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Advanced Quench Protection for the Nb_3Sn Quadrupoles for the High Luminosity LHC

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***Abstract*—The goal of the High Luminosity LHC project is upgrading the LHC in order to increase its luminosity by a factor five. To achieve this, twenty-four 150 mm aperture, 12 T, Nb_3Sn quadrupole magnets are to be installed close to the two interaction regions at ATLAS and CMS. This new generation of high-field magnets poses a significant challenge concerning the protection of the coils in the case of a quench. The very high stored energy per unit volume requires a fast and effective quench heating system in order to limit the hot-spot temperature and hence avoid damage due to overheating. Conventional protection systems based on quench heaters have a limited response time due to the thermal insulation between the heater and the coil. An advanced solution for the protection of high-field magnets is the CLIQ (Coupling-Loss Induced Quench) system, recently developed at CERN. Due to its fast intra-wire energy-deposition mechanism, CLIQ is a very effective, yet electrically robust, quench protection system. Various protection scenarios including quench heaters, CLIQ, or combinations of the two methods are analyzed and discussed, with the aim of minimizing the coil's hot-spot temperature and thermal gradients during the discharge. The proposed design assures a fully redundant system.**

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

I. Introduction

In order to achieve the targets of the High Luminosity LHC project, four quadrupole magnet systems are planned close to the two high-luminosity interaction regions (ATLAS and CMS), hence replacing the present LHC inner triplet magnets [1]. Each system will be composed of six, 150 mm aperture, two-layer, 12 T, Nb_3Sn quadrupole magnets, four with a magnetic length of 4.2 m and two of 7.15 m [2]–[5].

The very high stored energy per unit volume in these new-generation Nb_3Sn accelerator magnets poses a serious risk to their safety in the case of a quench. A fast quench detection and an efficient quench heating system are required in order to avoid damage due to overheating. Only systems capable to transfer most of the coil winding pack to the normal state in a few tens of millisecond can maintain the coil's hot-spot temperature below the design target of 350 K, currently assumed a safe limit with respect to permanent degradation [6].

Past studies concluded that a quench protection system based on quench heaters attached to the outer layer of the coils and an energy-extraction system barely maintain the coil's hot-spot temperature below safe limits and do not provide a comfortable degree of redundancy [2], [7], [8]. The addition of quench heaters attached also to the inner layer of the coils would provide the required level of redundancy [8]. However, a solution for effective and reliable inner quench heaters is still under development [9].

CLIQ (Coupling-Loss Induced Quench system) is a new quench protection method recently developed at CERN [10]–[12]. It provides an electrically robust and very effective protection system, which relies on the generation of inter-filament coupling loss in the matrix of the strands. CLIQ was successfully tested on magnets of different geometries (solenoid, quadrupole, dipole), superconductor types (Nb-Ti, Nb_3Sn), self-inductances, and sizes [12]–[18].

Various combinations of CLIQ and quench-heater systems attached to the outer (O-QH) and/or inner layer (I-QH) of the coils are analyzed with TALES (Transient Analysis with Lumped-Elements of Superconductors), a new software dedicated to quench-protection and failure-case studies [10], [19]–[21]. The hot-spot temperature and peak voltages to ground obtained are presented. The effect of strand parameters on the effectiveness of the protection system is addressed. Various failure scenarios are identified and analyzed to assess the level of redundancy of the protection system.

II. Quench Protection Schemes

Various options for the powering and protection of such magnets have been discussed. Connecting six magnets in the same circuit powered by a main power supply, schematized in Fig. 1, seems a cost-effective and practical solution due to the minimal number of high-current power supplies and current leads. One or more low-current power supplies can be added across some of the magnets to adjust their currents.

The parameters of the six series-connected magnets and their conductor are summarized in Table I [2], [3]. In the presented protection scheme, each magnet is protected by one CLIQ unit, connected through two internal terminals, and quench heaters attached to the coils. Note that the electrical order of the four poles of each magnet is optimized for achieving optimal CLIQ performance. Let P1-P4 be the names of the poles, ordered counter-clockwise; then the optimum order is P1-P2-P4-P3 [15], [16].

