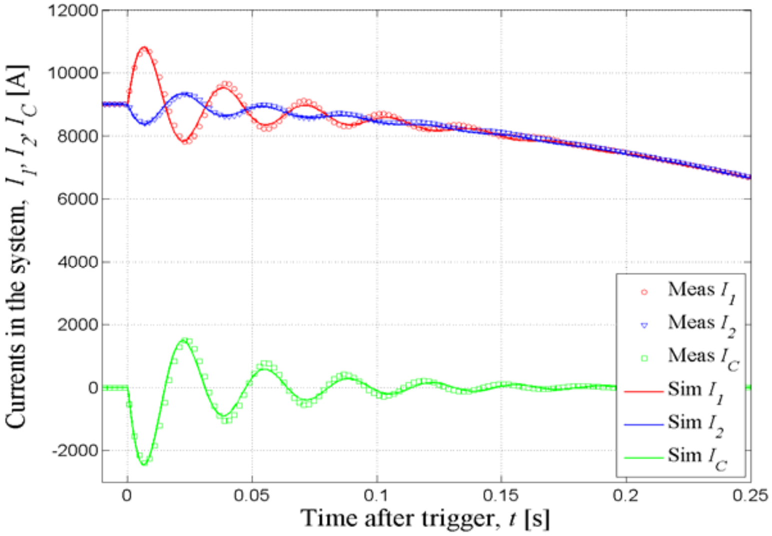

Figure 2. CLIQ test results: measured currents I_C and I_2, calculated current I_1=I_2-I_C, and simulated I_1, I_2, and I_C versus time, after the triggering of CLIQ at t=0.

The effective coil resistance R_Q developed during and after the CLIQ discharge, deduced by subtracting the inductive component from the measured voltages across the two branches L_1 and L_2, is shown in Figure 3 and compared to a similar discharge obtained when firing the hybrid system of a CLIQ and two 850 V quench-heater circuits. CLIQ starts the transition of part of the magnet in the first tens of milliseconds, and after about 50 ms additional resistance is developed by the quench heaters. Several tens of tests were performed under various operating conditions in order to validate the model over a wide range.

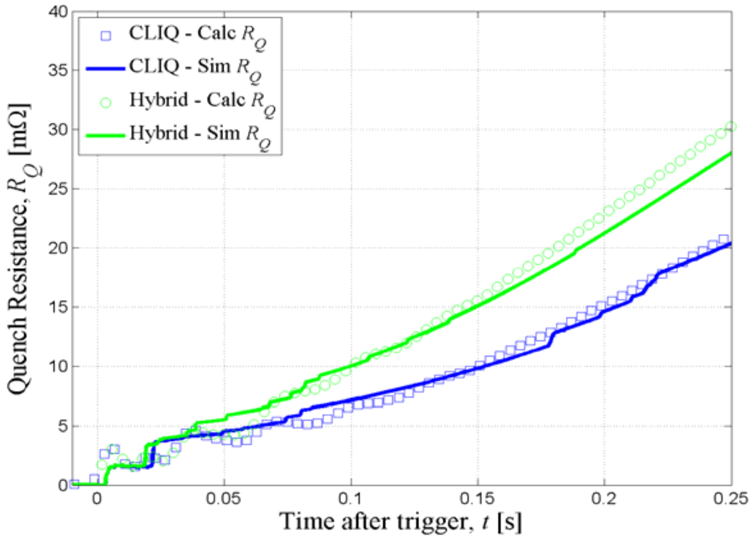

Figure 3. CLIQ and quench heaters test results: measured and simulated effective coil resistance R_Q versus time, after triggering CLIQ or the hybrid system (CLIQ+QHs).

4. Protection of a Large-Scale Quadrupole Magnet

After its validation on the test results of the short quadrupole magnet, the simulation model is further used to predict the electro-magnetic and thermal transients when a quench occurs in a full-scale, 9 m long, 12.8 kA, 43 mH, 3.5 MJ, quadrupole magnet with the same magnetic and cable characteristics as the 1.65 m magnet presented before.

