# Electrical Model of Frequency Loss Induced Quench Protection System for High Temperature Superconducting Magnets

Kikelomo Ijagbemi, Daniel Davis, Xi Yuan, Eric Stiers, Yuan Li, and Sastry Pamidi

***Abstract*—Frequency Loss Induced Quench (FLIQ) is an active protection system designed to generate heat from AC losses to uniformly and safely quench a superconducting coil. It drives an imbalance in the transport current between two or more sections of the magnet using the H-bridge design with Insulated Gate Bipolar Transistor (IGBT)s, whose gates are controlled based on the current feedback within its loop. This allows FLIQ to operate at resonance with the frequency of the load. The performance of FLIQ circuit was characterized using simulations to assess the relative effectiveness of the key parameters of voltage, frequency, and time. The results show that the voltage is the most effective parameter. It was shown that with the selection of appropriate values of the parameters, the FLIQ system released sufficient energy into the coil to quench it.**

***Index Terms*—Quench protection, high temperature superconducting magnets.**

## I. INTRODUCTION

FREQUENCY Loss Induced Quench (FLIQ) [1] is a system designed to drive an imbalance in the transport current between sections of a superconducting coil which initiates heat generation in the coil uniformly and quench it safely. FLIQ circuit as shown in Fig. 1 operates using a current controlled H-bridge design that maximizes its power output at resonance. The slow normal zone propagation and stability of HTS requires a much larger energy to quench when compared to LTS magnets. CLIQ [2] is an ac loss induced protection mechanism that requires an increase in voltage or capacitance to increase energy. FLIQ does not require increasing the capacitance as this decreases the excitation frequency which affects power input. Its capacity to operate at higher frequencies and voltages provides a solution to the challenge of large amount of energy required to quench a High Temperature Superconducting (HTS) magnet [3]. To design a quench protection for practical applications, knowledge of the sensitivities of the FLIQ parameters such as frequency, voltage, and time is essential.

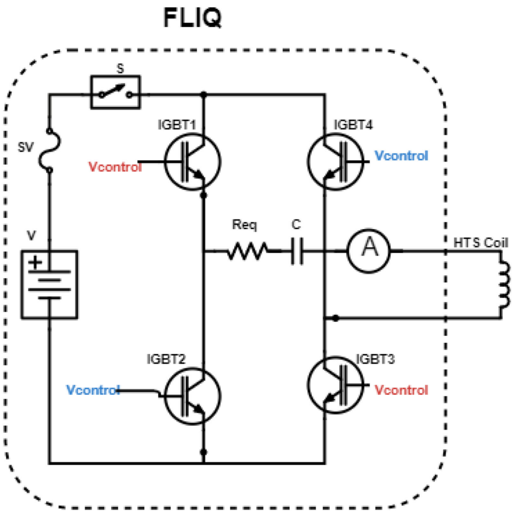

Fig. 1. FLIQ circuit.

To understand the FLIQ performance, numerical analysis was carried out using Laplace transform of convolution to determine the current after simplifying Fig. 1 into a series RLC circuit. This model was developed in MATLAB. (1) shows the numerical function that describes FLIQ current as a function of frequency, voltage, and time. The simulation work reported here is a significant extension of our earlier simulation effort described in [4] which considered enthalpy margin of a REBCO coil and how much energy is needed to quench the coil as field, field angle, frequency, and voltage changes. This paper also discusses the changes in FLIQ parameters as the magnet transitions from

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superconducting to normal state, the electrothermal effect and the estimation of ac loss on a sample coil. In (1), $k$ is the number of iterations and it is limited to 5 as this gives a good representation of the current signal and increases simulation speed.