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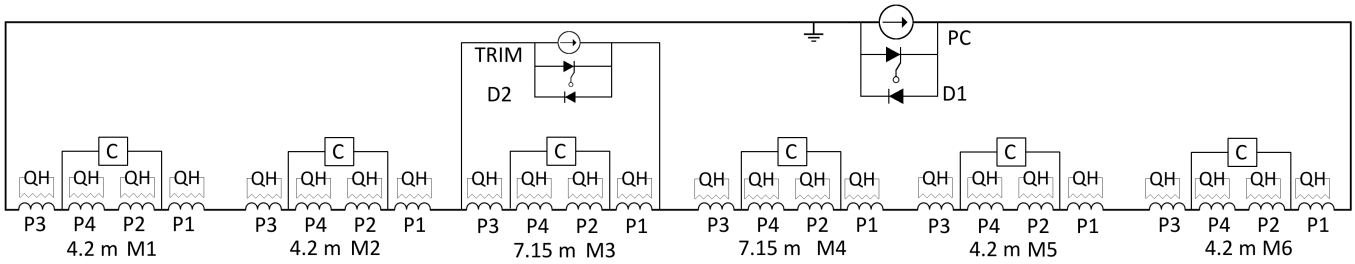

Fig. 1. Schematic of the proposed powering and protection scheme of each circuit including six Nb_3Sn quadrupole magnets (M1-M6), one main power supply (PC), a trim power supply (TRIM), reverse by-pass diodes across the power supplies (D1, D2), CLIQ units (C), and quench-heater units (QH).

TABLE I
MAIN MAGNET AND CONDUCTOR PARAMETERS [2], [3].

Parameter	Unit	Q1/Q3	Q2a/Q2b
Nominal current, $I_{\rm nom}$	A	16471	
Peak field in the conductor	T	11.4	
Operating temperature	K	1.9	
Magnetic length	m	4.20	7.15
Differential inductance at $I_{\rm nom}$	mH	34.4	58.6
Stored energy at $I_{\rm nom}$	MJ	4.7	7.9
Number of turns per pole	-	50	
Number of strands	-	40	
Strand diameter	mm	0.85	
Bare cable width	mm	18.363	
Bare cable thickness	mm	1.594	
Insulation thickness	mm	0.145	
Copper/Nb-Ti ratio	-	1.15	
Filament twist pitch	mm	19	
RRR of the copper matrix	-	140	

TABLE II
MAIN PARAMETERS OF THE ANALYZED PROTECTION SYSTEMS.

Name	Number of units	C [mF]	U_0 [V]	E_0 [kJ]
CLIQ	1	40.0	1000	20.0
O-QH	8	9.6	900	31.1
I-QH	4	9.6	900	11.4

Various protection configurations are analyzed, comprising combinations of CLIQ and Quench Heaters attached to the outer (O-QH) and inner (I-QH) layers of the coils. The design of the quench-heater strips follows the "Copper-plated heater design 2 (IL/OL)" proposed in [2]. Also, it is assumed that the protection elements of all magnets are triggered simultaneously, 16 ms after a quench starts in any of the magnets, accounting for quench detection, validation, and triggering. The capacitances C [F], charging voltages U_0 [V] and number of units of the protection systems considered in this analysis are summarized in Table II.

Energy extraction is not included in this study, since it is not deemed a cost-effective element in protecting this circuit. In fact, high-current circuit breakers are complicated, expensive, require a lot of space, and only extract a small fraction of the magnet stored energy for limited voltages to ground.

