

Frequency loss induced quench protection system for high temperature superconductors

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Abstract. A novel circuit design for Frequency Loss Induced Quench (FLIQ) protection system for safely driving REBCO coated conductor superconducting coils to quench is reported. The details of the H-bridge circuit design with Insulated Gate Bipolar Transistor (IGBT)s and the various elements used to build a prototype are reported. The results of a successful test of the circuit conducted to demonstrate the validity of the circuit design is presented.

1. Introduction

A fundamental problem with high temperature superconductors (HTS) is their high critical temperature (T_c) values and the stability that they impart. Low normal propagation velocities and high stability of HTS wires cause localized damage of magnet coils when there is a quench. Protection of HTS magnets for reliable operation has proven to be a challenge, particularly in Rare Earth Barium Copper Oxide (REBCO) superconductor, with the amount of energy that is required to get enough of the current into the metallic stabilizer to properly distribute the magnetic energy and minimize peak hot spot temperatures. A twist of a relatively new technique that relies on AC losses to distribute energy is Frequency Loss Induced Quench (FLIQ). FLIQ like Coupling Loss Induced Quench (CLIQ) [1] drives an imbalance in the transport current between two or more sections of a magnet. In order to drive this imbalance, FLIQ uses an H-bridge design with Insulated Gate Bipolar Transistor (IGBT)s, whose gates are driven based on the feedback response of the voltage across the bridge. This system optimizes frequency, as current resonates at the frequency of the LC network across the bridge. This paper discusses the novel circuit design, its working principle, and initial experimental demonstration of the performance of the protection quench circuit.

The FLIQ system employs the heat generated by AC loss in superconductor magnet windings deliberately achieved by applying electrical current oscillating at the frequency of the load. It uses induction heating methods which change the local current distribution and fields. Based on Faraday's law, change in current induces voltage caused by the created magnetic field. The change in magnetic field results in both eddy currents and magnetization losses in the superconductor, which increases the temperature of the conductor. With eddy current losses, the deposited thermal energy decreases as penetration depth increases due to the fact that the induced currents do not have an ohmic loss component in the superconductor, assuming the currents do not exceed the local critical current, I_c . The penetration depth is dependent on the resistance of the metallic stabilizer on the superconductor and the frequency.



A higher frequency is desirable for the system. The penetration depth of the induced currents is given as:

$$\delta = \sqrt{1/\omega\mu\sigma} \quad (1)$$

Where $\omega=2\pi f$

σ = conductivity

μ = magnetic permeability

f = frequency

The design characteristics of the FLIQ system include:

- Remote trigger using TTL Logic
- Adjustable activation time
- Adjustable frequency
- Zero-crossing capability
- Current feedback control
- Self-oscillation

2. Hardware

The FLIQ box consists of different sections that support the generation of AC Loss. It houses four IGBTs connected in an H-bridge and the driving circuit. The FLIQ circuit is sectioned into four parts: the power supply board, the current sensing board, the driving/control circuit, the enable actuation circuit. The capacitor is connected at the center of the bridge in series with the coil through two high current feed-throughs. In order to operate at high frequencies, the capacitance can be low, as FLIQ, unlike CLIQ does not rely on a capacitor bank. The purpose of the H-bridge mechanism is to allow the flow of current in two directions and supports the zero switching capability that generates the signal used to control to the gate driver input.

2.1. The Power Supply Board

The power supply board supplies power to the IGBTs driver circuit. It has an input voltage of ± 18 V regulated to different voltages needed to power other sub-circuits of the system. This PCB has a 7815 unit to regulate the input voltage to +15 V, a 7812 to regulate +15 V to +12 V, and a 7809 to regulate +12 V to +9 V, a 7805 to regulate +9 V to +5 V, a 7915 to regulate -18 V to -15 V. These voltage regulators are a series of three-terminal ICs with fixed output DC voltages. They are cased as a TO-220 package with an output current of up to 1 A. Each of these regulators is internally designed to ensure safe operation and internal current limiting, thermal overload protection, and short-circuit protection.

