Numerical simulation of the cable breakage based on electromagnetic NDE method for ITER cable-in-conduit conductors

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1. Introduction

Superconducting cable is the core component of CICC conductor which carries tens of thousands of amps of current under extreme operating conditions. Once operated, they cannot be repaired and replaced for life. Its quality directly affects the performance of the conductor and even affects the safety of the superconducting Tokamak device. Due to the multi-level composite structure, it is easy to cause partial damage or even strand breakage of the superconducting cable in the complex deformation mode. Clear deformation and even damage of the Nb3Sn strands were found during cabling, as shown in figure 2. The extreme operating conditions of low temperature, high current and strong magnetic field will further aggravate the damage of the strand, which affects the current carrying capacity of the cable. It was found that the critical performance is reduced by more than 5% when local damage depth of the strand exceeds 0.35mm in the latest report. Therefore, it is vital to inspect superconducting cables on-line during the manufacture and operation process.

Fig. 1. lay out of disassembled cable

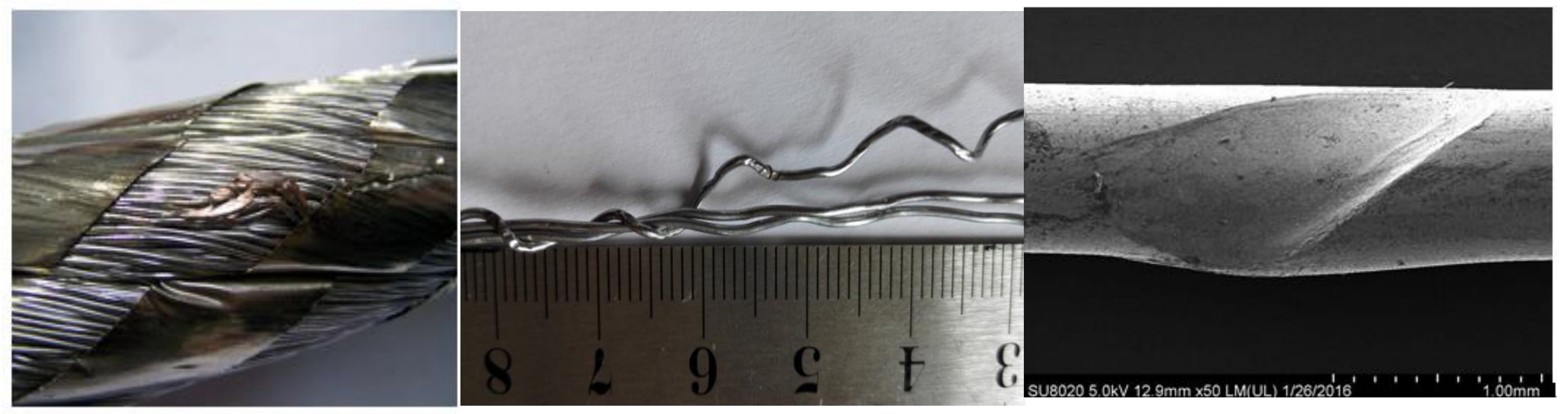


Fig. 2. Damaged of Nb3Sn strand

2. Test principle of the breakage strands inspection

Electromagnetic NDE method is researched for the breakage strands inspection, the test principle is descried in the following:

- ◆ Measuring the magnetic induction intensity distribution around the cable through the electromagnetic probe;
- ◆ Calculating the internal current distribution of the cable based on the measured magnetic field signal inversion;
- ◆ Infers the wire breakage rate of the superconducting cable ;

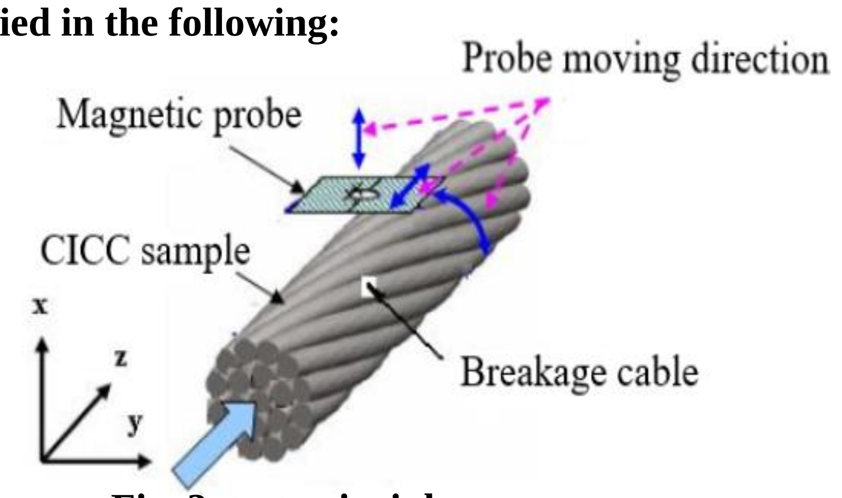


Fig. 3. test principle

Numerical model for Nb_3Sn cable

The models were set the Cartesian coordinate system in the center of the cross section of the cable. The cross section of the cable is the X–Z plane, and its length is along the Y direction. All the models below are built according to this coordinate system. Fig.5 gives the models built for the second stage and the third stage.