4.1. Quench at Nominal Current

The performance of the three quench protection options, CLIQ, quench heaters (QHs), and the hybrid system (CLIQ+QHs) is analyzed simulating the electro-magnetic and thermal transients after a quench occurring at nominal current (I_0=12.8 kA). Figure 4 shows the current I_1 and the quench resistance R_Q resulting from the triggering of the protection systems, namely two 800 V QHs attached to the outer layers of the magnet, a 28.2 mF, 800 V CLIQ system, or the hybrid system composed of the combination of CLIQ and QHs.

It can be observed that CLIQ initiates a transition after about 20 ms, roughly at half the delay time of the quench heaters. As briefly explained in the next section, the transition induced by CLIQ is located in the inner layer of the magnet, and for this reason the quench initiated by CLIQ causes a slower increase of the magnet resistance. In fact, the inner layers of the magnet are composed of a cable with a cross-section about 30% larger than in the outer layers, and thus the resistance and the Ohmic loss per unit length are less. Furthermore, the propagation of the quench occurs towards the outer low-magnetic field region where the current sharing temperature is higher and hence the normal zone propagation is slower.

The use of the hybrid system combines the advantages of CLIQ and quench heaters in a positive way. In fact, a transition is quickly initiated in the inner region of the coil by the coupling loss introduced by CLIQ, while simultaneously the heat diffused by the quench heaters starts a secondary transition in the outer layers. Moreover, the normal zone propagation towards areas still in the superconducting state is much faster because they are pre-heated by the loss deposited by CLIQ. As a result, the current discharge is faster and most importantly the resulting hot-spot temperature in the coil is significantly decreased.

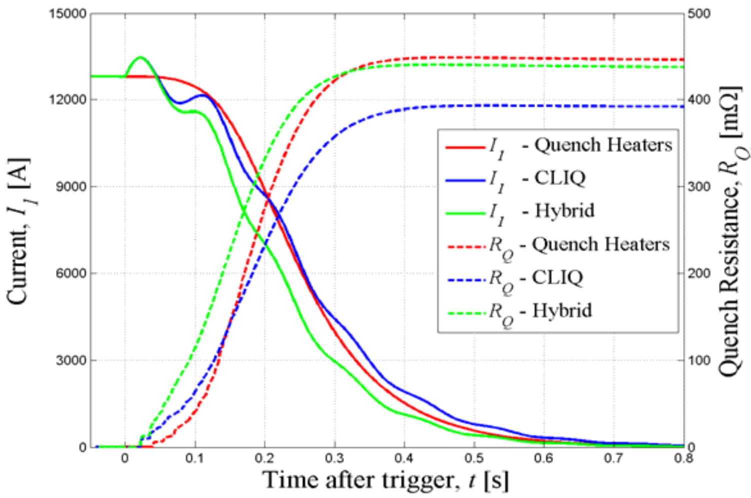

Figure 4. Predicted behaviour of CLIQ and quench heaters in a full-size 9 m long quadrupole magnet. Simulated current I_1 and quench resistance R_Q versus time, obtained by triggering the three protection systems after a quench at nominal current (I_0=12.8 kA) at t=0.

Furthermore, the conductor's hot-spot temperature following the protecting of the magnet with the three variants is calculated in order to further assess the performance of the different protection schemes. The hot-spot temperature $T_{hot\text{-}spot}$ is calculated under conservative assumptions, considering a quench occurring under adiabatic conditions in the worst possible position and imposing a delay of 20 ms for quench detection and triggering of the protection system. The worst-case location for the hot-spot is the high-magnetic field region in the outer cables, where the magnetic field is similar to that of the cable in the inner layer but the cross section is smaller. Figure 5 shows the simulated $T_{hot\text{-}spot}$ obtained protecting the magnet by means of the three system variants charged with voltage U in the range 800-1600 V.

Two quench-heater circuits similar to those used for the protection of the 1.65 m magnet (peak current ~60 A, discharge time constant ~50 ms) and attached to the outer layers of the coil keep the magnet hot-spot temperature within the high but may be acceptable limit of 300 K only if charged with $U \geq 1$ kV (see Configuration 1, C1, in Figure 5). Firing two additional quench heaters on the outer layer reduces the hot spot temperature by about 50 K to some 250 K (C2). Placing four quench-heater circuits between the inner and outer layers of the coil further improves the quench-heater performance (C3). So far, however, quench heaters attached to the inner layers are considered troublesome. Following the simulation an R&D effort to solve this and making them reliable is fully justified.

