EXPERIMENTAL STUDY OF CHARACTERISTICS OF CABLE FOR FAST-CYCLING SUPERCONDUCTING MAGNETS

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Abstract

Fast-cycling magnetic fields, produced by superconducting magnets of the SIS300 accelerator, generate cable losses, which should be reduced by increase of contact resistances between wires in the cable. For this purpose various methods of cable interstrand resistance increasing are used successfully. But the values of contact resistances have strong influence on a stability, which could be characterized by minimum quench energy (MQE).

From this point of view at IHEP it was carried out the experimental study of Rutherford type 19-strand superconducting cable with high value of contact resistances. Contact resistances and MQE measurements were performed. The description of features of samples, the measurement scheme and procedure are presented along with the experimental results.

INTRODUCTION

Last years IHEP developed the superconducting magnets for modern particle accelerators using fast-cycling magnetic fields. IHEP participates actively in FAIR project. In particular it is responsible for the development of superconducting correctors, quadrupole magnet of accelerator ring SIS300, and also for the choice of its design current carrying element [1]. Maximum magnetic field in this quadrupole coil is 3.5 T and field ramp rate is about 0.8 T/s [2].

The high and fast-ramping field in superconducting magnet generates large AC losses. For the purpose of reduction of losses try to make cable with relatively high value of the adjacent resistance Ra, which is the side-by-side resistance between adjacent pairs of strands, and the crossover resistance Rc, which is the resistance of each crossover contact. The knowledge of these resistances values, and also the ways of their control has great value already at a magnet design stage.

Two years ago we reported the results of study of cables with Ni or Cr coated surfaces of strands and it was shown that AC losses in the SIS300 quadrupole can be effectively suppressed by increasing of interstrand contact resistances by such coating. In recent time for quadrupole the cable design was chosen with stainless steel core. For such cable the interstrand resistances can be controlled independently by means of a high-resistance metallic core (Rc) and by proper oxidation of the wire surface (Ra).

Main task of this work was the study of the influence of cable curing parameters on the interstrand resistances value. Due to profound effect of these resistances on stability against short point heat pulses the minimum quench provoking energy of cable was measured too.

INTERSTRAND RESISTANCES

The tested cable consists of 19 NbTi strands with diameter of 0.825 mm. The strands are coated by a 0.5-μm thick Staybrite. The cable has a core with thickness of 25 μm and width of 6 mm, which is made from an annealed 316L stainless steel foil. The cable is fully keystoned and it is 8.25 mm wide and has average thickness 1.447 mm without insulation. The transposition length is 60 mm.

All tested samples were made from the same original cable. The preliminary heat treatment was done in order to form the high resistive oxide layers on the surface of cable strands. The pieces of original bare cable were heat treated in air under no pressure at 200ºC during 2 and 4 hours. Then cable was insulated be three layers of polyimide tape. The last layer was PIXEO adhesive tape.

Four cable pieces were stacked with the alternation of keystone angle direction. This package was placed into the fixture mould, which consists of two massive iron block equipped by electrical heaters and temperature sensors. After the mould was placed into the hydraulic press and the curing was performed according to regime, shown in Fig. 1.

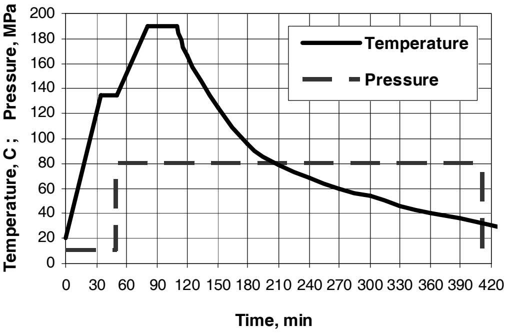

Figure 1: Curing cycle of stack of samples.

From the cured stacks the testing samples were cut, placed into sample holder and were compressed at room temperature once again up to 80 MPa on the length of 60 mm (one transposition length) and were fixed with help of bolts. Two inner layers in stack were equipped by potential taps and were used for measurement with the help of the VI method [3]. Current up to 100 A was fed into two opposite strands of cable sample (strands 1 and 10 in our case, Fig. 2 a), which was immersed into liquid helium bath. Voltage drop on strands 3, 5, 7, 9, and 10 was measured relative to strand 1. For example, the resulting profile of normalized voltage versus strand

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position is presented in Fig. 2 b) for original sample without preliminary heat treatment. For other samples this profiles are closed to straight line too. That is typical for the cases, when Ra is more than two orders of magnitude lower than Rc. In this case Ra equals to 8*V/I with 5% accuracy [4], where I is a current and V is voltage drop between two opposite strand 1 and 10.

