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First experience with the new Coupling Loss Induced Quench system

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ABSTRACT

New-generation high-field superconducting magnets pose a challenge relating to the protection of the coil winding pack in the case of a quench. The high stored energy per unit volume calls for a very efficient quench detection and fast quench propagation in order to avoid damage due to overheating.

A new protection system called Coupling-Loss Induced Quench (CLIQ) was recently developed and tested at CERN. This method provokes a fast change in the magnet transport current by means of a capacitive discharge. The resulting change in the local magnetic field induces inter-filament and inter-strand coupling losses which heat up the superconductor and eventually initiate a quench in a large fraction of the coil winding pack.

The method is extensively tested on a Nb–Ti single-wire test solenoid magnet in the CERN Cryogenic Laboratory in order to assess its performance, optimize its operating parameters, and study new electrical configurations. Each parameter is thoroughly analyzed and its impact on the quench efficiency highlighted.

Furthermore, an alternative method is also considered, based on a CLIQ discharge through a resistive coil magnetically coupled with the solenoid but external to it. Due to the strong coupling between the external coil and the magnet, the oscillating current in the external coil changes the magnetic field in the solenoid strands and thus generates coupling losses in the strands. Although for a given charging voltage this configuration usually yields poorer quench performance than a standard CLIQ discharge, it has the advantage of being electrically insulated from the solenoid coil, and thus it can work with much higher voltage.

1. Introduction

New-generation high-field superconducting magnets require a very efficient quench protection system which can quickly discharge the energy stored in a coil. Conventional protection systems, such as energy-extraction systems and quench heaters, have drawbacks and limitations. The value of an extraction resistor R_{EE}, and hence the decay time, is limited by the maximum safe voltage in the circuit $U_{EE} = R_{EE}{\cdot}I$. Quench heaters rely on the thermal diffusion across insulation layers, an inherently slow process, and increase the risk of electrical break-down.

A new Coupling-Loss Induced Quench (CLIQ) protection system was recently developed at CERN. This method features a capacitive discharge through a current lead connected to an internal point of a coil, resulting in a fast change of the local magnetic field in the conductor. As a result, coupling losses are generated in the copper matrix of the superconductor which heat up the coil and quickly initiate a quench due to the enhanced temperature. The CLIQ was successfully tested on a 2 m long quadrupole magnet in the CERN magnet test facility [1–2].

Nevertheless, testing the method on a small-scale test magnet allows a more thorough analysis of the system behavior thanks to the reduced time required for each test and to the additional voltage taps available for measurements. The CLIQ is tested on a Nb–Ti solenoid magnet at CERN in order to assess its performance, optimize its operating parameters, and study various electrical configurations. The effect of each parameter on the system performance is thoroughly investigated.

Moreover, an alternative CLIQ design is tested, based on a capacitive discharge through a copper external coil surrounding the solenoid magnet. Such a system is electrically insulated from the magnet but can deposit heat in the solenoid coil by introducing coupling losses in its strands.

2. The Coupling Loss Induced Quench system

The CLIQ system, presented in [1–2], is schematized in Fig. 1. Its design is based on a protection scheme proposed in [3–4] but with the addition of the patented reverse diode D [5]. The CLIQ is

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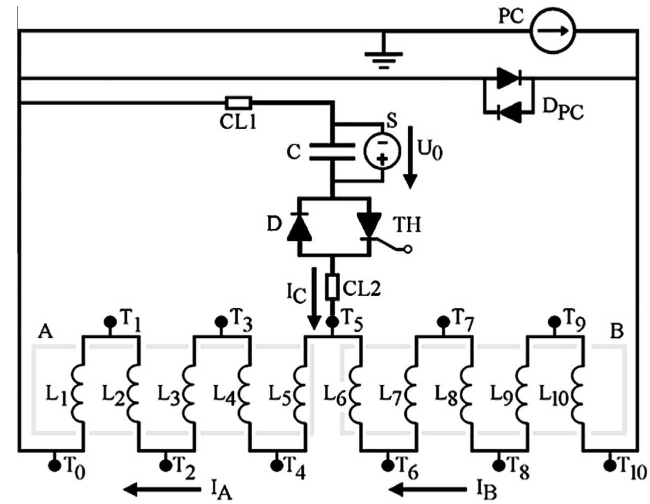

