Development of a 10 m quasi-isotropic strand assembled from 2G wires

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A B S T R A C T

Quasi-isotropic strands made of second generation (2G) high temperature superconducting (HTS) wires are attractive to applications of high-field magnets at low temperatures and power transmission cables at liquid nitrogen temperature in virtue of their high current carrying capability and well mechanical property. In this contribution, a 10 m length quasi-isotropic strand is manufactured and successfully tested in liquid nitrogen to verify the feasibility of an industrial scale production of the strand by the existing cabling technologies. The strand with copper sheath consists of 72 symmetrically assembled 2G wires. The uniformity of critical properties of long quasi-isotropic strands, including critical current and n-value, is very important for their using. Critical currents as well as n-values of the strand are measured every 1 m respectively and compared with the simulation results. Critical current and n-value of the strand are calculated basing on the self-consistent model solved by the finite element method (FEM). Effects of self-field on the critical current and n-value distributions in wires of the strand are analyzed in detail. The simulation results show good agreement with the experimental data and the 10 m quasi-isotropic strand has good critical properties uniformity.

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1. Introduction

Because of excellent high-field and high-current performances, 2G HTS wires show great potential for use in applications such as high-field fusion magnets at low temperatures and power transmission cables at liquid nitrogen temperature. However, in these applications, currents in the range of kA are mostly required. To achieve such currents, several wires have to be connected in parallel. In the past years, in order to get high current HTS cables (conductor, strand), several cable designs have been proposed, such as twisted stacked tape cable (TSTC), conductor on round core (CORC) cable, Roebel cable, quasi-isotropic strand and CroCo cable [1–5].

Since the quasi-isotropic strands were first proposed in 2015, many properties of them have been investigated or numerically simulated like the critical current anisotropy at 77 K in low magnetic fields [4], thermal stability at 4.2 K and 77 K temperatures [6,7], AC losses properties at 77 K [8], quench behavior with over current at power frequency [9], mechanical properties of bending and twisting at 77 K and cryogenic temperatures [10–12]. The aforementioned investigations were done by short strand samples, which often owe better properties than the long ones. In order to verify the reasonableness of an industrial scale production of the quasi-isotropic strand by the existing cabling technologies, the critical current and its uniformity of long quasi-isotropic strand after manufacture needs to be studied particularly. The operating current of long quasi-isotropic strand is directly determined by the minimum critical current along its length. n value which is used to characterize the steepness of the E–I relationship of superconductor could be effected by magnetic field. However, the effect of self-field on the n-value distribution in wires of the quasi-isotropic strand and n-value of the whole quasi-isotropic strand has not been ever estimated before, but n-value of each strand of a Roebel cable has once been predicted by utilizing the average pinning force of wires as input [13].

Recently the self-consistent model, basing on the asymptotic limit of Faraday’s equation when time approaches infinity, has been widely used to estimate the critical currents of superconducting devices with high accuracy and fast speed [14–16]. In calculation, the self-consistent model uses \( J_c(B, \theta) \) of the wire as input which is extracted from the experimental data involving a process solving an inverse problem to fit the parameters of the predefined expression [17].

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In this contribution, a 10 m length quasi-isotropic strand is manufactured and successfully tested in liquid nitrogen. The strand with copper sheath consists of 72 symmetrically assembled 2G wires. Critical current, magnetic field distribution as well as n-value of the strand are calculated by a 2D FEM simulation based on the self-consistent model. In the simulation, the resistance between the stacked wires is negligible and the AVG criterion \( I_c \) is the current at which the average electric field in the cross section reaches the critical value \( E_c \) is adopted to obtain the critical current. The influence of the self-field on distributions of critical current and n-value is analyzed. To study the uniformity of critical properties of 10 m quasi-isotropic strand, critical current and n-value are measured every 1 m along its length in the tests. At last, the experimental data are compared with the numerical results and the uniformity of critical properties is discussed.

### 2. Structure and manufacture of the quasi-isotropic strand

A quasi-isotropic strand has a cyclic symmetry geometry, as shown in Fig. 1(a). The superconducting component is located in the central area of the strand and has 72 stacked wires symmetrically distributed in parallel to form four sub-strands each of which consists of 18 2G wires. The sub-stands are labelled by light green Roman numerals from I to IV in the figure. The 2G wires used in fabricating the strand were manufactured by Superpower and the main parameters of the wire and strand are listed in Table 1. The filling materials between superconducting component and copper sheath are aluminum foil and aluminum filler to improve the strand’s thermal conductivity and mechanical properties. The copper sheath providing the mechanical protect encases the central superconducting part and filling materials.

![Fig. 1. Schematic cross-section of quasi-isotropic strand and photo of the 10 m strand sample. (a). Schematic view of the strand cross section; (b) Photo of the 10 m quasi-isotropic strand.](image)

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of REBCO wire</td>
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<td>mm</td>
</tr>
<tr>
<td>Width of REBCO wire</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Critical current (77 K, sf)</td>
<td>45</td>
<td>A</td>
</tr>
<tr>
<td>Thickness of aluminum foil</td>
<td>0.1</td>
<td>mm</td>
</tr>
<tr>
<td>Inner diameter of copper sheath</td>
<td>7</td>
<td>mm</td>
</tr>
<tr>
<td>Outer diameter of copper sheath</td>
<td>8</td>
<td>mm</td>
</tr>
<tr>
<td>The length of strand</td>
<td>10</td>
<td>m</td>
</tr>
<tr>
<td>Number of wires</td>
<td>72</td>
<td>–</td>
</tr>
</tbody>
</table>

The 10 m length quasi-isotropic strand was produced in Zhongtian Technology Company by machine as show in Fig. 2. The fabricating process of the strand is same as the one of manufacturing the short sample which was ever described in [4]. Because the strand had a 10 m length, so for convenient in the transportation and tests, the strand was spiraled into the circular shape after manufacture, seen Fig. 1(b). The strand has a bending radius of 650 mm, which is much larger than the critical bending radius 352 mm of quasi-isotropic strand, so the bending does not have any effects to his critical properties [10].

### 3. Numerical simulation of critical properties of quasi-isotropic strand

The wires are stacked tightly into the quasi-isotropic strand, which results in a strong electromagnetic interaction between them. This self-field is quite substantial and can profoundly influence the effective critical current and n-value of the strand. The effective critical current is much lower than the sum of critical current of the composing wires. n-value of the whole quasi-isotropic strand is also lower than the n-value of single wire. So in order to accurately estimate the critical current and n-value of quasi-isotropic strand, the complex \( j_c(B, \theta) \) of the HTS wire as well as the geometric layout of the quasi-isotropic strands should be taken into account in the simulation. In the end, all calculations in this paper were performed by using the commercially available FEM software package COMSOL Multiphysics.
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