

## NOVEL QUENCH DETECTION SYSTEM FOR HTS COILS\*

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### Abstract

As a part of High Temperature Superconducting (HTS) Magnet R&D, small coils are being built and tested to study quench properties in a systematic manner. For this purpose, multi-channel quench detection, fast and slow data logger, current ramp controller and energy extraction system was developed. This system had to be flexible, compact, economical and easy to use. The system is based on LabView and Field Programmable Gate Array (FPGA) hardware from National Instrument.

### INTRODUCTION

Brookhaven National Laboratory is developing HTS magnets for Muon Collider [Ref 1] and Facility for Rare Isotope Beams [Ref 2], [Ref 3]. Advances in HTS magnet technology has placed stringent requirements on the quench detection system. Conventional quench detection systems based on analog electronics, developed for Low Temperature Superconductor (LTS) coils are not fast, flexible and precise enough. Main difference between HTS quench and LTS quench is in the normal zone propagation (NQP) velocities. NQP of HTS is much slower, about 1-10mm/sec as compared NQP of LTS, which is 1-2m/sec. This difference requires that HTS quench detector system responds hundred times faster than the conventional LTS quench detector.

Slow moving quench in HTS also poses another problem in coils with large stored energy. If the current through coil is not interrupted quickly, very large amount of energy can be deposited in very small normal zone. The resistive voltage developed across a small normal zone is also very small, of the order of few 100 microvolts as opposed to few 100 millivolts in case of large normal zone in LTS coils. Detection of few 100 microvolt signals among background noise also needs special attention. To address these requirements quench detection system with following specifications was developed.

- Quench detection response time: less than 5msec.
- Quench detection voltage threshold (overall): about 1mV.
- Coil current interruption time after quench detection: about 100microsecond.
- Voltage measuring electronics to have Channel to channel and channel to ground isolation of at least 300V

The performance of this system was evaluated by studying quench and voltage tap data of a small pancake coils made from second generation HTS tapes from Super Power Inc.

### SYSTEM HARDWARE

The system consist of two real time controller platforms from National Instrument (NI) [Ref 4]., energy extraction Insulated Gate Bipolar Transistor (IGBT) switch from Infineon Inc [Ref 5]., dump resistor and an industrial PC as show in Fig. 1. Main functions to be performed by the system are 1) Quench detection, 2) Slow data logging, 3) Transient data logging during interval just before and after quench, 4) Coil current ramp profile control, and 5) Energy extraction.

The quench detection platform consists of NI CRIO backplane powered by reconfigurable Field Programmable Gate Array (FPGA) technology, a real time controller, a DAQ module with 4channel, 50KS/s simultaneous sampling, 16 bit A/D and a 16channel fast digital IO module. Transient and slow data logger platform consist of NI PXI chassis, a real time controller, four PXI DAQ modules each with 8 channel, 16 bit, 50KS/s simultaneous sampling A/D and two PXI DAQ modules each with 16 channel, 250KS/s, multiplexed,. 16 bit A/D. PXI chassis also house four NI SCXI-1125 isolation modules. These modules provide 300V channel to channel isolation and 300V channel to ground isolation. Both of the above targets are monitored and interfaced via local network connection to industrial PC.

Energy extraction during quench is achieved by simultaneously turning off IGBT switch (fig.2) and power supply to divert freewheeling current through dump resistor thus dissipating coil stored energy into the dump resistor. Value of dump resistor R is selected based upon total circuit induction and rate at which energy needs to be extracted. If the copper to superconductor ratio of the wire is large and quench resistance is small relative to the dump resistor, the value of dump resistor can be computed approximately by following equation (Ref 7).

$$I^2 t_d + I^2 L / 2R = 1500A^2 \quad (1)$$

Where I is initial quench current (kA), L is the total circuit induction (H), A is copper cross sectional area (cm<sup>2</sup>) that stabilizes the superconducting wire and R is in ohms. Dump resistor can be grounded at centre to limit the peak voltage to ground