$$I_F\,(t) = \frac{1}{bL} \times \left[ e^{-at}\cdot \left[b\cos(bt) - a\sin(bt)\right]\cdot \frac{4V}{\pi}\sum_{k\,=\,1,odd}^{\infty}\frac{1}{k}\sin(k\omega t)\right] \tag{1}$$

$$a = \frac{R_{\,eq}\,(t)}{2L},\ b = \sqrt{\omega^2 -\ a^2},\ \omega = {}^{1}\!\big/\!\sqrt{LC}$$

- $I_F$ is the FLIQ current
- $V$ is the voltage of the energy source
- $t$ is time
- $L$ is the effective inductance of the HTS coil
- $C$ is the capacitance in series with the FLIQ output
- $R_{\,eq}(t)$ is the effective resistance of the circuit

## II. FLIQ PARAMETRIC SIMULATION

The magnet is electrically simulated as an inductor with a non-linear resistance. This is representative of the change in resistance in high temperature superconducting magnets during the transition to normal state [5][6]. The FLIQ parametric effect is shown in Fig. 2. Voltage, frequency, and activation period are kept constant at 300 V, 500 Hz, and 0.5 s, respectively when one of the parameters is changing. The average energy within an activation period is determined by the expression:

$$Energy = \frac{1}{T}\int_0^T P\,(t)\ dt \approx \frac{\sum_{i=0}^{T}\ P\,(t_i)\cdot\ \Delta t}{T}\ \ [\,J\,] \tag{2}$$

where, $P(t) = I_F(t)^2\cdot R_{\,eq}(t)$ , and $\mathrm{t} = \mathrm{i}\cdot\Delta t$

Considering an exponentially dynamic resistance of a REBCO coil [7][8], frequency is directly proportional to the amount of FLIQ energy deposited, increasing the DC voltage and time increases the average energy exponentially. Voltage is the most effective parameter in producing higher amplitudes when compared to other parameters. Frequency has a linear relationship with energy, i.e., reducing the capacitance of the circuit will linearly increase the average energy. However, when compared to other parameters, the frequency of the circuit has the least effect on the amount of energy deposited but influences how quickly energy can be deposited. The most effective parameters are the DC voltage, time, and frequency in that order.

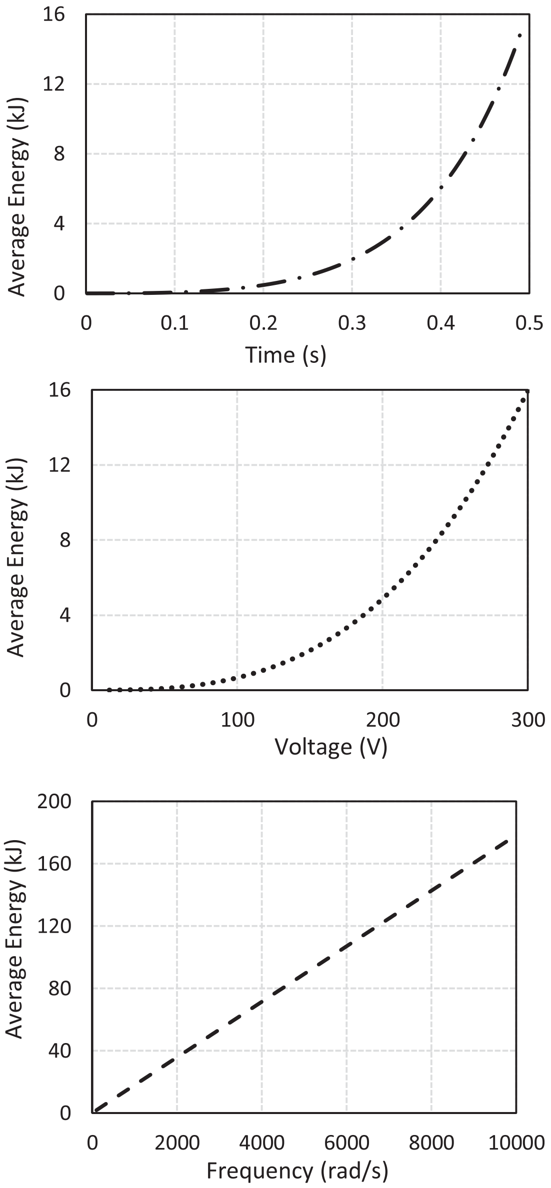

Fig. 2. Parametric effects of FLIQ considering time, voltage, and frequency.