An 18 V Metal-Oxide Varistor (MOV) is connected to the input to the 7915 to protect the Integrated Circuit (IC) against voltage spikes. MOVs have a non-linear voltage-current characteristic i.e. they have a high resistance at low voltage and low resistance at high voltage [2]. Therefore, when a high transient voltage is supplied, the resistance becomes very small and it clamps the voltage to a safe level. In addition, a 0.33 μ F electrolytic capacitor is connected to the input pin of the regulators to filter unregulated input and a 0.1 μ F electrolytic capacitor is connected to the output pin to filter out high-frequency noise from the regulated output. A minimum of 2 V is required for the IC to perform its function as a regulator and its maximum output current is approximately 2.2 A. The operating temperature range of the system is about -65 to 150 °C. Other components on the board are two six-pin Phoenix connectors used to distribute the regulated voltages. These connectors have a rated current and voltage of 12 A and 320 V respectively and have 7.62 mm pitch spacing. It accommodates up to 24 wires of 12AWG.

2.2. Current Sensing Board

The current sensing board has a non-contact current sensing transducer (HFTS-800P) that uses Hall Effect measuring principle to measure the current across the load. Its rated measuring range is -1200 A

to +1200 A. This non-contact current sensor with galvanically isolated primary and secondary side is used to measure the imbalance current that controls the switch as the state of the imbalance voltage

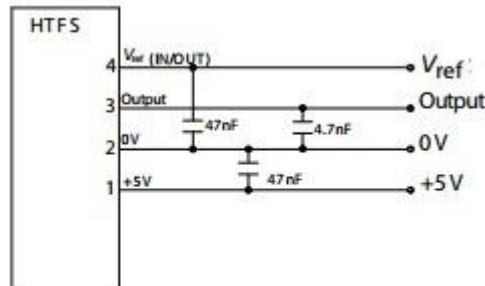


Figure 1. Block diagram of the current sensor [3]

changes when the imbalance current approaches zero; this explains its zero-crossing logic. The secondary side has the electronic circuit with pins soldered to the PCB as shown Figure 1, while the primary side is the high power side that senses the high current. The current transducer is powered with +5 V and produces the output voltage based on the equation:

$$V_{REF} \pm \left(1.25 * I_P / I_{PN}\right) \text{ Volts} \quad (2)$$

Where, I_P is the sensed current across the load,

I_{PN} is the primary nominal current of 800 A

and reference voltage (V_{ref}) is $1/2 V_c \pm 0.025$.

In Figure 1, capacitors are connected across the input and output terminals of the current sensor to filter unregulated signals. The current sensor further improves the reliability of the FLIQ system due to its wide range of measurement. The output voltage and reference voltage is supplied to a comparator. The comparator compares the output voltage of the current sensor to the reference voltage and produces an output that serves as an input signal to the gate drivers. A diode is connected to the output of the comparator in order to prevent backward flow of current or high voltage surges from other PCBs to the comparator and invariably protect the current sensor as well. The current sensor has been tested and proved to perform the zero- crossing switching objective.