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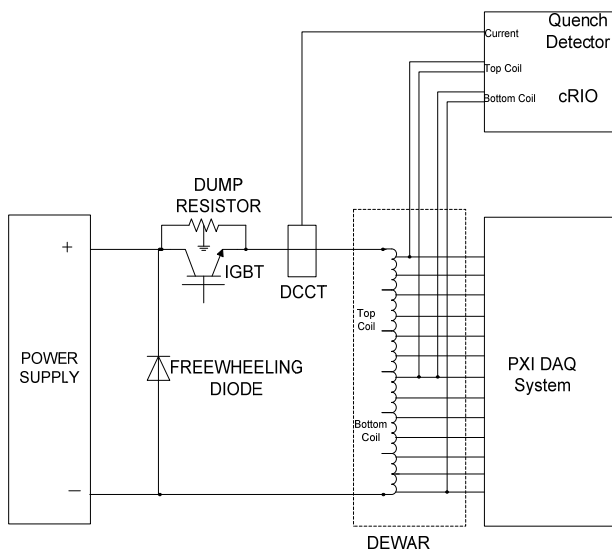


Figure 1: System block diagram and layout.

## SOFTWARE

Software for the quench detection system was developed using Graphical design language LabView from National Instrument. It consists of three separate LabView VIs (Virtual Instrument) modules. 1) FPGA code for quench detection running on CRIO target, 2) Real time data logging and monitoring code running on PXI target and 3) Host code running on industrial PC to provide HMI (Human Machine Interface) see fig.5.

FPGA code for quench detection implements two schemes. In first scheme the voltage across one half of coil under test is compared to voltage across other half of coil, if the difference exceeds pre-set threshold, a quench signal is transmitted via digital output to turn off IGBT switch and power supply.

Second scheme detects the quench during current ramping phase. Here instantaneous ramp rate is computed from the coil current signal, and then from the known value of coil inductance,  $L di/dt$  voltage across coil is computed. This computed value is compared with measured coil voltage. If the difference exceed pre-set threshold, a quench detected signal is transmitted to IGBT switch and power supply. In both the schemes it is very critical to make very accurate and fast measurement of coil voltage among background noise. Conventional method of filtering using 4 Hz low pass filter build in DAQ module increases response time by few 100msec, this cannot be tolerated in case of HTS quench. A novel scheme of real time discrete filtering is implemented taking the advantage of FPGA's very fast loop time (50 $\mu$ sec -100 $\mu$ sec). It works as follows. Every time a sample of coil voltage exceeds a pre-set quench threshold (generally between 0.5mV to 5mV ) a counter is updated, if the value of following coil voltage sample falls below the quench threshold, counter is reset to zero. If pre-set

number (generally between 5 and 10) of successive samples exceed quench threshold i.e. counter continuously counts without resetting, quench detected signal is issued. Noise due to switching mode power supply or burst of stray EMI is thus effectively eliminated giving effective filter response time of 250 $\mu$ sec to 500 $\mu$ sec.

The real time code running on PXI target logs and displays all voltage tap values. Since this is slow data more conventional filtering method of averaging over large number of power line cycles is used. The pre and post quench data of voltage taps values are recorded raw so that transient data is not lost and appropriate filter can be applied offline. PS control and reference signal for current ramp is also generated by this program.

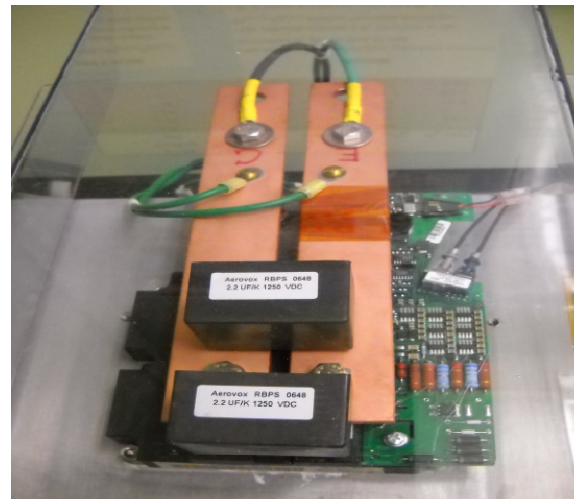


Figure 2: IGBT Switch.