## III. ELECTROTHERMAL EFFECT

The adiabatic heat equation [9]–[12] was calculated using (3), the electro thermal effect of FLIQ system on a REBCO coil was simulated considering the condition where operating current is at 0.1 of the critical current, $I_c$ and total current is greater than the lowest $I_c$(23.4T,85.7°) at a background field of 20 T and FLIQ is activated using a constant voltage source for a period of 0.5 s.

$$I(t)^2\left[R_t\,(T)\,\frac{l}{A_t}\right] = \left[V_{cu}\gamma_{cu}C_{cu}\,(T) + V_{Hast}\gamma_{Hast}C_{Hast}\,(T)\right]\frac{\partial T}{\partial t} \tag{3}$$

- $l$ is the length of the magnet
- $T$ is temperature
- $I\ (t)$ is total current in the tape
- $t$ is time
- $A_t$ is the tape cross-sectional area
- $R_t(T)$ is the resistance load per unit length
- $C_{cu}(T)$ , $C_{Hast}(T)$ is the specific heat capacity of copper and hastelloy respectively

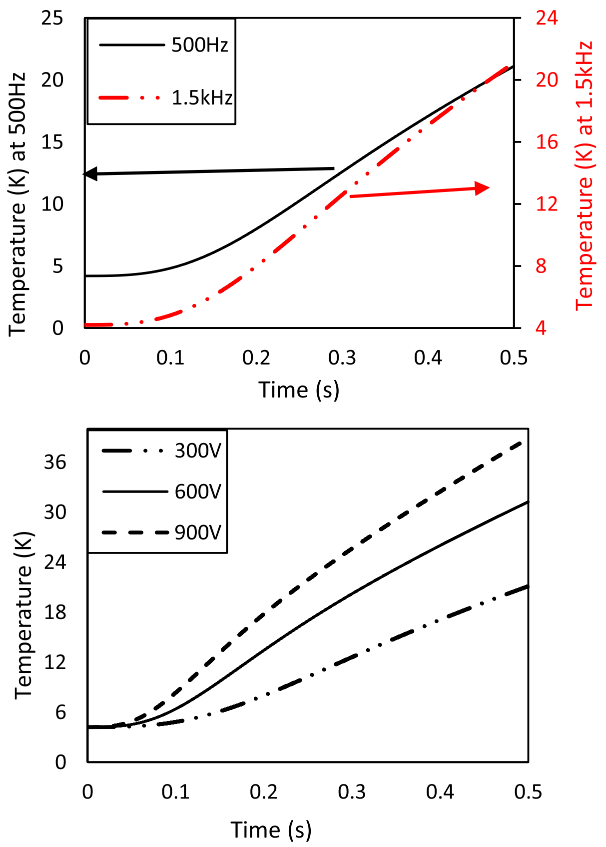

Fig. 3. Electrothermal effect of capacitance at 300 VDC and voltage at 500 Hz.

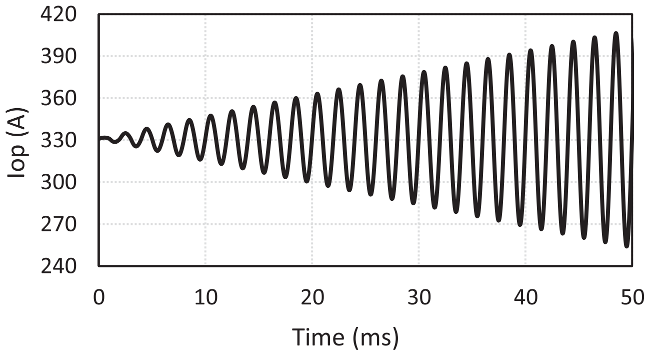

Fig. 4. Current versus time after FLIQ discharge at Iop = 331 A.

