Thermal Stability Analysis of a Stainless Steel Reinforced Stacked YBCO Cable

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Abstract. The thermal stability analysis of a stacked strand consisting of the YBCO tapes with square cross-section is presented. Symmetrically arranged YBCO tapes are sheathed by stainless steel. The thermal stability characteristics, including the minimum quench energy (MQE) and the quench propagation velocity (QPV), are calculated by finite element analysis method. The experimental results show that the MQE and QPV of stainless steel reinforced strand are consistent with the simulation results.

1. Introduction

In order to increase the current carrying capability of the high temperature superconductor (HTS) wires, some kind of twisting stacked tape cables (TSTC) are developed to overcome the anisotropic characteristic of HTS wires including Bi2223 and ReBCO [1]-[4]. One of the TSTC is composed of symmetrically arranged ReBCO wires with different directions. The perpendicular component of the self-generated magnetic field of one ReBCO stack could be reduced by nearby stack with 90°. Therefore, the anisotropic characteristic of the TSTC could be improved.

Considering the large current density, the thermal stability characteristics including the minimum quench energy (MQE) and the quench propagation velocity (QPV) of the TSTC becomes a crucial part in application. The strand with round cross section and copper sheath has been analyzed [5]. However, the thermal stability of the strand with square cross section and stainless steel reinforcement has not yet been investigated. The paper concentrates on the thermal stability of the strand with square section and stainless steel sheath, which is analyzed by simulation and experiment.

2. Thermal stability analysis

2.1. Structure of stacked strand

The developed strand with square cross section is depicted in figure 1. 2G HTS wires are arranged symmetrically in the middle area of the strand. 72 wires are wrapped by aluminum foils and stainless steel is outside the aluminum foil. The main parameters are listed in Table I.
Table 1. Specifications of the stacked strand.

| Parameters                              | Value   |
|-----------------------------------------|---------|
| Thickness of YBCO tape                  | 0.11 mm |
| Width of YBCO tape                      | 2 mm    |
| Thickness of aluminum foil              | 0.1 mm  |
| Width of YBCO component                 | 4 mm    |
| Width of the strand with reinforcement  | 5 mm    |
| Critical current of stainless steel strand | 600 A   |

2.2. **Theoretical analysis**

A 3-D finite element analysis (FEA) model of the proposed stacked strand with YBCO tapes is developed to calculate the MQE and QPV. The simulation time is set as 200 s since the maximum recovery time is about 200 s, and the 3-D heat conduction equation is given by

\[
\gamma C \frac{\partial T}{\partial t} = \nabla (k \nabla T) + G_j + G_d
\]

where \(T\) denotes the temperature;
- \(k\) is the thermal conductivity, W/m·K;
- \(C\) is the volumetric heat capacity, J/m\(^3\)·K;
- \(\gamma\) is the mass density, kg/m\(^3\);
- \(G_j\) (J/m\(^3\)) is Joule heat which is as follows:

\[
G_j = \left( \frac{\rho_s I_s^2}{A_s} + \frac{\rho_{SS} I_{SS}^2}{A_{SS}} \right) / A (T \geq 0)
\]

\[
I_o = I_s + I_{SS}
\]

where \(\rho_s\) and \(\rho_{SS}\) are the resistivity of YBCO wire and stainless steel, respectively; \(I_s\) and \(I_{SS}\) separately are currents in YBCO wire and stainless steel; \(I_o\) represents operation current; \(A_s\), \(A_{SS}\) and \(A\) stand for total cross-sectional area of the YBCO wire, stainless steel and the strand.

Consequently, the MQE can be calculated by

\[
MQE = G_d V_h
\]

where \(G_d\) (J/m\(^3\)) stands for heat disturbance and \(V_h\) (m\(^3\)) is heated volume. \(G_d\) is a heat pulse and the duration of the heat pulse is 20s. The amplitude is changed while the duration remains unchanged in the simulation.

In order to reach superconducting state, the strand is immersed in the liquid nitrogen. The following equation describes thermal exchange between the strand with liquid nitrogen

\[
- \mathbf{n} \cdot (-k \nabla T) = h \cdot (T_{ext} - T)
\]
where $T_{ex}$ refers to external temperature; $h$(W/m²·K) is heat transfer coefficient and its fitting curve [6] is in figure 2.

![Figure 2. Heat transfer coefficient of stainless steel](image)

The sample length is $L=500$ mm and the heated area length is $L'=50$ mm, which is in the middle part of the TSTC. Half of the sample ($L/2=250$ mm) is analyzed since that both of terminals are symmetric, which can simplify the simulation. The schematic view of the heated area is shown in Fig. 3. The initial condition is $T(x)|_{t=0}=77$ K, and the boundary conditions are

\[
\begin{align*}
\frac{\partial T}{\partial x} |_{x=0} &= 0 \\
T(x)|_{x=25} &= 77
\end{align*}
\]  

(5)

![Figure 3. The heated area](image)

2.3. Simulation

The heat disturbance $G_d$ is applied to the heated area for several seconds, while the transported current of the TSTC maintains. Quench does not occurs during this process since the initial value of $G_d$ is small enough. With $G_d$ gradually increasing, the quench finally happened, and $MQE=G_dV_h$ is the minimum quench energy at this current.

