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High-temperature superconducting magnet for use in Saturated core FCL

Z Bar-Haim[1], A Friedman[1,2], Y Wolfus[2], V Rozenshtein[1], F Kopansky[2], Z Ron[1], E Harel[1], N Pundak[1] and Y Yeshurun[2]

1Ricor-Cryogenic & Vacuum systems, En-Harod 18960, Israel.

2Institute of Superconductivity, Department of Physics, Bar-Ilan University, Ramat-Gan 52900 Israel

freidma@gmail.com

Abstract. A HTS magnet system used in a saturated core Fault Current Limiter (FCL) device is described. The superconducting magnet, operating in DC mode, is used in such FCL design for saturating the magnetic core and maintaining low device impedance under nominal conditions. The unique design of the FCL poses constrains on the DC HTS magnet. A model which meets all the necessary special requirements have been realized in a compact magnet design that is optimized for its electrical characteristics while minimizing its mass and volume. The coil, made of Bi-2223 tapes, has 50000 Ampere-turns required to maintain the core in a saturated state at nominal current in the limiting circuit. Unique, nonmagnetic cryostat made of Delrin was used. Cooling of the coil has been realized by two cold heads: one double-stage head that provides a cooling power of 6 W at 20 K and a single-stage head with a cooling capability of 40W at 70 K. This magnetic system has been successfully integrated and tested in a 120 kVA FCL model. The design, characteristics and tests of this magnetic system are described.

1. Introduction

Superconducting coils made of high-temperature superconductors (HTS) have been incorporated during the last decade in prototype devices such as separators, motors, generators, transformers, SMES and MagLev Each application dictates specific requirement for the HTS coil. Here we describe the design and test results of the cryocooled coil used for our 120 kVA model of "saturated core" Fault Current Limiter (FCL) that was completed and successfully tested [1].

Fault Current Limiter is one of the most attractive applications of HTS in power systems, an application which has no classical equivalent [2]. In designing HTS FCL one may think of two approaches: One approach, considered to be straightforward and attractive, is the resistive FCL, which has been under development in a number of institutions, see for example, Refs. [3,4]**.** Interest in the resistive FCL has been recently further increased in view of the mass production of the second generation (2G) tapes exhibiting a relatively high normal state resistance [4]. Another promising approach for FCL is the so called “saturated core” FCL [1,5,6]. In this approach, a magnetic core is saturated by a DC superconducting coil exhibiting low impedance in an AC coil wound on the same core and connected in series to the grid. During fault conditions, the high short currents drive the core out of saturation and high impedance is passively and immediately introduced into the grid to limit the

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uprising currents. The saturated core FCL was introduced back at the 1980s (for references see [1]). While it exhibited proven technological advantages, it has failed to reach a commercial stage because of its large volume/mass and a coupling problem between the AC and DC circuits that reduces the FCL efficiency. In a recent research and development project, we have introduced an original approach to the saturated core FCL that decreases the volume and mass of the FCL and significantly reduces the magnetic coupling [1]. By overcoming these barriers, the saturated core FCL can comply with utility demands and serve as a protective device in the grid.

The novel approach to saturated FCL imposes unique constraints to the HTS DC coil used therein. Most significant are the limited allowable space for the cryostat and the requirement for reduced eddy-currents at the cryostat walls. It is the purpose of this manuscript to describe the realization of the HTS magnet system under these constraints.

2. Coil and cryostat design

For the 120 kVA FCL demonstration model [1], single HTS coil was used (figure 1a). The cryostat, with the HTS coil inside, is mounted on the short limb of the core while a copper coil envelops both long limbs. Such geometry poses space constraints on the magnet design. The copper coil that serves as current limiting reactor has to be elongated to provide the required ratio between the impedance at fault conditions to the impedance at normal operation. For a fixed number of AC coil turns, N, a cross-section of the core, S, was selected so that $S_{Fe}=U_{FCL}/444\cdot N$, where U_{FCL} is the voltage drop on the FCL terminals at fault conditions. In our device, $S_{Fe}=0.12x0.12$ m^2. This size limits the internal diameter of cryostat d by $0.12x\sqrt{2}=0.17$ m. The size of a window between the core and the copper coil restricts the volume of the cryostat with HTS coil.