2.3. Enable Signal Actuation

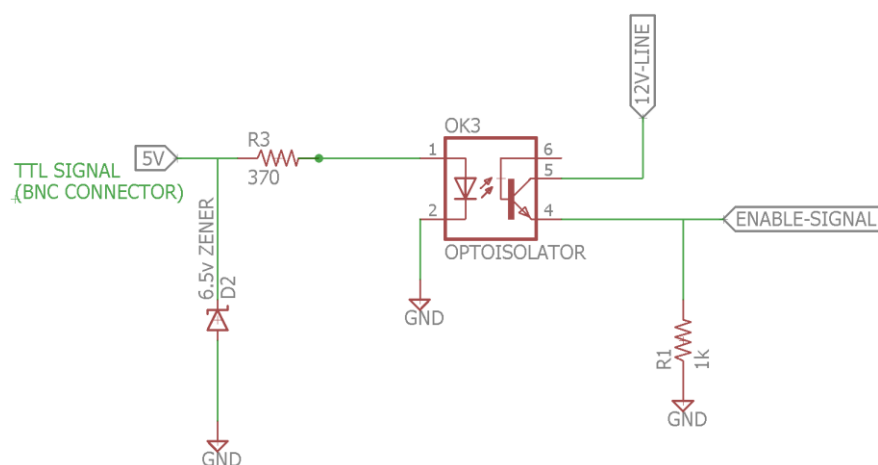


Figure 2. Enable Signal Control

Actuation of the FLIQ system is controllable via a remote Transistor-Transistor Logic (TTL) signal supplied via a BNC connector. The TTL signal has a maximum output threshold to determine when the signal is high and a minimum output threshold level to determine when the signal is low. The 6.5 V Zener diode in Figure 2, acts as a transient suppressor in case an overvoltage is been supplied. The Zener swings into a breakdown mode of operation and instantly clamps the overvoltage to a safe level to limit the voltage to ≤ 5 V signal. An optoisolator is connected between the supplied TTL signal and enable pin of the gate driver. This is to protect and electrically isolate the supplied voltage from the rest of the circuit in case an unregulated high voltage transient is supplied. The 1 k Ω resistor connected across the enable signal makes the system activate only when the enable signal is high because the enable input of the gate driver has a 100 k Ω resistor drawn to V_{DD} (voltage supply).

2.4. H-bridge switching control and Zero crossing

The H-bridge provides the high frequency and high current power needed to drive the superconducting coil. The H-bridge can be divided into two-half sections, the top half of the bridge has

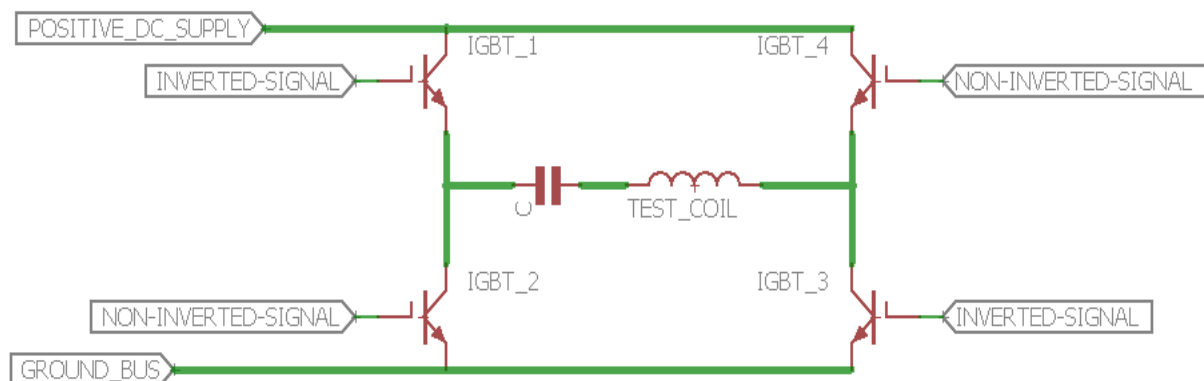


Figure 3. Block Diagram of the H-Bridge

two IGBTs labelled IGBT 1 and 4 and the bottom half of the bridge has IGBT 2 and 3.

The IGBT used in the FLIQ system is model FZ600R12KE3 rated for 1200 V_{CES} with a continuous forward current of about 600 A and powered with 12 V battery through a pair of high current feed-through. IGBT 1 and 3 are controlled with the inverting gate driver and IGBT 2 and 4 are controlled with the non-inverting gate driver. This is to ensure that only two adjacent IGBTs are powered at the same time as voltage is applied in two directions. Based on Figure 3, none of the top IGBTs or bottom IGBTs should be powered at the same, otherwise the entire system will be shorted.