A. Thermal Analysis

The performances of the configurations listed in Table III in terms of hot-spot temperature $T_{\rm hot}$ [K] as a function of the initial current are shown in Fig. 2. All configurations can maintain $T_{\rm hot}$ below the design value of 350 K at the nominal current of 16.47 kA, corresponding to 75% of the short-sample limit. However, O-QH provide little margin and rely on quench-back effects, which are difficult to predict reliably. Note that the same simulation yields $T_{\rm hot}$ of 358 K if quench-back effects are not taken into account. A CLIQ-based system can reduce $T_{\rm hot}$ to about 250 K at nominal current. Either "CLIQ and O-QH", or "O-QH and I-QH", can further decrease $T_{\rm hot}$ to some 230 K. The implementation of CLIQ and QH on both layers does not significantly reduce $T_{\rm hot}$.

Temperature gradients between coil sections during the magnet discharge has to be limited to reduce the local thermal stress, which may degrade the performance of the fragile Nb_3Sn coils. Thus, the windings have to be transferred to the normal state as uniformly as possible to distribute more homogeneously the magnet's stored energy.

The temperature distributions in the coil windings are analyzed and compared for the different protection configurations. The average value $T_{\rm ave}$ [K] and standard deviation σ_T [K] of the temperature at the end of the discharge

TABLE III
PROTECTION PERFORMANCE OF THE ANALYZED CONFIGURATIONS.

Configuration	$T_{\rm hot}$ [K]	$T_{\rm ave}$ [K]	σ_T [K]	Δ_T [K]
O-QH	303	109	35	140
O-QH + I-QH	228	109	28	100
CLIQ	253	109	32	112
CLIQ + O-QH	227	111	22	85
CLIQ + O-QH + I-QH	218	110	23	82

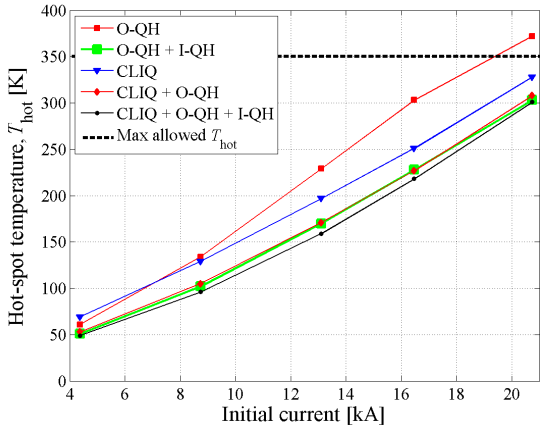

Fig. 2. Comparison between different protection configurations (see Table III). Simulated hot-spot temperature versus initial magnet current.

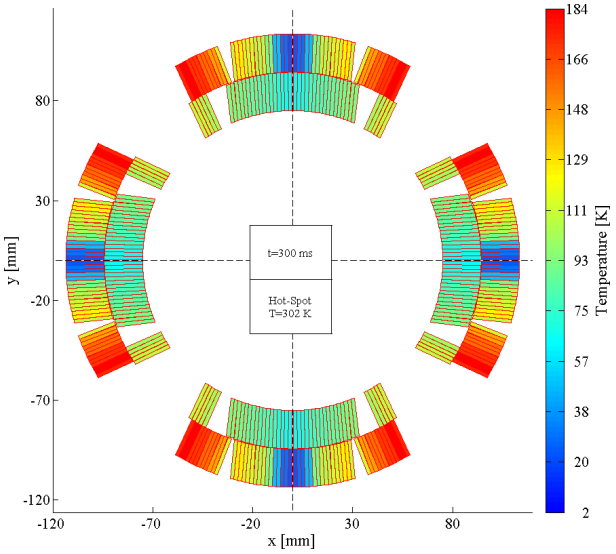

Fig. 3. Simulated magnet temperature over the cross-section of the windings of any of the quadrupole coils, at 300 ms after triggering the protection system "O-QH" at nominal current.

