CHARACTERIZATION OF SUPERCONDUCTING CABLE FOR K-500 SUPERCONDUCTING CYCLOTRON MAGNET COIL

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Abstract

An experimental set-up has been designed and developed for the electrical characterization of NbTi multifilamentary composite cable at liquid helium temperature under magnetic field up to 7 Tesla. The cable has been used to make K500 superconducting cyclotron magnet coil at Variable Energy Cyclotron Centre, Kolkata. The superconducting critical current is the most important parameter in the design and operation of magnet. The constant electric field (0.1 μvolt/cm) criterion is used to define critical current. The critical current is measured in different magnetic fields, which is applied perpendicular to the direction of current. The critical current is measured taking sample from different spools. As the available pieces of cable are not long enough, there would be at least five number of joints in the winding. Joints are made in-house on the coil winding machine by brazing copper substrate and soft soldering the superconductor elements of the cable. The 100mm lapping length is kept between superconductors in the joint. Joint resistance being a continuous disturbance must also be made minimum as possible. Therefore it is required to standardize procedure for superconducting jointing for minimum resistance and sufficient mechanical strength to withstand the tension, during winding of the coil. Therefore experimental set-up has been designed and developed to carry out the tests. Test results show high critical current density with good filament uniformity indicated by its high quality index. Joints were made in-house on coil winding machine and test results indicate that they have acceptably low resistance and carry sufficient current.

INTRODUCTION

The K-500 superconducting cyclotron is in advanced stage of construction at VECC, Kolkata [1]. In order to support the construction activities of this Cyclotron, cryogenic experimental set-up has been designed and developed for the electrical characterization of NbTi multifilamentary composite cable at liquid helium temperature under magnetic field up to 7 Tesla. This experimental work was undertaken as VECC-SINP collaboration programme. NbTi superconducting coil is used to produce magnetic field. The superconducting cable is multi-filamentary composite of diameter 1.29mm embedded in a copper matrix. The cable is again soldered within a groove on rectangular copper substrate (2.794mm × 4.978mm) for cryogenic stability. About 35Kms length of superconducting cable is used for winding the K-500 magnet coil. As the cable is not long enough, there are five numbers of joints in the winding. These are made in-house on the coil-winding machine by brazing copper substrate and soft soldering the lap joint between two superconducting elements of the cable. The lap length of each joint is kept 100mm. The joint is measured to ensure that the joint resistance is low enough for continuous operation utilizing nucleate boiling to cool the joint, and to ensure adequate mechanical strength [3]. Joint resistance is an important design issue. Therefore joint resistances are measured and the procedure for cable jointing is standardized. The mechanical strength of the joint has been verified up to liquid nitrogen temperature. Test results indicate, that they have acceptably low resistance, have sufficient mechanical strength and carry sufficient current.

The superconducting critical current is an important parameter, which determines the performance of any superconducting magnet. In any superconductor, the critical temperature (T_C), the critical magnetic field (H_C) and the critical current density (J_C) mark the limit of the superconducting state. The T_C and H_C are both determined by the chemistry of the superconducting material, whereas the J_C is radically changed within a given superconducting material (by a factor of 1000 or more) by different metallurgical processing, and therefore the materials microstructure. It is a measure of the conductor's current carrying capacity. Therefore, it is necessary to determine the critical current and thereby the critical current density of the superconducting cable for its electrical characterization. In superconducting composite the transition to the normal state with increasing current occurs gradually. Empirically, the voltage developed is proportional to the nth power of current during the transition to normal state i.e. $V \propto I^n$, where n is defined as the quality index of the cable and for ideal superconductor n is infinity [4]. It is caused by the steady state flow of magnetic flux in the specimen. Unlike a thermal runaway or flux jump, this is a stable and reversible condition. It is believed that the low value of the quality index is caused by the non-uniformity i.e. sausaging effect, in the diameter of the filaments. The n-value is determined from the conductor's V-I plot. Critical current is usually determined by using standard measurement criterion. Here we have used constant electric field criterion, in which the critical current is accepted as the current at which the voltage developed exceeds a constant electric field value (0.1 μvolt/cm). The critical current is measured in different magnetic field, which is applied perpendicular to the direction of current.