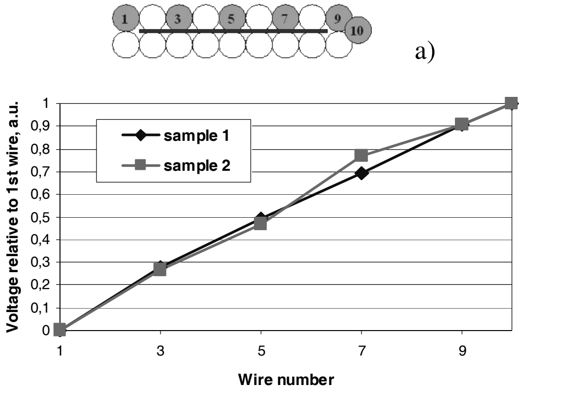

Figure 2: Cable sample cross section a) and the example of voltage profile across the samples b).

The dependence of adjacent resistance Ra upon the time of preliminary heat treatment is presented in Fig. 3. As evident from figure Ra = 100 μOhm is achieved even without preliminary heat treatment. This value is sufficient to restrict the Ra-specific losses by value < 5% of total quadrupole losses. Thereby Rc was measured only on the sample without preliminary heat treatment.

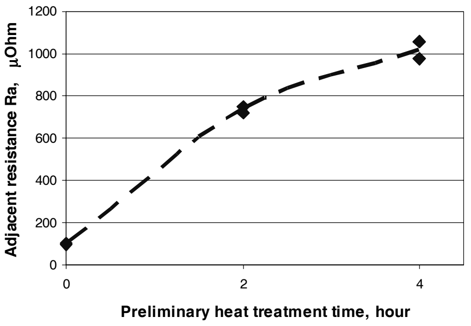

Figure 3: The influence of preliminary heat treatment on the final value of Ra.

The method of direct measurement of Rc was used. The sample was cut and prepared similarly described in [4]. That is: the small part of a cable is clamped in the central part and cable sides are cut off to interrupt the current transfer through the wire from the top to the bottom layer, the strands leaving in a longitudinal direction are untwined, all free ends of strands belonged to the same layers are soldered for maintenance of the even current distribution across the core. Thus contact between strands from different layers occurs only through the core. Described in [5] measuring procedure was used. Fig. 4 presents the dependences of crossover resistance Rc upon pressure up to 80MPa on the cable surface. Loading and unloading branch of curves are presented. Such high value is much greater than required (more than one order of magnitude).

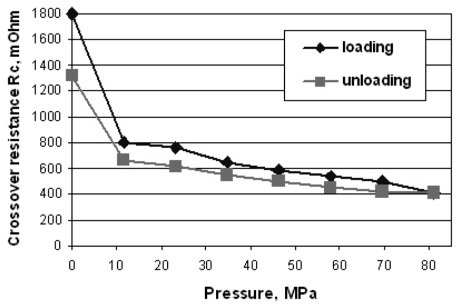

Figure 4: Rc evolution upon pressure for cored cable without preliminary heat treatment.

MINIMUM QUENCH ENERGY

Measurements were performed into the liquid helium bath at the external magnetic field 6 and 3.5 T, applied normal to cable wide side on the length of 500 mm. The sample is the extended closed loop of 2.7-m cable, which forms the secondary winding of the superconducting transformer described in detail in [6]. On one end it covers current-measuring coil, and on the other it covers the primary coil of transformer. The direct and return cables in the central straight part of loop are put to the aligning flute in a special fixture along with two extra cable pieces, what provides rectangular cross section of whole stack, which are pressed on 800 mm length. Applied pressure of 80 MPa is kept by the bolt joints, uniformly distributed along the fixture. This fixture is used as a mould for curing and then as a sample holder during measurement. It is necessary to notice that in the absence of the suitable equipment for such long sample we could not reproduce curing cycle, shown in Fig. 1. Therefore, the sample, squeezed initially up to 80 MPa, was inserted in the furnace with temperature of 160ºC and then temperature was changed according to Fig. 1.