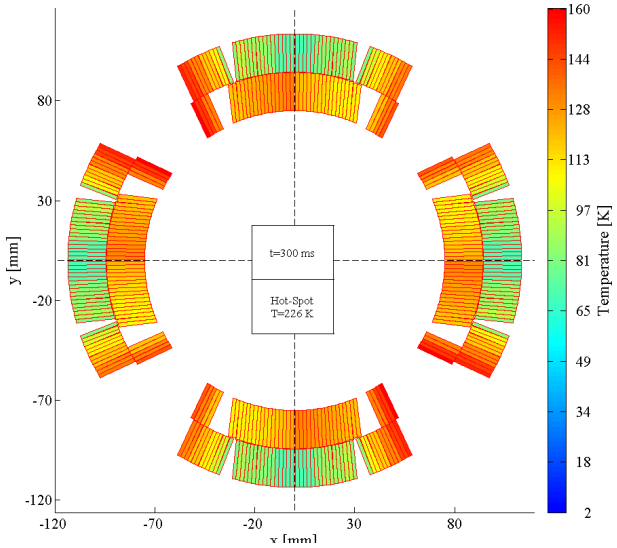

Fig. 4. Simulated magnet temperature over the cross-section of the windings of any of the quadrupole coils, at 300 ms after triggering the protection system "CLIQ and O-QH" at nominal current.

are reported in Table III. The configurations achieving the most homogeneous temperature distributions include CLIQ and O-QH. In fact, these two elements are most effective in depositing heat in different areas of the magnet: CLIQ in the inner layer and in the midplane [10], whereas O-QH in the outer layer. As a result, at nominal current about 90% of the winding pack is transferred to the normal state in the first 20 ms after triggering. The difference between the highest and lowest temperature reached in the windings excluding the hot-spot, Δ_T [K], also shown in Table III, is reduced from 140 to 85 K by implementing this hybrid protection system instead of O-QH. The addition of I-QH does not improve significantly the thermal uniformity, as they deposit heat only in windings that are already heated up very quickly by CLIQ.

The simulated temperature profiles in the magnet cross-section obtained at the end of the discharge after triggering only outer quench heaters or "CLIQ and O-QH" are shown in Figs. 3 and 4, respectively. Triggering only O-QH, the windings located in the high magnetic-field region of the outer layer are overheated, and those in the midplane outer region are barely heated. On the contrary, with a hybrid protection most windings turn simultaneously to the normal state, and the dis-homogeneity in the temperature distribution is mainly due to magneto-resistivity.

B. CLIQ and Outer Quench Heaters

A system combining CLIQ and O-QH is attractive since it provides high redundancy, a homogeneous temperature distribution, and it provides electrical robustness through use of CLIQ [14]. The results of the simulation of a circuit discharge at nominal current are shown in Fig. 5. Given the different lengths of the magnets connected in series, the currents introduced by CLIQ units connected to short and long coils differ. Thus, the currents in the short and long coil sections across which CLIQ units are connected, $I_{\mathrm{B,s}}$ and

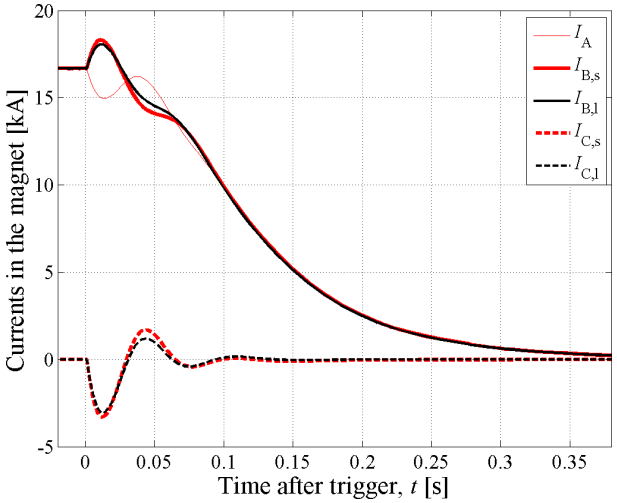

Fig. 5. Magnets protected by "CLIQ and O-QH" at nominal current. Simulated currents in the system versus time.

$I_{\mathrm{B,l}}$ [A], reach slightly different peak values. On the contrary, the same current flows in the coil sections across which no CLIQ unit is connected, I_{A} [A].