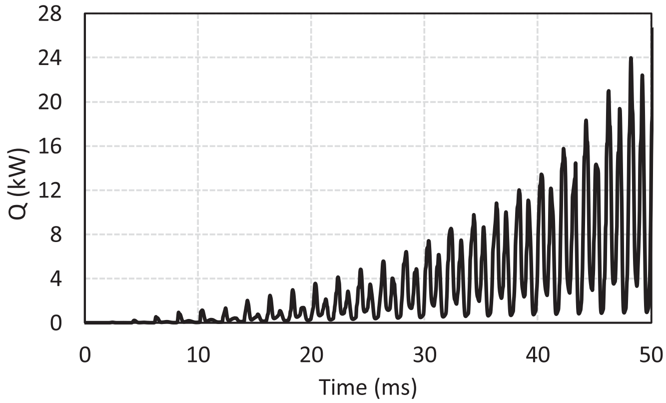

Fig. 5. Instantaneous AC loss after FLIQ discharge.

- $V_{cu}, V_{Hast}$ is the volume of copper and hastelloy respectively
- $\gamma_{cu}$ , $\gamma_{Hast}$ is the density of copper and hastelloy respectively.

## A. *Effect of Capacitance*

The results of the simulations in Fig. 3 show that the oscilating FLIQ current introduces energy that raises the temperature of the magnet in a period of 0.5 s at 300 VDC. The result describe how increasing the operating frequency of FLIQ, which also means a reduction in capacitance, will raise the temperature of the magnet in order to quench it safely.

## B. *Effect of DC Voltage*

Fig. 3 shows that an increase in the DC voltage of the FLIQ circuit will significantly raise the temperature of the magnet more than an increase in frequency. Therefore, due to its larger effects, the energy required to quench the coil will reduce with increasing voltage.

## IV. AC LOSS ESTIMATION ON REBCO COIL

The performance of the coil was investigated at 0.75 $I_C$, 20 T background field when FLIQ current frequency is 500 Hz. The DC voltage was 300 V. The simulation results show the AC loss in the magnet during the first 25 cycles after FLIQ initiation. Critical current, $I_c$ of the REBCO tape was calculated using the practical fit functions for transport critical current described in [13] with an n-value of 30, used to calculate the voltage-current (V-I) characteristic of the superconductor.

AC loss [14] was estimated using (4), where $\Omega$ is the cross sections of the pancake in the HTS magnet, $E(t)$ is the electric field, and $J(t)$ is the instantaneous current density. The integral $Q$ gives the instantaneous ac loss (W) of the HTS magnet.

$$Q = \int_{\Omega} 2\pi r \cdot E(t) \cdot J(t) \cdot \delta\Omega \ [W] \tag{4}$$

In Fig. 4, the operating current ($I_{op}$) in the magnet was ramped to 0.75$\cdot I_C$ before FLIQ current is introduced. FLIQ produced about 2 T within 25 cycles with total activation time of 50 ms. At 0.75$\cdot I_C$, 500 Hz, 300 VDC, the total instantaneous AC loss shown in Fig. 5 is about 3.6 MW and the total energy within 50 ms is 182.4 J.

## V. CONCLUSION

The performance of Frequency Loss Induced Quench (FLIQ) was characterized as a function of the key parameters such as voltage, frequency, and time. From the comparisons of the results, the voltage is the most effective parameter. Using a REBCO coil as a test case, it was shown that FLIQ system released about 99 times the minimum energy needed to quench the coil at 0.75 $I_C$, 20 T background field when FLIQ frequency is 500 Hz. Future work will include simulation and testing with other coil types and determination of the optimal range of parameters.

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