The number of the Ampere-turns of DC bias coil is defined by the magnetic field strength in the core necessary to saturate it when a nominal AC current flows through the AC coil. Rough estimation of the Ampere-turns value is given by the product of the required field strength and the core perimeter. Finite element simulations (using "Vector Fields" software) of the static magnetic field in the core at the peak AC current in normal (figure 1b) and fault (figure 1c) conditions have been performed. The magnetic field strength is very inhomogeneous over the length of the core. At normal conditions (nominal peak value of AC current), both long limbs are saturated to an average value of magnetic induction of about 2.05 T with a small difference between limbs. At that time, the short limb under the coil is saturated to about 2.5 T. To receive such magnetic induction values the number of the Ampere-turns required in the HTS coil is about 50,000. For a maximal DC current of about 50 A, we have selected the number of turns to be 1,100, which include a 10% of spare windings. During a fault the AC coil drives one long limb out of saturation while the counter limb is driven further into deeper saturation (figure.1c).

The height of the cryostat is about 120 mm, dictated by the distance between the long limbs. Taking into account necessary gaps between the coil and the cryostat walls and wall thickness, we have restricted the height of the coil to about 50 mm. This corresponds to 6 double pancakes. Inner diameter of the coil is defined by the necessary distance between the coil and the cryostat wall. Parameters of the coil are listed in table 1. Magnetic fields values were calculated and verified by measurements of the magnetic field in the center of the coil.

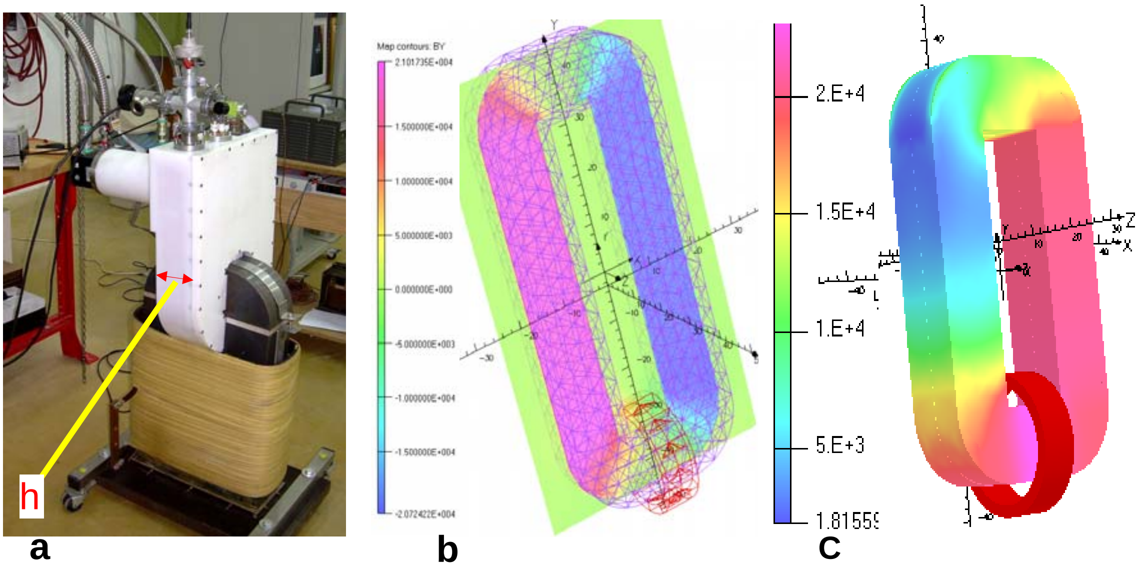
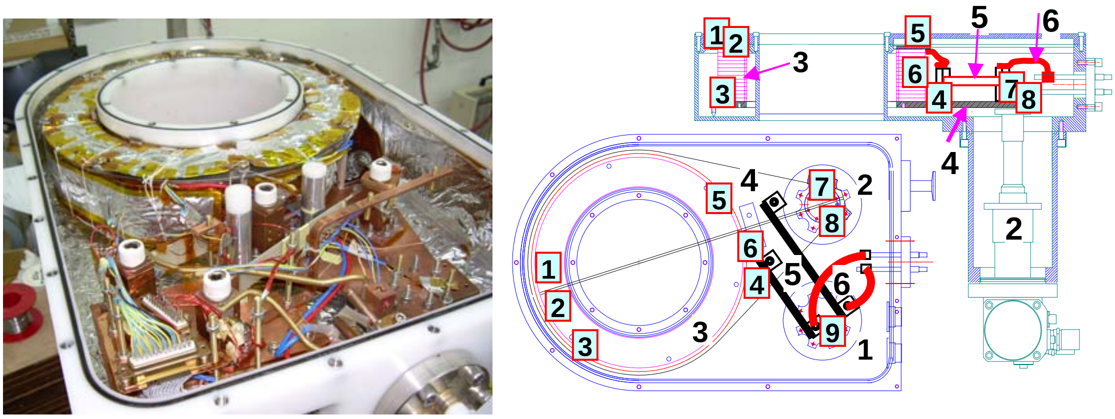


Figure 1. 120 kVA model of FCL. a - view of the device, b – distribution of the axial component of magnetic induction in the core at normal operation, c – distribution of magnetic induction in the core during fault at peak AC current.