C. Effect of Strand Parameters

CLIQ technology utilizes inter-filament coupling loss to heat up the conductor. Hence, strand parameters have an important impact on the performance [10]. In strands with longer filament twist-pitch and lower transverse resistivity, more coupling loss is generated, but with a higher characteristic time constant; and vice-versa [22]. In order to quantify these effects, simulations are performed with varying combinations of filament twist-pitch (17 to 21 mm), RRR of the matrix (75 to 250), magneto-resistivity (4 to 5 $10^{-11}\Omega\mathrm{m}\mathrm{T}^{-1}$), and effective transverse resistivity (50 to 200% of the matrix resistivity).

The simulated hot-spot temperatures are comprised in the range of 214 to 264 K and 209 to 231 K in the case of a CLIQ

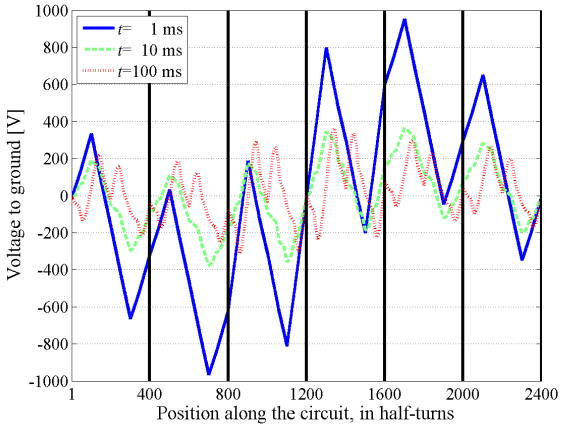

Fig. 6. Simulated voltage to ground along the magnet circuit 1, 10, and 100 ms after triggering a "CLIQ and O-QH" protection system at nominal current. Every position represents a half-turn of the six coils. Each coil consists of 400 half-turns.

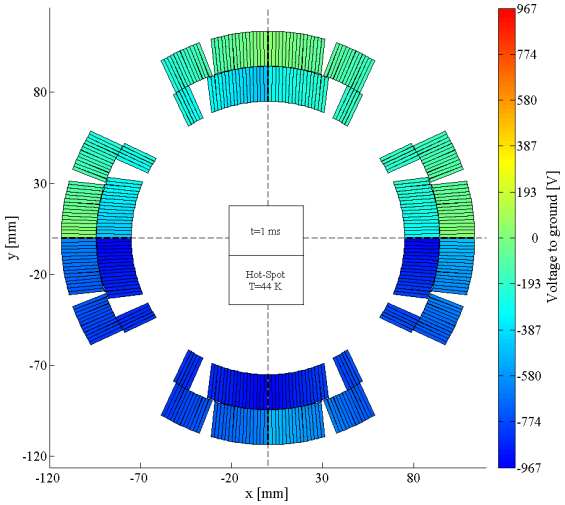

Fig. 7. Simulated voltages between coil windings and ground, over the cross-section of M2 (see Fig. 1), at 1 ms after triggering the "CLIQ and O-QH" protection system at nominal current.

or "CLIQ and O-QH" configuration, respectively. Comparing these results to Fig. 2, one can conclude that variations in the strand properties will not limit the CLIQ performance.

D. Electrical Analysis

The series connection of multiple magnets of different lengths influences the voltage distribution along the circuit during the circuit discharge. In the case of a CLIQ discharge, just after triggering (t=1 ms) the voltages over the coil sections across which the units are connected is fixed to the initial CLIQ charging voltage. Instead, the voltages across the other coil sections depend on their coil lengths.

The resulting voltage distribution along the circuit is plotted in Fig. 6. Voltages to ground as high as $\pm$1 kV develop just after triggering CLIQ. After some parts of the coils are transferred to the normal state, the inductive and resistive voltage components are well distributed along the circuit and the voltages to ground are rapidly reduced.