Protecting this particular quadrupole coil using a stand-alone, 28.2 mF CLIQ system and connected following Figure 1, is acceptable with a charging voltage above 1.2 kV (C4), and increasing C does not significantly improve the figure (C5). The CLIQ performance can be optimized by integrating it in the magnet design from the start, in particular the current lead position for injection of the single current, or the use of multiple injection current leads at optimum positions to maximize the AC current delivered by CLIQ and generate heat at multiple zones, or with the variation of the filament or strand twist pitches to increase the heat-generating coupling losses.

Nonetheless, even the not-optimized CLIQ system acting on the long quadrupole can considerably improve the performance of a quench-heater based protection system. A hybrid system composed of a 28.2 mF CLIQ and two outer quench heaters charged to 800 V, limits the hot-spot temperature to below 280 K without relying on the undesirable inner quench heaters (C6). Besides, the addition of a CLIQ can enhance the overall performance of well-performing quench-heater systems (C7 and C8). The hybrid configurations transfers the coil to the normal state roughly twice as fast as the quench heaters alone do, and 1.6 kV hybrid configurations turn 90% of the coil winding-pack to normal state in 15-25 ms. Some of the simulations of higher voltage configurations show hot-spot temperatures very close to the theoretical limit constituted by the performance of an ideal protection system switching instantaneously the whole coil to normal state associated with a minimum hot-spot temperature of 160 K.

Finally, the performance of an energy-extraction system is simulated (C9). The value of the extraction resistor is chosen so as to obtain a maximum voltage in the circuit similar to the previous cases. The hot-spot temperature is kept below 300 K only at the maximum voltage of 1 kV.

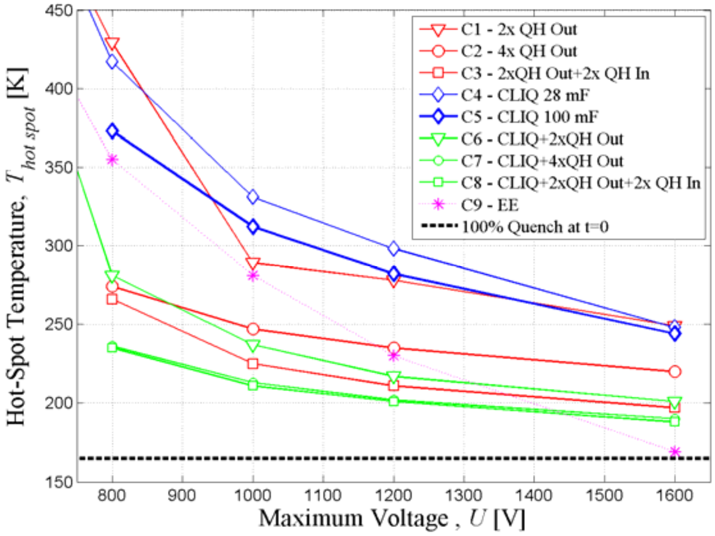

Figure 5. Prediction of the hot spot temperature in the 9 m long quadrupole magnet. Comparison between calculated hot-spot temperatures versus maximum voltage U obtained by triggering various protection systems after a quench at nominal current (I_0=12.8 kA).

4.2. Temperature Distribution

Furthermore, the efficient synergy between CLIQ and quench heaters is evident when observing the evolution of the magnet temperature distribution after triggering the protection system. Figure 6 shows a comparison between the simulated temperatures in the magnet after triggering four 800 V quench heaters (Configuration C2), one 28.2 mF, 800 V CLIQ (C4), or one 800 V hybrid system (C7).

Stand-alone outer quench heaters rapidly initiate a normal zone in only part of the magnet outer layers (see Figures 6q1, 6q2), but the heat needs to diffuse through several insulation layers before reaching the inner layer. In the inner layer the transition starts only after about 90 ms (see Figure 6q3).