Fig. 1. Schematic of the Coupling-Loss Induced Quench (CLIQ) protection system and of the test solenoid magnet (Configuration T0–T5, see Section 3).

composed of a capacitor bank C, a floating voltage supply S, two additional resistive current leads CL1 and CL2 connecting the system to the superconducting coil, a thyristor TH, and a reverse diode D. The capacitor bank is charged by S with a voltage U_0. When a quench is detected, the thyristor is activated resulting in a current I_C to be discharged through CL1 and CL2. This introduces a current change with opposite direction in the two branches of the coil A and B. The presence of the reverse diode allows continuous oscillations of I_C.

The time evolution of the CLIQ system is found by solving the following equivalent system:

$$\begin{cases} I_A = I_C + I_B \\ (L_A + M_{AB}) \cdot \dot{I}_A + (L_B + M_{AB}) \cdot \dot{I}_B + R_{Q,A} \cdot I_A + R_{Q,B} \cdot I_B + U_D = 0 \\ U_C = L_A \cdot \dot{I}_A + M_{AB} \cdot \dot{I}_B + R_{Q,A} \cdot I_A + (R_{\mathrm{CL1}} + R_{\mathrm{CL2}}) \cdot I_C + U_{TH} \\ I_C = C \cdot \dot{U}_C \\ I_A(0) = I_B(0) = I_0 \\ I_C(0) = \dot{U}_C(0) = 0 \\ U_C(0) = U_0, \end{cases} \tag{1}$$

where I_A and I_B are the current flowing in A and B, L_A and L_B the self-inductances of A and B, M_{AB} their mutual inductance, $R_{Q,A}$ and $R_{Q,B}$ the quench resistance developed in A and B, U_D the voltage drop across the diode D_{PC}, U_C the voltage across C, R_{CL1} and R_{CL2} the resistance of CL1 and CL2, U_{TH} the voltage drop across the thyristor TH, and I_0 the initial magnet transport current.

At the moment of the CLIQ discharge, it can be assumed that the large majority of the coil is in superconducting state, i.e. $R_{Q,A} \approx R_{Q,B} \approx 0$. Under this assumption, the system can be analyzed as a series RLC circuit composed of the equivalent circuit resistance $R_{eq} = R_{\mathrm{CL1}} + R_{\mathrm{CL2}} + U_{TH}/I_C$, the equivalent inductance of the coil circuit L_{eq}, and the discharging capacitance C. L_{eq} can be calculated by solving system (1) for constant L_A, L_B, and M_{AB}:

$$L_{eq} = (L_A \cdot L_B - M_{AB}^2)/(L_A + L_B + 2M_{\mathrm{AB}}), \tag{2}$$

which correspond to the impedance of two mutually coupled inductors in parallel. In real cases the self-inductances L_A and L_B decrease with the frequency due to dynamic effects linked to coupling currents, which change the amount of magnetic flux linked to the superconducting coil. It can be shown that if $R_{eq} < 2\sqrt{L_{eq}/C}$ the response of the RLC system is a damped oscillation. Neglecting the limited voltage drop across D_{PC}, the voltage across C and the current I_C are equal to:

$$U_C(t) = U_0 \cdot \exp(-\alpha t) \cdot \left[\cos(\omega t) + \frac{\alpha}{\omega}\sin(\omega t)\right], \tag{3}$$

and

$$I_C(t) = C\frac{dU_C(t)}{dt} = -CU_0 \cdot \frac{\omega^2 + \alpha^2}{\omega} \cdot \exp(-\alpha t) \cdot \sin(\omega t), \tag{4}$$