The peak voltage to ground is reached in M2 (see Fig. 1) just after triggering CLIQ. The simulated distribution of the voltages between its windings and the ground is shown in Fig. 7. All windings located in the inner layers of two poles reach voltages to ground between 800 and 1000 V, and all windings in the outer layers of two poles reach between 400 and 800 V. Since at this early stage almost no electrical resistance is developed in the coil, this distribution is mostly due to the inductive voltages forced by the CLIQ units, and hence it is independent of the triggering of outer or inner QH. If QH are triggered simultaneously with respect to CLIQ, the peak voltage between the windings and the QH strips reaches $1000 \pm U_{0,\mathrm{QH}} \approx 1450$ V. The superposition of the two voltage transients can be avoided by delaying the QH triggering by some 10 ms, with limited effect on the hot-spot temperature.

In the case of quench-heater based systems, unbalanced voltages to ground develop mainly due to the non-uniform transitions to the normal state of the various coil sections. The peak voltages are reached about 100 ms after triggering QH. These voltages do not exceed $\pm$400 V both in the case of O-QH and "O-QH and I-QH" systems.

E. Parallel Elements

The peak voltages to ground reached during a CLIQ discharge can be reduced to about $\pm U_0/2$=500 V by installing by-pass diodes across each magnet, thus limiting the voltage over each coil to the diode opening voltage, usually a few volt. However, the installation of diodes inside the cryostat may present difficulties due to the very high expected radiation dose in the interaction regions.

Alternatively, a similar reduction of the voltages to ground can be achieved by means of parallel resistors across each magnet. These elements are only needed for equalizing the voltages over the magnets, and not for carrying the circuit current after the magnets are quenched, therefore they can be of relatively high resistance and limited power rating. During magnet operation, at the nominal current change of 16.5 As^{-1} leakage currents of about 965 and 565 mA are expected through 1 Ω resistors mounted across the long and short coils, respectively, resulting in cryogenic loads of 930 and 320 mW. These leakage currents are very well reproducible and can be easily corrected by the power supplies. The resistances of the resistors could also be scaled to the self-inductances of the coils of different lengths in order to introduce more similar current errors in the magnets.

Fig. 8 shows the distribution of the voltages to ground along the circuit during a "CLIQ and O-QH" discharge, in the case 1 Ω parallel resistors are installed across each magnet. By effect of the additional parallel branches, the voltages across the magnets are equalized, and as a result the peak voltage to ground does not exceed 500 V. During the discharge, pulsed currents with peak values of about 220 and 120 A are pushed through the resistors across the long and short coils, respectively, resulting in power dissipations of 3.2 and 0.8 kJ.

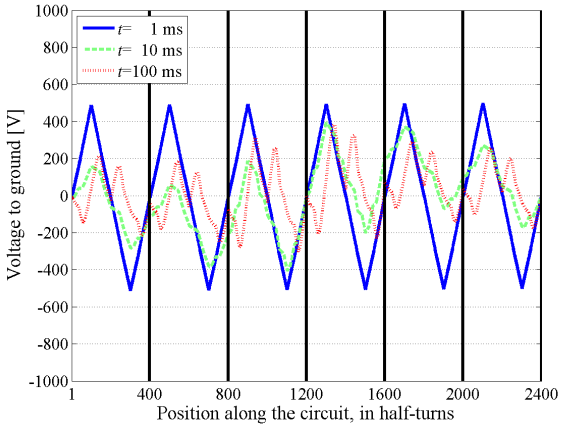

Fig. 8. Simulated voltage to ground along the magnet circuit 1, 10, and 100 ms after triggering a "CLIQ and O-QH" protection system at nominal current, including 1 Ω parallel resistors across each magnet. Every position represents a half-turn of the six coils. Each coil consists of 400 half-turns.

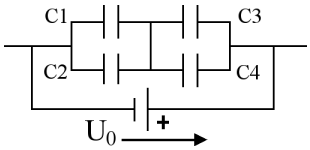

Fig. 9. Schematic of the capacitor bank of a redundant CLIQ unit composed of a series of two capacitors in parallel.