On the contrary, CLIQ is most effective when acting on the inner layers where the magnetic field is highest, but it deposits much less energy in the outer low-magnetic field regions (see Figures 6c1, 6c2, 6c3).

The hybrid configuration quickly turns most of the coil to normal state by means of the combined effect of the two systems (see Figures 6h1, 6h2, 6h3). After about 60 ms most of the coil winding pack is in normal state. The temperature distribution resulting from this more global normal zone initiation is very homogeneous, which makes the hybrid system an ideal protection system for Nb_3Sn magnets in which excessive thermal stress may damage the magnet coil.

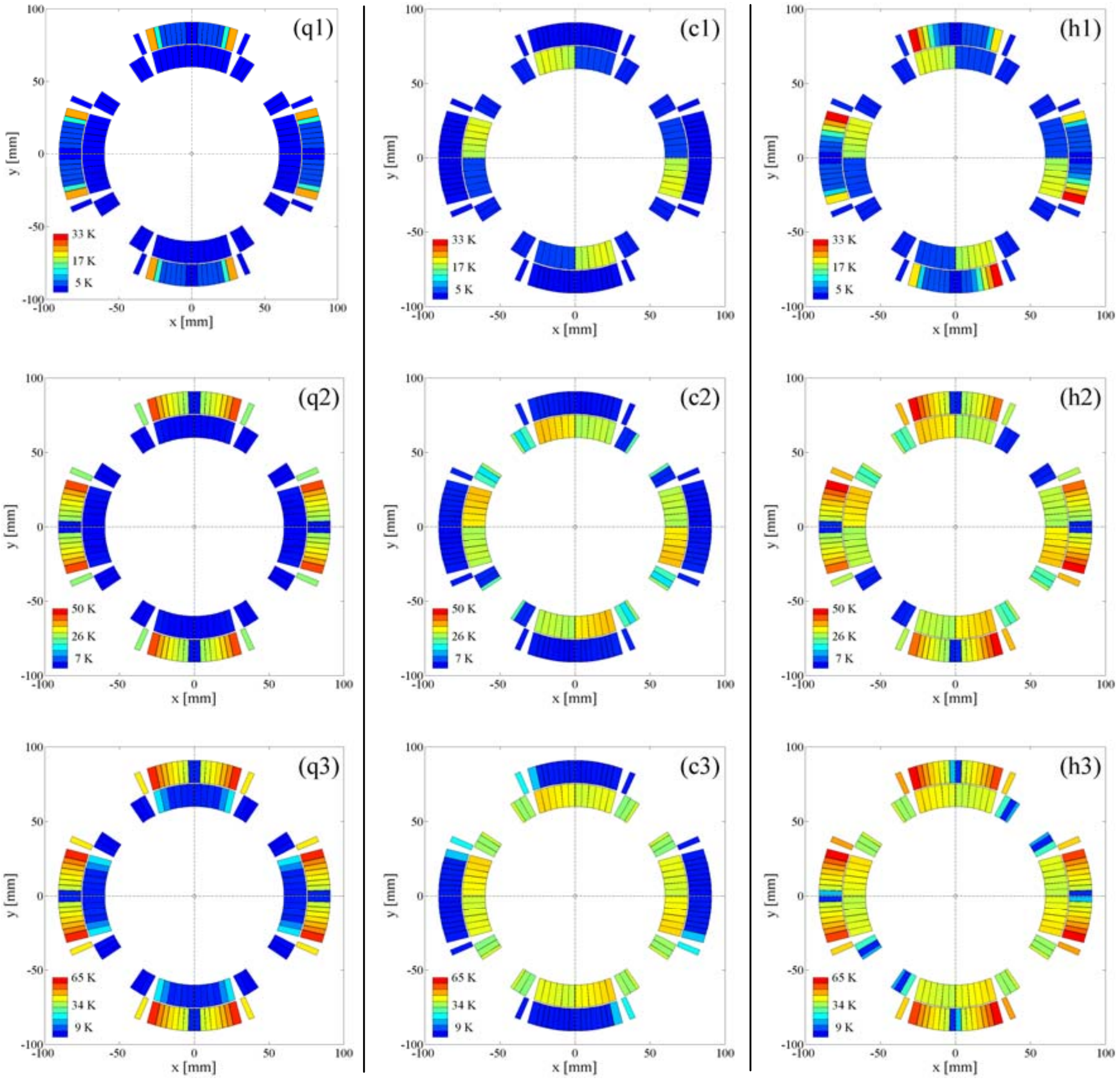

Figure 6. Simulated magnet temperature distributions in the quadrupole coil windings cross section featuring 4 blocks of windings in two coil layers, at 30, 60, and 90 ms after triggering the protection system. Configuration C2 (q1, q2, q3): four 800 V outer quench heaters. Configuration C4 (c1, c2, c3): CLIQ with 28.2 mF, 800 V. Configuration C7 (h1, h2, h3): hybrid system CLIQ+QHs at 800 V.

4.3. Quench at Intermediate Currents

Finally, the effects of a quench at intermediate currents are studied. Figure 7 shows the simulated hot-spot temperature at various current levels between 3 and 9 kA obtained by triggering the three different protection systems with maximum voltage U=1 kV. This range of current may not be safe for a magnet protected by systems that rely on the coil quench resistance to quickly discharge the current. In fact, the lower Ohmic losses, proportional to the square of the current, and the higher current sharing temperature due to the reduced magnetic field imply a lower normal zone propagation velocity and temperature rise in the coil. As a result, the current discharge time is longer and the temperature of the hot-spot can be significantly higher.