Table 1. Parameters of the coil.

Inner diameter, mm	214
Outer diameter, mm	294
Height, mm	54
number of double pancakes	6
number of turns	1080
Length of wire, m	860
Maximal tested current, A	100
Nominal current, A	50
Maximal radial magnetic field on the coil surface, T at nominal current (without magnetic core)	0.38
Maximal magnetic field in the coil center, T at nominal current (without magnetic core)	0.26
Maximal magnetic field, T at nominal current (without magnetic core)	0.54
Stored energy at nominal current (without magnetic core), J	440

For the magnet design we used the concept of the compact HTS magnet that has been used in a magnetooptical device [7]. Figures 2a-2c show the details of the present magnet and the accompanied cryocooler. The HTS coil 2 was attached to a thick copper plate 4 the other end of which was bolted down to the flange of the second stage of cryocooler 3. Copper plate 4 was segmented to prevent eddy currents. Two cold heads manufactured by Ricor-Cryogenic & Vacuum systems were used: two stages cold head 6/30 (cooling capacity 6W@20K and 30W@70K) and a single stage cold head with 40 W cooling capacity at 70K). Vacuum sealed current terminals were connected to brass current leads 6 whose second ends were attached to posts cooled by the single stage cold head. These posts and the coil were connected by homemade cryosavers 5. Nine Pt100 thermometers were mounted on sections of the system as shown in Figs. 2b and2c. The front part of the cryostat volume, containing the cryosavers and the cold heads, was protected from radiation by copper screen connected to the single stage cold head. Super-insulation was used above the coil, the copper screen and below the bottom surface of copper plate 4.



a b c

Figure 2. General view (a) and drawings of the cryostat with HTS coil(b and c). 1 - one stage cold head, 2 – coil, 3 - two stage cold head, 4 – copper plate, 5 – cryosavers (homemade), 6 – brass current leads. Numbers in small rectangles show positions of the Pt thermometers.

Another difficulty, unique to the saturated core FCL, is the AC stray fields in the close vicinity of the AC coil. Since by its nature, the core is saturated in nominal state, some of the AC field lines close out of the core at the space near the AC coil. As the compact design of the FCL dictates close vicinity between the cryostat and the edge of the AC coil, eddy currents, which might change the pre-defined coil impedance, are induced at the cryostat walls. Thus, we have selected to make the cryostat of non-metallic parts. The cryostat was made from a single bulk of Delrin, worked out by a CNC. To the best of our knowledge, this is the first time Delrin is used for large-scale cryostats.

3. Characterization of pancakes and coil at 77 K

The coil is wounded of standard reinforced BSCCO wire (made by American Superconductors Corp.) with minimal self-field critical current 115 A at 77 K. We tested each double pancake individually and inside the assembled coil, in liquid nitrogen. V-I curves of pancakes and coil are well described by the power l aw $E = E_0(I/I_C)^n$. Values of the critical current I_C and index n of the individual double pancakes are listed in table 2. In evaluating I_C we used the common criterion E_0=1 µV/cm.

Table 2. Critical current I_C and index n of the double pancakes.

Pancake	1	2	3	4	5	6
I_C, A	68	67.1	67	64.4	70.1	68.4
n	15	12.7	13.3	12.6	12.85	13.4

After completing the individual tests, the six double pancakes were connected by small bridges of nonreinforced Bi-2223 tape soldered with low temperature In-Sn solder. Contacts resistance is about 1 µOhm. Voltage taps were connected to both ends of each pancake. Figure 3 shows the V-I curves measured on individual double pancakes, on upper half of the coil (pancakes 1 -3) and on the whole coil. The inset shows the corresponding V-I curves. Apparently, the voltage and the electric field of the internal pancakes is much smaller than that of the outer ones, reflecting the fact that internal pancakes are exposed to smaller self magnetic field. Note that the electric field on the outer pancakes is well above the average electric field on the coil. For determination of the safe operating current the V-I data have to be used for calculating the electric field distribution in the coil [8].