III. CLIQ Failure Analysis

In order to improve the redundancy of each CLIQ unit, each capacitor bank can be composed of a series of two capacitors in parallel, as shown in Fig. 9. With this device, the effectiveness of the unit is assured even in the case one capacitor is damaged and becomes an open or a short circuit. Whilst the probability of a damaged capacitor is very low, the impact of such failures has to be analyzed carefully. In the case of an open-circuit failure, the capacitance of the bank becomes $2/3C$. In the case of a short-circuit failure, it becomes $2C$, and the voltages across two capacitors double. For example, if capacitor C1 (see Fig. 9) becomes a short circuit, the voltage U_0 is applied over C3 and C4. Hence, a redundant CLIQ unit is composed of capacitors rated for a voltage as high as U_0, and each with capacitance 1.5 times higher than the minimum required for an effective protection.

In both failure cases, the hot-spot temperature reached in the coils is hardly affected. In fact, the effectiveness of the CLIQ system is not significantly reduced by a different capacitance, its power deposition being roughly proportional to the charging voltage and independent of the capacitance [10], [12]. Furthermore, the electrical resistances developed in the coils protected by unfailing systems are all in series and contribute to the discharge of the circuit current.

On the contrary, the voltage distribution in the circuit can be affected by the failure of a capacitor of a CLIQ unit. The less symmetric oscillating currents then introduced in the coil sections result in less homogeneous transitions to the normal state, which in turn make the distribution of inductive and resistive components less uniform. Figure 10 shows the voltage distribution along the circuit in the two failure cases, as compared to the no-failure case shown in Fig. 6. In all fault cases, the voltages just after triggering (t=1 ms) are unchanged, whereas the voltages during the magnet discharge are distributed less uniformly. However, the voltages never exceed the initial peaks reached just after triggering the protection system.

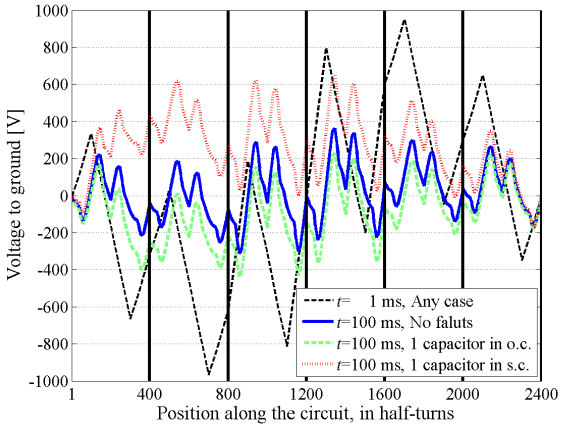

Fig. 10. Effect of failures in a capacitor of a CLIQ unit: open circuit (o.c.) and short circuit (s.c.). Simulated voltage to ground along the magnet circuit, 1 and 100 ms after triggering a CLIQ and O-QH protection system at nominal current.

IV. Conclusion

Various options for the protection of the Nb_3Sn high-field quadrupole magnets are analyzed. The protection schemes include CLIQ units and Quench Heaters attached to the outer and/or inner layers of the coils. All configurations maintain the hot-spot temperature below the design value of 350 K after a quench at nominal current. The hot-spot temperature can be reduced by about 50 K by implementing a CLIQ-based system, or by about 75 K by implementing outer and inner quench-heaters or CLIQ and outer quench heaters.

The combination of CLIQ and outer quench-heaters exploits the synergy between the two systems, which are most effective in heating up distinct sections of the coil. As a result of the very homogeneous transition to the normal state, thermal gradients in the coil during the discharge are minimized. Furthermore, the simultaneous triggering of two independent systems based on different principles and mainly active on different coil sections assures a very high level of redundancy.

The series connection of multiple magnets of different lengths in the same circuit poses some concerns regarding the peak voltages to ground developed during a CLIQ discharge, in particular in the case of failures of system components. These effects could be mitigated by means of by-pass diodes or resistors installed across each magnet in order to equalize the voltages over each magnet. However, the installation of such elements in the magnet area may present difficulties due to the very high expected radiation dose and current tracking. Further investigations into these matters are required.

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