In central part on inner surface of cable loop the spot-like measuring heaters [7] were made. Heaters are allocated on the centre of broad face of cable strictly above the single strands. Thin strips of NbTi foil were put over the heater for the current delivery, whereas the cable strands are used as a current return path. The potential taps were soldered to narrow side of the cable. Simplified measuring scheme is shown in Fig. 5. Management of measurement and data acquisition are carried out through the interface bus GPIB. At current ramping the continuous registration of a sample current and voltage is performed by nanovoltmeter Agilent 34420A that provides the measuring of critical current or detecting a quench, caused by a thermal disturbance. The linear ramp of a current is used. At the appointed current the small heat disturbance with duration 50 μs was generated onto one cable strand by the measuring heater, which is fed by the power amplifier with P_{max} = 400 Wt. The amplitude of heat pulse is specified by the function generator. Short pulses of heater current and voltage are digitized with the 50 ns period by digital oscilloscope, connected via wideband insulating amplifiers.

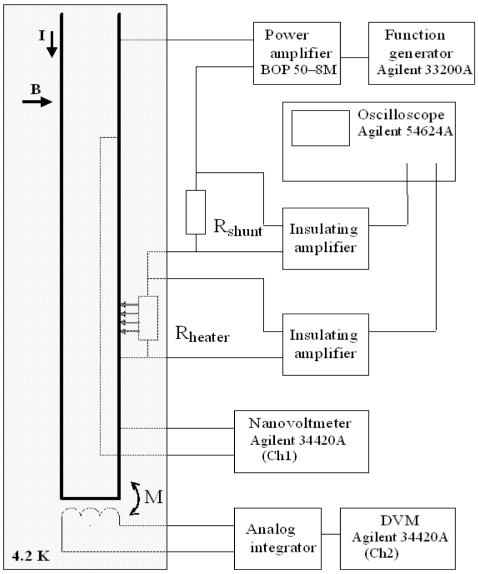

Figure 5: The measuring scheme.

Then the energy, deposited in heater, is calculated. This energy is varied step by step and the minimum energy, which provoke quench, is found for every appointed current. The sharp increase of voltage over of the sample and the subsequent sharp decrease of a current in cable is a quench indicator. The cable is quenched manually for providing the same initial current distribution into the cable strands and then a new current ramp is used before each heater firing.

Such as MQE measurement is iterative process, the accuracy is determined by step of change of the heater energy, whereas the instrumental error is much lesser. In our case metering error was < 20 %. In particular for this reason the nothing scaling factors like [8] was used here. As to a first approximation, as MQE it is interpreted the dissipated into heater energy, which leads to quench of whole cable. A careful analysis is performed in [9].

The dependences of MQE versus current for the cored cable are presented in Fig. 6. For comparison the similar dependences was measured and it is shown in Fig. 7 for Ni-coated cable, whose MQE is significantly greater.

CONCLUSIONS

Preliminary heat treatment for this cable is not necessary. Adjacent resistance has enough value to reduce eddy current losses in cable to the reasonable level. However, very large value of Rc in cored cable is redundant from the point of view of decreasing of losses and from the other hand it makes worse the conditions of current redistribution between wires.

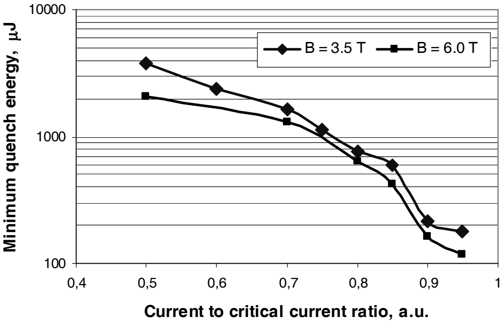

Figure 6: Minimum Quench Energy for cored cable.

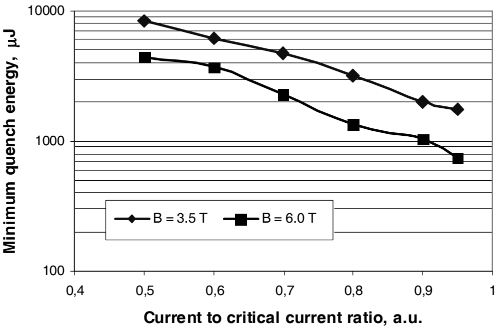

Figure 7: Minimum Quench Energy for Ni coated cable.

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