![Figure 4. The quench simulation of the TSTC with $I_o=400$ A and heat disturbance of 5.45 J](image)
Figure 4 shows the initial state, quench recovery process and the steady state when 5.45 J was applied to the TSTC operated at 400 A. According to the simulation results, the quench did not happen for the heat disturbance was not enough.

![Temperature Graph](image1)

**Figure 5.** The quench simulation of the TSTC with $I_o=400$ A and heat disturbance of 9.73 J.

Figure 5 shows the initial state, quench propagation process and completed quench state, when 9.73 J heat disturbance was applied to the TSTC operated at 400 A.

![Graph](image2)

**Figure 6.** MQE and QPV vs $I_o$.

Figure 6 shows the MQE as well as QPV of the SS strand at different operation current. According to the simulation results, the MQE decreases when the operation current increases. On the contrary, QPV increases along with the operation current, since it is difficult for the strand to keep superconducting state if the operation current increase closer to the critical current. If the operation current is lower than 400 A, little Joule heat is generated inside of the TSTC. Therefore, quench mainly caused by outside heat disturbance. If the operation current is larger than 400 A, heat is generated rapidly inside the strand after the heat disturbance. Consequently, the generated heat transfers and Joule heat contributes to the quench process.

3. Experiment and discussion

![Device Schematic](image3)

**Figure 7.** Schematic view of device for generating magnetic field.
Figure 7 shows the schematic view of the device for generating magnetic field. The direct current magnetic field would generate in air gap when the current flowed through the copper coils around the iron core. The height of the air gap is 10 mm and it is suitable for the strand to pass. The cross section of the iron core is 50 mm×50 mm. The maximum value of the magnetic field is 1 T. The difference of the field is less than 3.0%. The strand is placed in air gap with magnetic flux density of 1.0 T, and the $I_c$ of the strand could be reduced to 350 A from 600 A.

![Figure 7](image)

**Figure 8.** Experimental arrangement: (a) Photo of experiment arrangement; (b) Enlarged schematic view of sample and magnetic field; (c) Voltage testing circuit

The stainless steel reinforced TSTC is placed at the center of the magnetic field, and the operation current of the TSTC is set to 400 A and 500 A, and the applied magnetic flux density if 1.0 T. Figure 8 shows the testing circuit where the voltage against time could be recorded by the transient recorder. $V_0$, $V_1$, $V_2$, $V_1'$ and $V_2'$ separately correspond to voltage taps [8]. The distance between $V_1$ ($V_1'$) and $V_2$ ($V_2'$) is $\Delta L=40$ mm and the distance between $V_1$ as well as $V_1'$ with $V_0$ is $L''=65$ mm. Consequently, different heat disturbance is applied to test the quench process.

![Figure 8](image)

**Figure 9.** Quench process of the TSTC at 400 A.

Figure 9 presents the quench waveform voltage against time if $I_o= 400$ A. Curves are $V_0$, $V_1$, and $V_2$ respectively. The first voltage tap to quench is $V_0$. Therefore, MQE can be defined as

$$E = \int_0^t \Delta U I_o dt$$

(6)

where $\Delta U$ denotes the voltage variation compared with the situation without magnetic field, and QPV can be calculated as follows:

$$\nu = \Delta L / \Delta t$$

(7)

where $\Delta t$ is quench time [9].
Table 2. Simulation and experimental results of the developed strand.

| $I_o$ (A) | MEQ(J) Simulation | MEQ(J) Experiment | QPV (m/s) Simulation | QPV (m/s) Experiment |
|----------|------------------|------------------|---------------------|---------------------|
| 400      | 8.74             | 8.41             | 0.181               | 0.236               |
| 500      | 7.56             | 7.83             | 0.254               | 0.329               |

Tables 2 shows the simulated and experimental MEQ and QPV of the strands with sheathe of stainless steel, which indicates that simulation results are qualitatively in agreement with experimental results. The slight difference between the simulation results and the experimental results may come from the difference of thermal conductivity and heat capacity used in the simulation and the experiment.

4. Conclusion
Thermal stability analysis of a kind quasi-isotropic stacked strands with square cross section and stainless steel sheath is presented by simulation and experiment. According to the simulation and experimental results, the MQE decreases when the operation current increases. On the contrary, QPV increases along with the operation current.

5. Acknowledgments
This work was financially supported by China Southern Power Grid (GDKJXM20172613).

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