INDUCTIVELY COUPLED PULSED ENERGY EXTRACTION SYSTEM FOR 2G WIRE-BASED MAGNETS *

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Abstract

This project seeks to develop a novel method for quench protection of high-temperature superconducting (HTS) magnets based on coupling the magnet with a high-power resonant coil. The quench protection is realized by applying an electromagnetic pulse through the resonant coil and disrupting the superconducting state in the conductor. This creates a large (10s of meters) normal zone in less than 10 ms thus ensuring even distribution of the energy dissipation. The proposed protection system does not involve generation of high voltage on the coil leads and does not contribute to cryogenic losses. The system is easily scaled to a magnet of arbitrary size. Preliminary design and POC bench top test preparations are presented below.

INTRODUCTION

Recent progress in high-field performance of the second-generation (2G) HTS conductors [1, 2] has enabled design and development of ultra-high field magnets. This is possible because YBCO, the core material of 2G wire, holds the record for the upper critical field, Hc2. A combination of high Hc2 and high mechanical strength (700 MPa yield strength [3] for SuperPower Hastelloy-based wire) position the 2G wire as the only viable conductor for ultra-high field, > 20 Tesla, superconducting magnets.

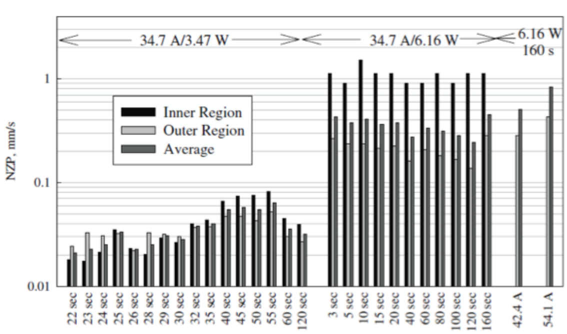

Figure 1: Typical NZP velocities measured in test 2G wire coils [4].

The key component of 2G wire is the epitaxial YBCO layer. This layer, which is only 1-1.5 micron thick, carries all the current of the superconductor. The major problem is its slow rate of Normal Zone Propagation (NZP). As shown in Figure 1, experimental measurement of NZP velocity in 2G wires yields values below 1 mm/s. Such a low propagation velocity results in concentrated energy dissipation and irreversible damage of the magnet during an unprotected quench. The problem is further exacerbated by the low thermal mass and poor thermal conductivity [5] of the YBCO layer. Thus carefully designed protection systems are required to protect 2G superconductors from catastrophic damage.

The established active and passive [6] quench protection systems for traditional low-temperature (LTS) magnets [7] are ill-suited for HTS magnets because their energy extraction is too slow. The measured NZP velocity means the stored energy has to be extracted or redistributed within a few seconds to prevent catastrophic damage. A traditional energy extraction system based on a dump resistor and a semiconducting switch would require several kilovolts on the coil to achieve fast extraction. Such a high voltage creates multiple problems for the interfacing electronics and the current source. Redistribution of the normal zone by resistive heaters is problematic since the thermal conductivity of insulating materials, used to separate the heater from the coil, drops at cryogenic temperatures due to the phonon freeze-out. This effect prevents efficient coupling of the heater elements to the superconductor.

TECHNICAL APPROACH

By inductively coupling a strong electromagnetic pulse via a resonant LC circuit, the normal zone propagation in the coil will be accelerated. The AC field induces currents in the superconducting layer with the current density exceeding that of the critical current density, J_c. This creates a large normal zone, uniformly distributing the dissipation through the magnet body. The method does not rely on thermal heating of the conductor, thus potentially enabling nearly instantaneous protection.

Quench Modeling

The 2G wire coil (in the following DC coil) was modeled as 120 mm OD, 80 mm ID double-pancacke stack. We used the following functional dependence to approximate the critical current field dependence: $I_c = I_0/(1+B/B_0)^a$, where I_0=300 A, critical current in self field, B_0=0.05 Tesla is the individual pinning field and *a*= 0.7 the pinning exponent. This is the typical I_c(H) behavior of SuperPower wire. The current density was calculated by dividing the current by the average area of the conductor, which was comprised of 50 micron Hastelloy substrate, 40 micron Copper stabilizer and 65

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micron Kapton insulation. The DC coil was excited at 80 % of Ic, generation the maximum DC field of 0.3 Tesla. The AC coil is modeled as a 6 turn flat coil wound from 4 mm copper wire. The AC coil is excited with a 200 A current, which is applied as a short burst during the quench protection phase.