The gate drivers shown in Figure 4 are integrated circuits with eight pins. They supply the inverting and non-inverting signal. Pin one and pin eight (VDD) are the supply pins, pin 2 (IN) is the

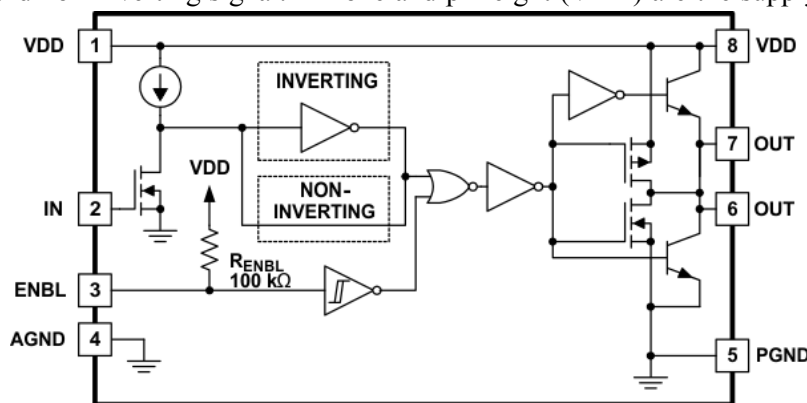


Figure 4. Block diagram of the gate driver IC [4]

input pin, pin3 (ENBL) is the enable pin, pins 4 and 5 (AGND and PGND) are ground terminals for the

input and output sections, pin 6 and 7 (OUT) are connected as outputs. The enable input is the remote TTL signal and the input signal is the comparator output, which is a function of the current measured across the load.

Table 1. Gate Driver Logic

	ENABLE	INPUT	OUTPUT
INVERTING DRIVER	0	0	0
	0	1	0
	1	0	1
	1	1	0
NON-INVERTING DRIVER	0	0	0
	0	1	0
	1	0	0
	1	1	1

The output of the gate drivers supplies the gate-emitter voltage (V_{GE}) needed to control and allows current flow through a pair of IGBTs at a given time. The primary function of the gate drive circuit is to convert logic level control signals into the appropriate voltage and current for efficient and reliable switching of the IGBT module [5]. The V_{GE} signal for IGBT 1 and IGBT 4 is supplied through an optocoupler; this is to create a voltage difference or floating potential to the gate and emitter terminal of the top two IGBTs.

2.5. H-bridge Load

The H-bridge load refers to the inductance of the coil and the connected capacitor in series. The output of the H-bridge is hooked up to the coil via a pair of high current feed-throughs and the resonance frequency of the FLIQ system is based on the equation:

$$f = 1/\sqrt{2\pi LC} \quad (3)$$

Switching of the H-bridge generates the high-frequency AC voltage needed to heat the superconducting coil like using an induction heating method. This mechanism reduces hot-spot temperature by making the entire winding pack return to normal state.