EXPERIMENTAL SET-UP AND PROCEDURE

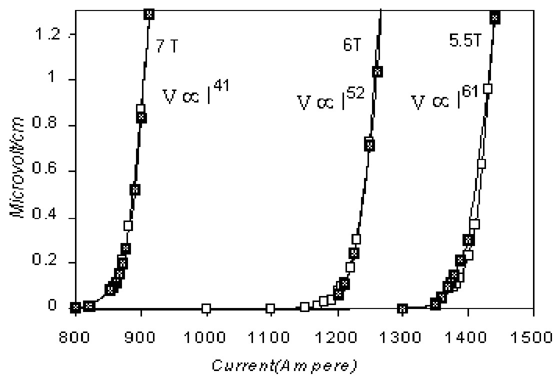
A Standard Magnet Dewar (SMD) has been procured from Oxford Instrument, USA. This is liquid nitrogen shielded Dewar with a common vacuum jacket surrounding both liquid nitrogen and liquid helium reservoirs. Its top plate along with central flange, superconducting magnet and its support, vent port with a pressure relief valve and a rupture disc and provision for different feed through ports are designed and fabricated to meet our requirements and also to gain basic idea for the construction of future magnet cryostat. The boil-off helium gas from the header of the cryostat is sent back to gasbag through recovery line. The central flange is used as an access port for easy insertion of sample. The set-up was so designed to be easily disassembled for 1/5 scale of K-500 main magnet coil testing, otherwise it is too large for central access port. All ports are designed to minimize heat in-leak and avoid contamination of helium inside the cryostat. A provision is made to initially fill the liquid from the bottom of cryostat and to top up liquid helium from above its free surface subsequently. To minimize the radiation heat flow down the neck of cryostat, five thin and highly polished stainless steel radiation shields are used for each central and top flange plates. The geometry and location of these baffles are optimised for maximum effectiveness. Two vapour cooled current leads of maximum 1500A current capacity are used to provide the current to the short sample. The heat capacity of cold helium vapour is used in counter flow direction to minimize liquid helium consumption. Each current lead is attached with superconducting bus bar made of Nb_3Sn sandwiched between coppers. Several temperature sensors are mounted inside the cryostat to monitor the temperature during cool down and one level sensor is used to monitor the liquid level. Another small cryostat has been used for the calibration of liquid helium probe, temperature sensors and I-B plot for superconducting magnet. Pre-cooling of the interior liquid helium chamber is performed in a controlled manner to avoid any thermal stress. Both joint resistance and critical current is measured by passing DC current through a sample and measuring voltage along the length using standard four-probe method. The samples are made spiral-shaped having outer diameter of 40mm and placed inside the bore of 7T superconducting magnet which produce field perpendicular to the direction of current in the sample. Care is also taken to ensure that the sample is adequately supported to resist Lorentz force. Voltage taps are placed sufficiently distance apart to produce adequate voltage sensitivity. Voltages are measured with the help of Keithely nano-voltmeters. All necessary arrangements are made to minimize the noise level. The measurements are also performed for decreasing current to get, if any hysteretic effect. Several samples are prepared and tested for critical current and joint resistance measurement.

RESULTS AND DISCUSSIONS

Samples are made from cables selected randomly from different spools. The critical current is measured for each sample under different magnetic fields. The critical current is obtained by continuously monitoring the voltage drop across the sample as the current increases. The noise level is about 10nvolt/cms, which is an order of magnitude lower than the voltage criterion defining the critical current. The V *vs* I plot of one of the conductors under three different magnetic fields is shown in figure 1 for both increasing and decreasing currents. Hysteresis is not observed, indicating the absence of heating or quench during measurement. The quality index obtained by fitting V-I data to power law ($V{\sim}I^n$) are more than 40, which indicate the good quality of the wire without any significant sausaging effect in the filaments. It is observed that the quality index decreases with increase of magnetic field. The critical current density is obtained by taking only NbTi area is shown in Table no.1. High critical current density obtained, is related to the number and strength of pinning sites present in the material. The small variation of less than 3% in J_C Vs B, plot for three different samples as shown in figure 2 accounts for either the measurement error and/or small variation in microstructures of material. Ideally all three curves corresponding to different samples should be same. The joint resistance is measured under different magnetic fields to observe the magneto-resistive effect as shown in figure 3. Some non-linearity is observed in lower magnetic fields, below about 1Tesla. Common solder is superconductor having a critical field of 0.3Tesla [2]. So at or near zero magnetic fields the solder between the two superconducting cables will also behave like superconductor below a certain current ~200A, which is observed in our measurement. The performance of joint resistance to higher current exhibits no degradation or quenching of sample. So test results indicate that they have acceptably low resistance and carry sufficient current. Residual resistivity ratio of copper substrate is also measured at different magnetic fields and the results obtained satisfied our requirement.

Table 1

Magnetic field (B)	5.5 Tesla	6 Tesla	7 Tesla
J_C (Amp/mm^2)	2464 ± 37	2160±36	1535±41
Quality Index (n)	61	52	41



□ -: Increasing current ✕ -: Decreasing current

Figure 1: Conductor V-I Plot

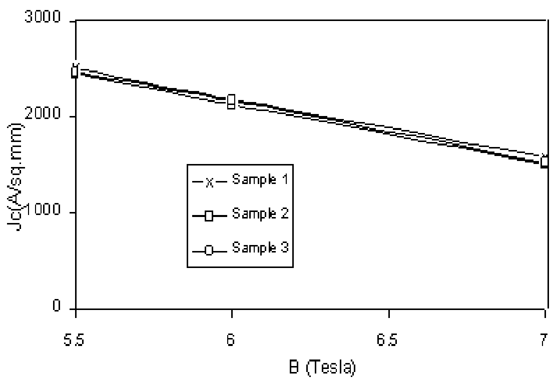


Figure 2: J_C Vs B plot

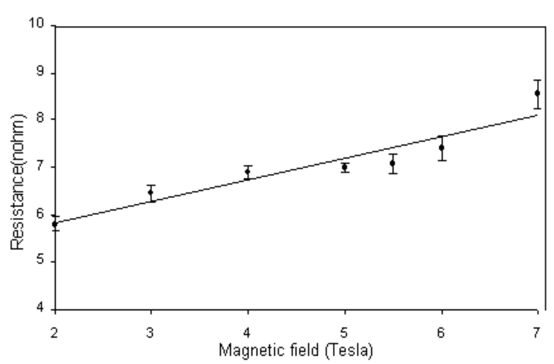


Figure 3: Joint resistance variation with applied magnetic field

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