The DC field profile was generated in the standard magnetostatic module of COMSOL 3.5, using axial symmetry. The AC field penetration process had two components: interaction of the AC field with inductive currents in the copper stabilizer and penetration of AC field into the superconducting layer. The inductive current interaction was modeled by the COMSOL "Azimuthal Induction Currents" module in 2D axial symmetry geometry. The penetration into the superconductor was simulated by a custom script using well-known Brandt equations [8].

Penetration of AC field into the coil winding is limited by the skin-effect in the copper stabilizer layer. Figure 2c shows that the optimum 50% penetration is achieved at frequencies below 200 Hz. In the design we choose 150 Hz as the operation frequency. This combines manageable size of reactive components with deep winding penetration.

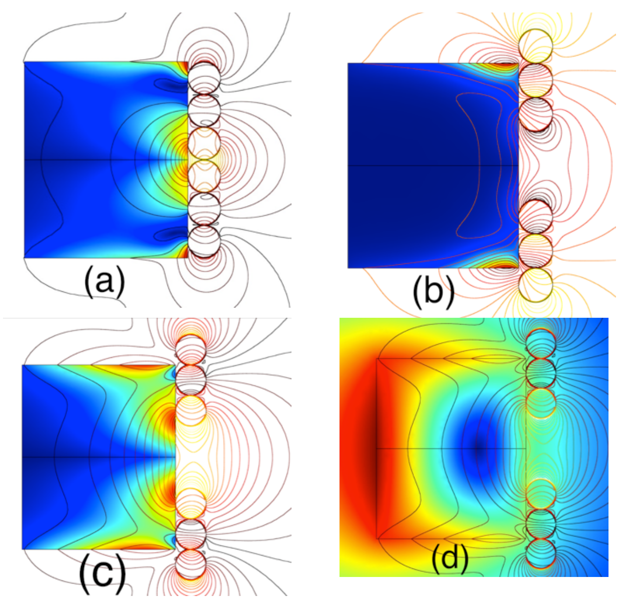

Figure 2: Resonant coil optimization showing field penetration color map and AC field contour map with initial geometry configuration (a), 1000Hz operation (b), final optimized geometry and frequency (c) and final DC magnetic field color map and AC field contour map (d).

Proof of Concept Design

The outputs from the optimal simulation results were slightly adjusted to account for simpler first pass implementation into the proof of concept (POC) system design and to use less HTS. Although slightly less penetration and NZP are expected due to this design change as seen in Figure 3, further Phase I efforts may approach the optimal design following initial system functional validation. The POC design parameters set the coil current at 100 A, resulting in a 0.1 T center, 0.22 T maximum field with a stored energy of 6.6J.

Double stack pancake coils with voltage taps for monitoring normal zone formation were envisioned. The stack would be sandwiched between G10 phenolic plates with slots cut in them for tap lead egress. The entire assembly will be immersed in a LN2 bath enclosed within a *Janis* cryochamber.

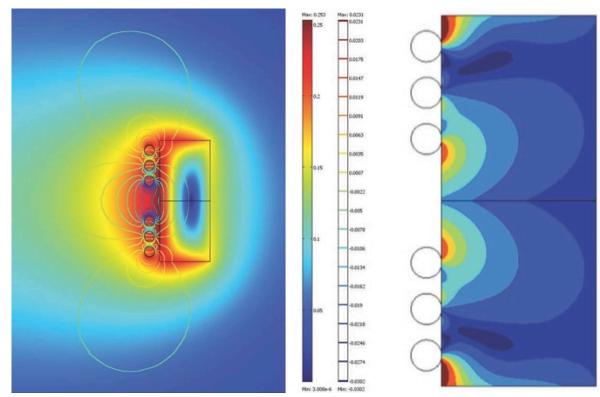

Figure 3: AC magnetic fields (left and shaded), DC magnetic fields (right contours) of the fabrication optimized simulations.

The main HTS coil is powered by a *TDK-Lamda* Genesys 3U 30V-333A power supply and the resonant coil is powered by a pair of *Kepco* BOP-10V-100A in parallel to provide the 200A resonant pulse. The main coil supply is protected with "low-side" switch (N-channel mosfet with the source tied to ground). The system only requires 150Hz pulsing and the *Kepco* BOP is capable of up to 800 Hz operation, permitting potential exploration of higher frequency spaces. This BOP replaced our original plan to build the resonant circuit, with the cost of the devices nearly equal to the projected parts and labor to build our own pulsed power supply.