Simulation results show that two outer quench-heater circuits are not sufficient to start a normal zone in the magnet for current below 9 kA. On the contrary, four quench heaters placed between the inner and outer layers of the coil keep the hot-spot temperature below 250 K at any current as shown in Figure 7, configuration C3.

One CLIQ system is sufficient to protect the magnet across the entire current range, and at low currents below 6 kA its performance is better than that of the quench heaters (C4-C5). In fact, the energy deposited by CLIQ in the highest-magnetic field region is high enough to initiate a transition of a significant portion of the coil even at low current.

The hybrid system effectively improves the performance of the two systems. Even when adding only two outer quench heaters to the CLIQ (C6), the hot-spot temperature is effectively maintained to the same values as obtained by triggering four inner and outer quench heaters. This result is achieved using a cheaper system (2+1 discharge systems instead of 4) and avoiding the installation of quench heaters between the inner and outer layers of the coil.

Lastly, it can be observed for this stand-alone magnet that an energy-extraction system is more efficient in discharging the magnet energy at low current (C9). Nonetheless, this system may be not economical for the protection of stand-alone magnets and inadequate for the protection of a chain of many superconducting magnets.

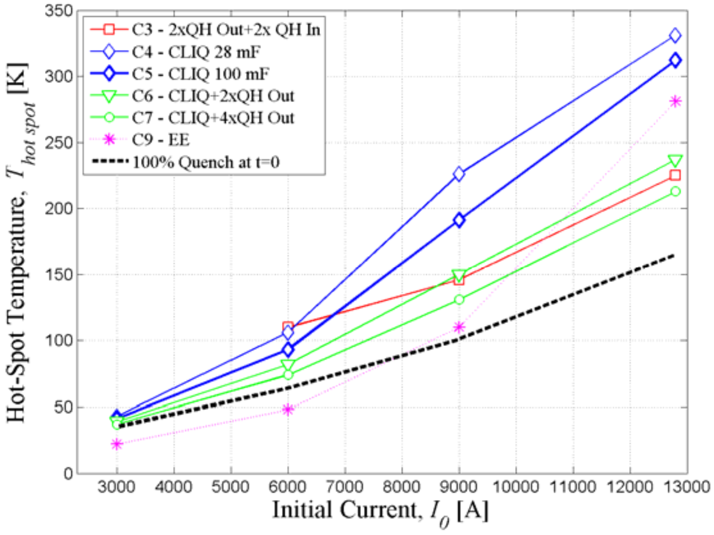

Figure 7. Simulation results of the long quadrupole magnet. Comparison between calculated hot-spot temperature versus initial stationary coil current I_0 at quench obtained by triggering various protection systems with maximum voltage of 1 kV.