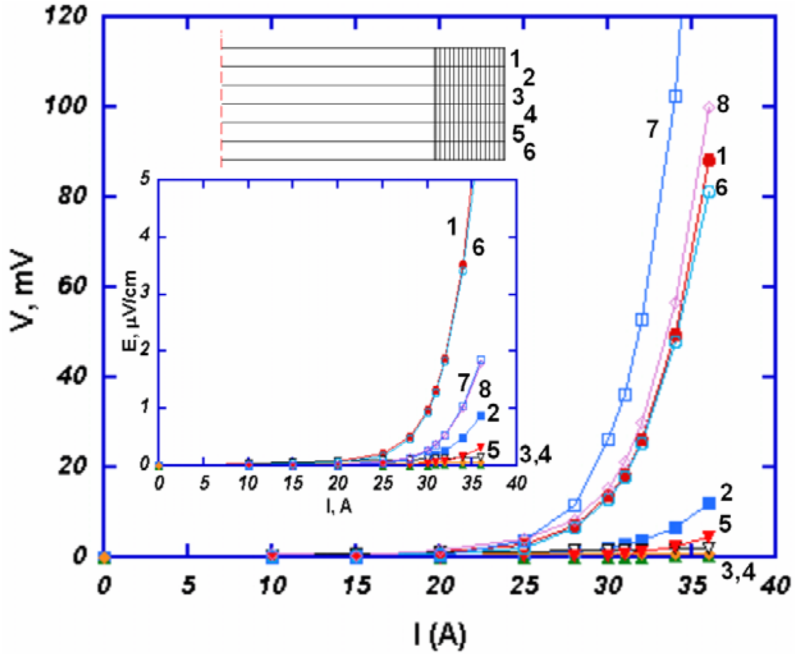


Figure3. V-I curves at 77 K of pancakes (1-6), half of the coil (pancakes 1-3) coil (7) and coil (8).

Critical current values of pancakes in assembled coil, coil itself and upper half of the coil are listed in table 3.

Table 3. Critical current I_C of the coil and double pancakes in the coil.

Pancake	1	2	3	4	5	6	Coil	Half of the coil
I_C, A	30.2	37.1	>40	>40	40	30.2	34	34

4. Cooling of the coil

For cooling of the coil each cold head was connected to a 3 kW compressor. Cooling process was controlled by nine Pt thermometers located on parts of the system as shown in figure 2b and c. Temperatures were continuously recorded by a multi-channel DVM during cooling and tests. Initial cooling process is shown on figure 4. The temperature of the single stage cold head was stabilized after about 1.5 hours at a temperature below 50 K. The temperatures of the coil stabilized after 22 hours of cooling at 40 K.

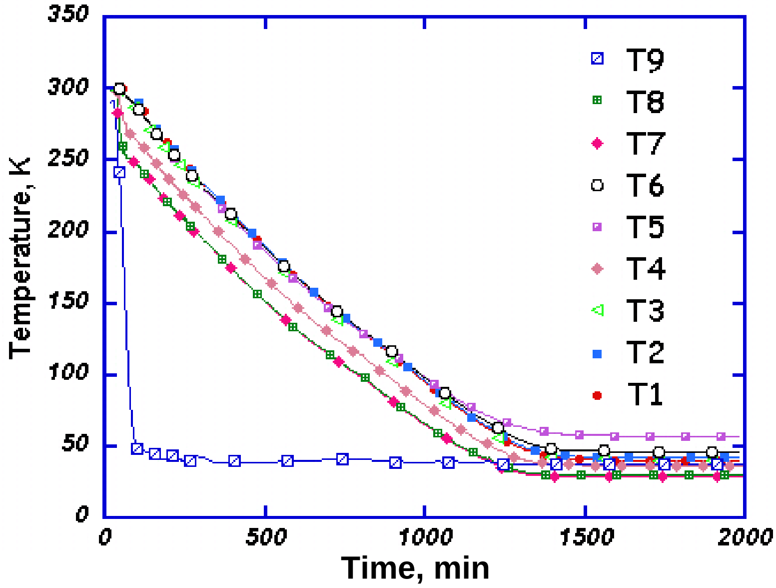


Figure 4. Time dependent temperature in various cryostat locations during the initial cooling process.

Summary

We described a successful manufacture of HTS magnet for special design of a saturated core FCL with constraints on space for the cryostat and on allowable eddy currents at cryostat walls. The success of this project promotes the use of HTS cryogen-free magnets in cases of limited space, where moderate magnetic fields/magnetomotive force are required. In particular, HTS may provide a preferable solution for magnetic systems with ferromagnetic core.

Acknowledgments

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