## TEST COILS

To test the system small pancake coils (fig.3) with outer diameter of 160mm and inner diameter of 100mm were wound using second generation, 4mm wide HTS tape from Super Power Inc. Total length of the tape was about 100m with voltage tap inserted at every 10m. Stainless steel tape of 0.025mm thickness is co-wound to serve as turn to turn insulation. Two such pancakes are then clamped between micarta flanges. The assembly (fig. 4) is then immersed in liquid nitrogen Dewar.

Manufacturer provided critical current value defined in terms of microvolt/cm for this conductor as  $1\mu\text{volt/cm}$  for a short sample and self-field. For magnet use and therefore for test purpose we use a more stringent criteria in defining critical current at  $0.1\mu\text{volt/cm}$ . This gave us the quench threshold set point of  $1\text{mV/coil}$  because each coil has 100m conductor.

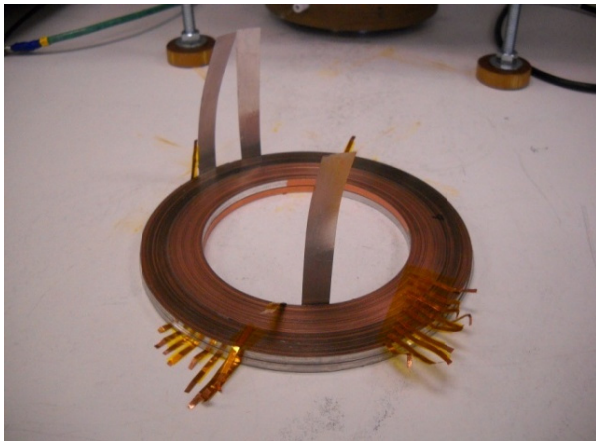


Figure 3: Test Coils



Figure 4: Coil Assembly

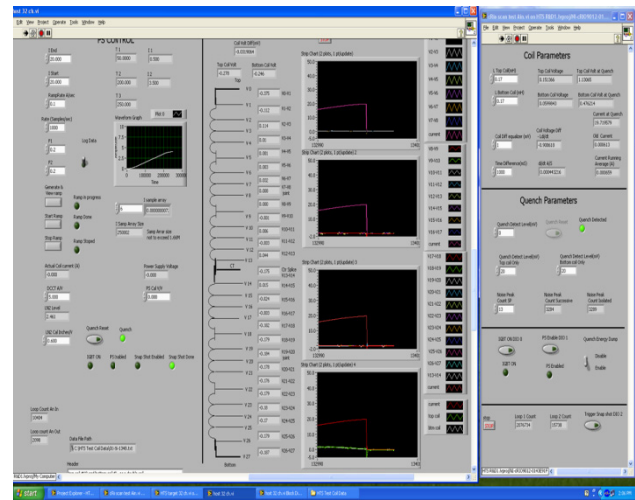


Figure 5: Host HMI Program.

## EVALUATION

To evaluate the performance of the system, we ramped the test coils in liquid Nitrogen ( $\text{LN}_2$ ) at different ramp rates up to 45A, multiple times, each time lowering the quench threshold voltage starting from 10mV going down to 1mV. We could successfully ramp the coil up and down at 1mV threshold, below that random trips started happening. After establishing minimum threshold, we started lowering the filter counter threshold value till we could maintain 1mV of quench threshold. We were able to lower noise spike counter down to 3msec interval without triggering spurious trips.

## CONCLUSIONS

The novel system described in this system confirms the usefulness of FPGA based system in protecting HTS coils. The quench detection in HTS demands the response time of 2-3msec and quench threshold as low as 1mV. Experiments using test coils immersed in  $\text{LN}_2$  showed that the proposed system satisfy these criteria and being compact and easy to operate is an indispensable tool for HTS R&D

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