For voltage tap monitoring, a *Measurement Computing* USB-2537 DAQ card was selected. This card can accommodate up to 64 single ended voltage channels that are needed for reasonable spatial resolution of the quench propagation. Moreover, this DAQ was also chosen for its 1 MS/s sampling speed and 16 bit resolution. Finally, the MC USB-2537 also offers a large common-mode voltage rejection of +/- 10 V, so that we can directly measure the voltage across all of the channels without signal isolation.

As the system utilizes 52 voltage taps on the super conducting coils, with an aggregate sampling speed of 1 MS/s, all 52 voltage taps can be sampled in just over 50 microseconds. Even with a factor of 2 allowance, 10 samples can be taken per tap every millisecond, thus defining the absolute temporal resolution limit of the system. Further, as the buffer size of the board is 1MS, all the data from a single event can be recorded without the necessity to clear the board buffer that would add further latency to the system.

FABRICATION AND INTEGRATION

A standard double stack pancake coil with HTS tape interconnects were manufactured at RadiaBeam Technologies. The turn to turn coil isolation was accomplished by co-winding the superconducting coil with kapton. To attach the voltage taps, a large copper block wrapped in heater tape was used as a warm backing plate while a precision temperature controllable soldering iron was used to heat the pre-tinned voltage taps until solder flow was observed. Pure Indium solder was used. The bare coil section was then carefully cleaned with isopropanol and lint free wipes prior to co-winding the kapton insulation tape. The pancake stack was dry wound on a custom-made mandrel, Figure 4 left, carefully designed to ensure the 10mm minimum bend radius of the HTS tape was not violated and ground wrapped with 0.006” DMD. The warm leads for the voltage taps were then soldered on and the assembled coil was sandwiched between a pair of G10 phenolic plates as seen in Figure 4 right. The warm leads are placed above the coil stack to ensure simpler assembly of the resonant coil around the perimeter of the assembly. The resonant coil was form wound in a flat pattern and bent to encompass the main HTS coil as shown in Figure 5, right.

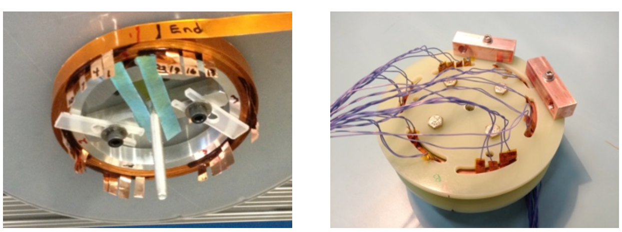

Figure 4: HTS coil on the winding fixture and shown with soldered voltage taps (left). Double pancake coil stack shown with tap leads soldered on and copper warm lead blocks.

EXPERIMENTAL PLANS

All the physical components have been completed and integrated into the cryostat as seen in Figure 5left. Final debugging of the controls and DAQ systems is currently ongoing with initial testing to start shortly. The experimental plans for testing this system will aim to search as broad a parameter space as possible. The main coil current, resonant coil current and frequency will be swept as we explore the system behavior. Further, various resonant coil geometries will be examined including the ideal optimized geometry as shown in Figure 2. Characterization of the NZP speed and optimizing the system to maximize the NZF will be the focus of these studies.

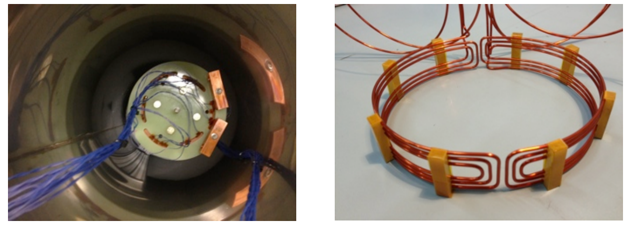

Figure 5: HTS coil placed cryochamber (left), resonant coils prior to forming around HTS coils (right).

CONCLUSIONS

The fundamental behavior of the induced quenching system has been examined through analytical studies and simulations demonstrating the potential viability of this system. Fabrication of the POC has been completed and the final debugging of the control system to be concluded in the very near future. The experimental work plan is in place with data to be acquired imminently.

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