with $\omega = \sqrt{\omega_0^2 - \alpha^2}, \omega_0 = 1/\sqrt{L_{eq} \cdot C}$, and $\alpha = R_{eq}/(2L_{eq})$. In most practical cases $\alpha \ll \omega_0$ and thus $\omega \approx \omega_0$. Assuming an initial transport current I_0, the current in the two branches is:

$$I_A(t) = I_0 + (L_B + M_{AB})/(L_A + L_B + M_{AB}) \cdot I_C = I_0 + f_{g,A} \cdot I_C, \tag{5a}$$

and

$$I_B(t) = I_0 - (L_A + M_{AB})/(L_A + L_B + M_{AB}) \cdot I_C = I_0 - f_{g,B} \cdot I_C, \tag{5b}$$

where $f_{g,A}$ and $f_{g,B}$ are purely geometric parameters if the self and mutual inductances are constant. The introduced current change in the two branches is thus

$$\begin{aligned} dI_A/dt &= f_{g,A} \cdot dI_C/dt \\ &= CU_0 \cdot \frac{\omega^2 + \alpha^2}{\omega} \cdot f_{g,A} \cdot [\omega \cdot \exp(-\alpha t) \cdot \cos(\omega t) - \alpha \\ &\quad \cdot \exp(-\alpha t) \cdot \sin(\omega t)], \end{aligned} \tag{6a}$$

and

$$\begin{aligned} dI_B/dt &= f_{g,B} \cdot dI_C/dt \\ &= -CU_0 \cdot \frac{\omega^2 + \alpha^2}{\omega} \cdot f_{g,B} \cdot [\omega \cdot \exp(-\alpha t) \cdot \cos(\omega t) - \alpha \\ &\quad \cdot \exp(-\alpha t) \cdot \sin(\omega t)]. \end{aligned} \tag{6b}$$

These oscillating currents change the local magnetic field inside the coil. Let z and r be the two directions perpendicular to the transport-current direction. In the case of a solenoid magnet, z is parallel to the solenoid axis and r is parallel to its radius. In steady-state the magnetic field along z and r in each superconducting strand k is a linear function of the transport currents in A and B, hence

$$B_{az,k} = f_{z,A,k} I_A + f_{z,B,k} I_B, \tag{7a}$$

and

$$B_{ar,k} = f_{r,A,k} I_A + f_{r,B,k} I_B. \tag{7b}$$

The parameters appearing in Eqs. (7a) and (7b) can be calculated by means of dedicated software, such as [6]. However, in a solenoid magnet usually $B_{ar} \ll B_{az}$. Hence, let the steady-state magnetic field in the z direction be $B_{a,k} = f_{A,k} \cdot I_A + f_{B,k} \cdot I_B$. When a superconducting strand is subjected to an applied field change $dB_{a,k}/dt$, an induced field change $dB_{i,k}/dt$ is created in the opposite direction due to inter-filament coupling currents [7]. Thus, the total local magnetic-field change is:

$$\begin{aligned} \frac{dB_{t,k}}{dt} &= \frac{dB_{a,k}}{dt} + \frac{dB_{i,k}}{dt} \\ &= CU_0 \cdot \frac{\omega^2 + \alpha^2}{\omega} \cdot (f_{A,k} \cdot f_{g,A} - f_{B,k} \cdot f_{g,B}) \cdot [\omega \cdot \exp(-\alpha t) \\ &\quad \cdot \cos(\omega t) - \alpha \cdot \exp(-\alpha t) \cdot \sin(\omega t)] \\ &\quad \cdot \left[1 - \exp\left(-\frac{t}{\tau_{if,k}}\right)\right], \end{aligned} \tag{8}$$

with $\tau_{if,k}$ the characteristic time constant of the inter-filament coupling currents,

$$\tau_{if,k} = \frac{\mu_0}{2\rho_{eff,k}} \left(\frac{l_f}{2\pi}\right)^2 = \beta_k \frac{\mu_0}{2}, \tag{9}$$

with l_f the filament twist-pitch, ρ_{eff} the effective transverse resistivity of the matrix, $\mu_0 = 4\pi \times 10^{-7}$ T m/A the magnetic permeability of