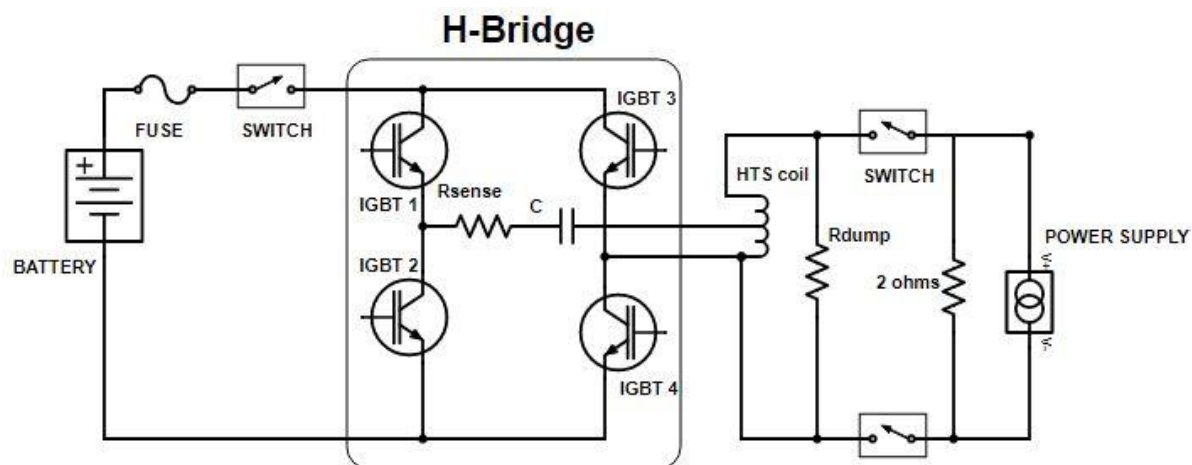


Figure 5. Electrical scheme of FLIQ test on REBCO 42-62

3. Experiment

The experimental setup shown in Figure 5 was carried out on a REBCO (42-62) coil in liquid nitrogen at a temperature of 77 K. As shown in the block diagram in Figure 5, the coil is connected at the centre to a capacitor in series in order to reduce the effective inductance of the coil. The objective of the test is to determine if the FLIQ system can quench HTS. The coil was submerged in liquid nitrogen in a bucket by hanging the coil on a wooden frame as a support structure. The Amatek SGA 10V/1200A power supply was connected via high current cables to the contactors and REBCO 42-62, which is connected in parallel with the dump resistor. The $2\ \Omega$ resistor across the power supply monitors the imbalance current.

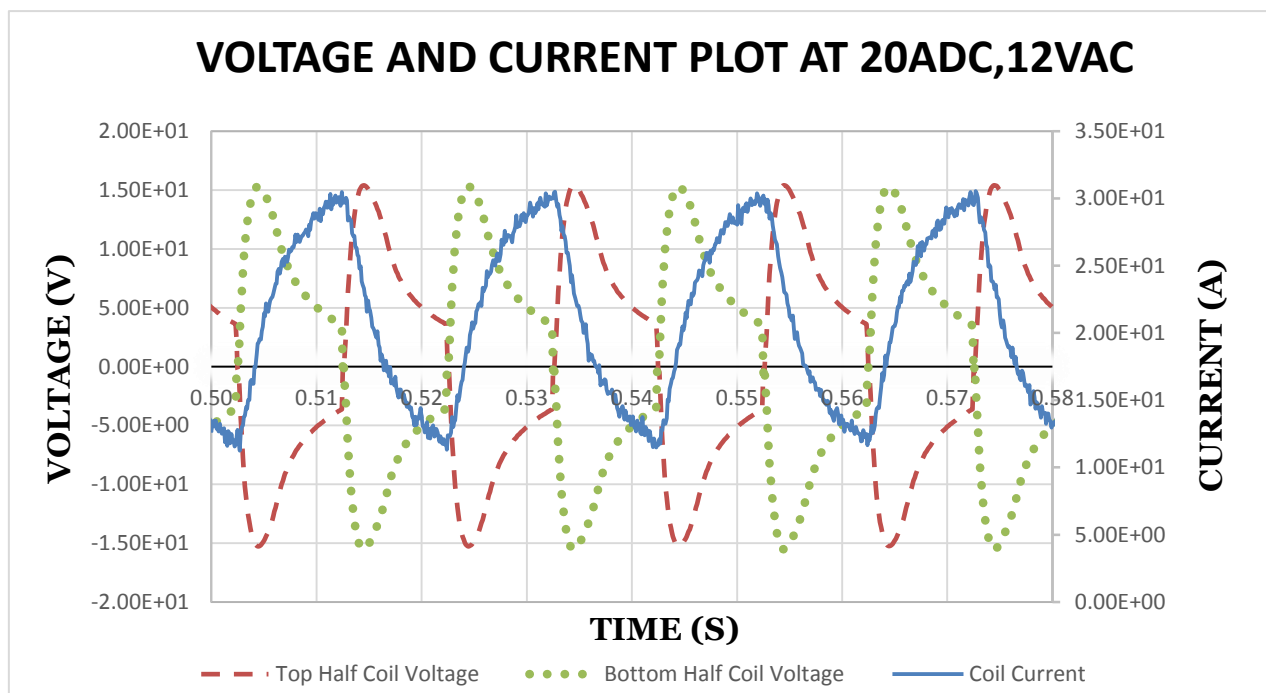


Figure 6: Plot of voltage and current against time at 12VAC

The dump resistor used acts as a preventive protection method to ensure the safe quenching of the coil. It is connected across the LC load to create a current path when the superconducting coil quenches. The dump resistor value may be changed depending on the expected coil current and the desired current decay time. In order to discharge the superconducting coil, the connection between the power supply and the rest of the circuit can be broken, thus the energy in the superconducting coil is dumped across the dump resistor, by opening the contactors. The contactors are normally open switches that respond to commands from the protection system within microseconds.