This manuscript was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044023 (2014).

5. Conclusion

A novel hybrid system for the protection of superconducting magnets is presented, comprising conventional quench heaters attached to the surface of coil windings and a recently-developed Coupling-Loss Induced Quench (CLIQ) system. CLIQ can efficiently introduce a fast change in the local magnetic field in the coil windings, thus developing high coupling losses thereby generating enough heat in the conductor to cause a fast transition to the normal state of a large volume fraction of the coil. The CLIQ system can be added to any magnet provided an additional current lead can be connected somewhere in between the standard coil terminals. Its cost and energizing system dimensions are similar to a conventional quench-heater system, and is robust and easy to replace. The combination of CLIQ and quench heaters is particularly beneficial since they cause different areas of a magnet to develop a normal zone. In fact, CLIQ causes a deposit of more heat in the inner coil layers conductor with high-magnetic field, whereas the quench heaters are easier to attach to the outer layer of a coil and diffuse heat more quickly to the outer cables.

Simulations carried out with a new 2D lumped-element model, including coupling loss calculations, heat propagation, and dynamic effects, show that the presented hybrid system is very effective in reducing the hot-spot temperature in a superconducting magnet after a quench. Moreover it results in a more homogeneous temperature distribution within the magnet.

The advantages of using CLIQ have been demonstrated on a magnet not specially prepared nor optimized for CLIQ. In general a much better performance of a CLIQ-based magnet protection can be expected in the case the magnet is designed for this case and current injection points can be optimized.

The addition of CLIQ to an operational quench-heater protection system will enhance the quench efficiency and at the same time improves the redundancy of the system. Alternatively, CLIQ can also be implemented as an easy repair option on a magnet with damaged quench heaters, thus avoiding costly and time-consuming repair work.

References

[1] K. Dahlerup et al., “The Protection System for the Superconducting Elements of the Large Hadron Collider at CERN,” *Proceedings of the 1999 Particle Accelerator Conference*, NY, USA, 1999, CERN LHC Project Report 283.

[2] R. Schmidt et al., “Protection of the Superconducting Corrector Magnets for the LHC,” CERN LHC Project Report 419, 2000.

[3] F. Rodriguez-Mateos and F. Sonneman, “Quench Heater Studies for the LHC Magnets,” *Proceedings of the 2001 Particle Accelerator Conference*, Chicago, USA, pp. 3451-3453.

[4] S. Vincent, L. Walckiers, A. Ijspeert, and F. Sonnemann, “Passive Protection by By-pass Resistor for Corrector Magnets Connected in Large Electrical Series,” CERN-MTA-IN-98-054, 1998.

[5] E. Ravaioli et al., “New, Coupling Loss Induced, Quench Protection System for Superconducting Accelerator Magnets,” *IEEE Trans. Appl. Supercond.*, vol. 24 submitted for publication.

[6] J. A. Taylor et al., “Quench Protection for a 2-MJ Magnet”, *Magnetics, IEEE Transactions on* , Vol. 15, no. 1, pp. 855-859, 1979.

[7] R. M. Schöttler and H. W. Lorenzen , “Temperature and Pressure Rise in Supercritical Helium during the Quench of Indirectly Cooled SC Coils”, *Cryogenic Eng. Conference Publication*, Vol. 41, pp. 325-334, 1996.

[8] “AC-Current Induced Quench Protection System,” application has been filed with the European Patent Office on June 28, 2013 under the application number EP13174323.9.

[9] A. Verweij, “Electrodynamics of Superconducting Cables in Accelerator Magnets,” chapter 4, PhD thesis University of Twente, The Netherlands, 1995.

[10] E. Ravaioli et al., “First Experience with the New Coupling-Loss Induced Quench System,” *Cryogenics*, submitted for publication, 2013.

G. Kirby et al., “LHC IR Upgrade Nb-Ti, 120mm Aperture Model Quadrupole Test Results at 1.8K,” IEEE Trans. Appl. Supercond., vol. 24 submitted for publication.