For the purpose of this test, the fuse limits the supplied current to its current rating. Therefore, the fuse protects the battery pack from receiving a feedback current in case there is a short to ground. To collect and determine various variables a National Instruments SCXI system was used with a high band filter of 20 KHz available on eight channels. The quench detection unit has different channels with a comparator and amplifier and sends a trip signal when the voltage passes its predetermined threshold. The test result in Figure 6 was supplied with 12 VAC, 20 ADC at a temperature of 77 K. The figure shows that the voltage across the coil oscillates at the frequency of the current and the voltages across the top half and the bottom half of the coil are opposite to each other. The voltage across the top and bottom half has a capacitive discharge, because some the energy from the battery charges the capacitor. To prevent this in future tests, a resistor will be connected across the capacitor to reduce the time constant, thereby enough energy will get to the metallic stabilizer.

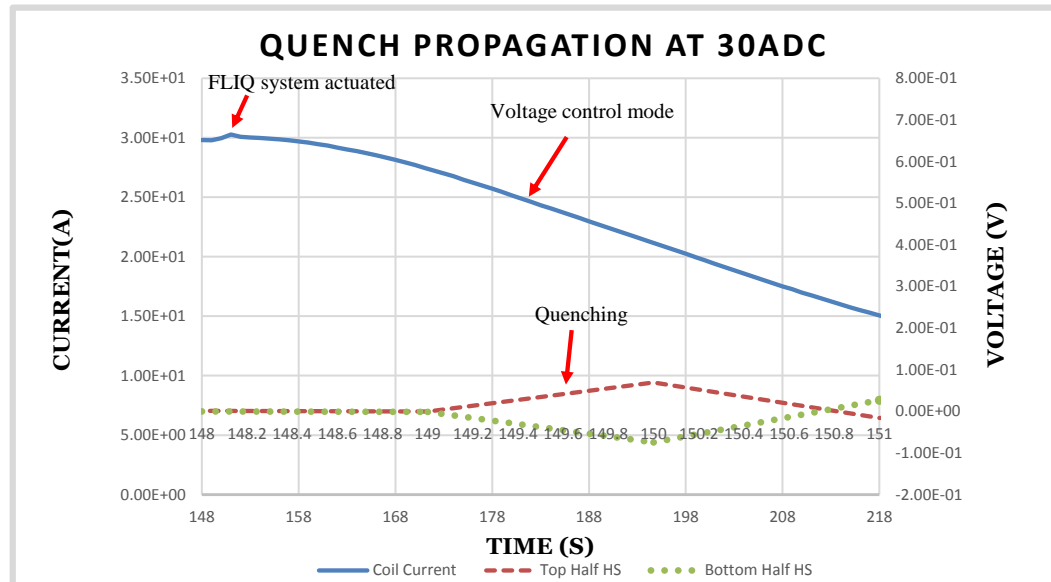


Figure 7. Quench propagation of REBCO 42-62 at 30ADC

Figure 7 shows that the FLIQ system quenched the REBCO 42-62 but due to the challenges we had with the DAQ system, the quench time could not be determined from this experiment.

4. Conclusion

The goal of this research effort is to build a protection system capable of safely quenching HTS coil. The FLIQ circuit design advances the protection technology for high temperature superconducting magnets and is capable of quickly distributing the heat energy uniformly in all the coil sections when a localized hot-spot is created. The experiment discussed in this paper is the first experimental test of the FLIQ system. The early stage experimental validation of the performance of the system demonstrated that FLIQ causes a safe controlled quench in the model coil. The FLIQ system is functional as it oscillates at the resonance frequency of the capacitor and superconducting coil, operates with adjustable time, can be remotely triggered and exhibit a zero crossing capability. The effort to understand the intricacies of the electrical and thermal aspects of driving large superconducting coils to a safe quench will be further explored and characteristic modelling of the FLIQ system is also being developed. In the future, other AC loss heating mechanism will be explored as an alternative to protecting high temperature superconducting coils.

Acknowledgement

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