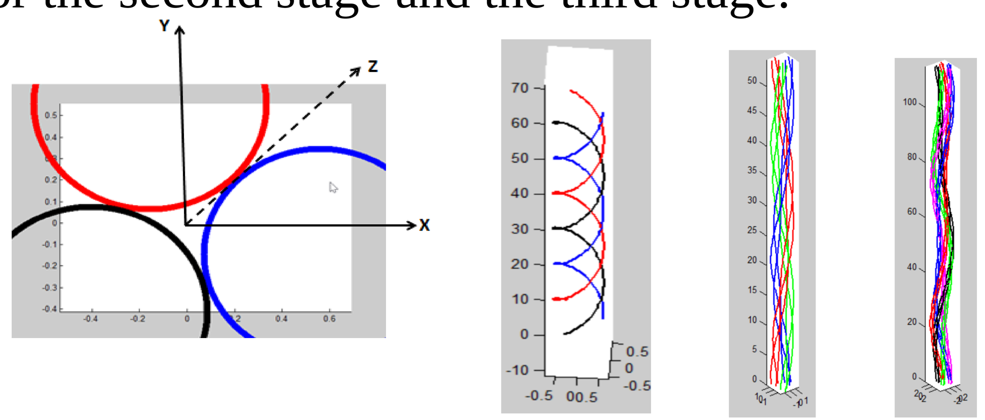


Fig. 4. Computational model with a Cartesian coordinate system

Current selection

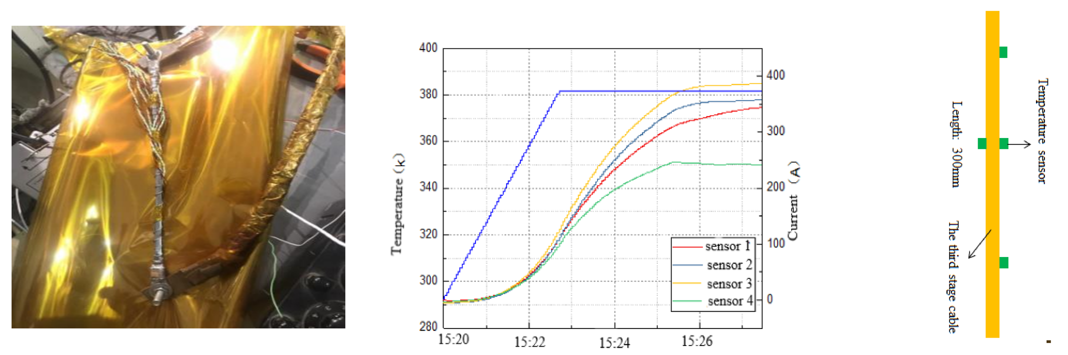
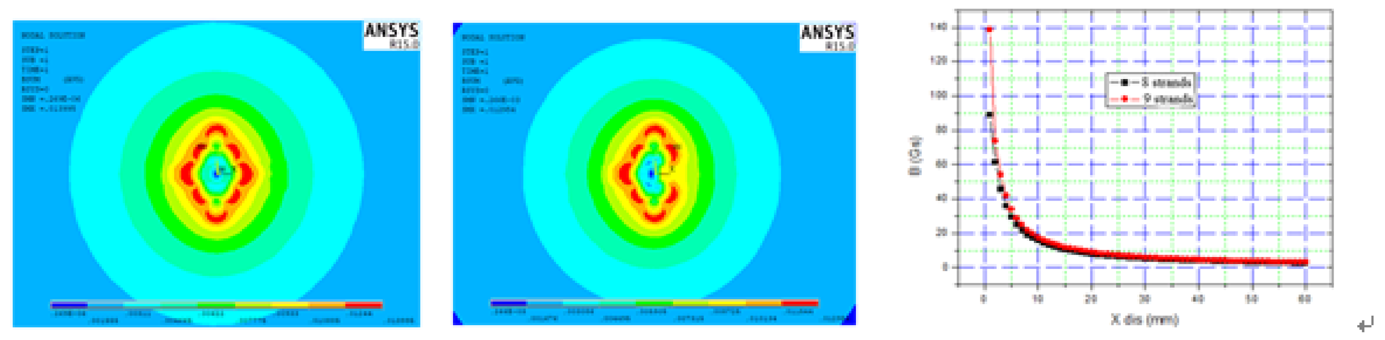


Fig. 5. Temperature rise experiment

- ☐ The target temperature shall below 150℃;
- ☐ 4 temperature sensors are used to monitor the temperature around the cable;
- ☐ The temperature stabilized at 382K after 3 min;
- ☐ 10A for each strand selected

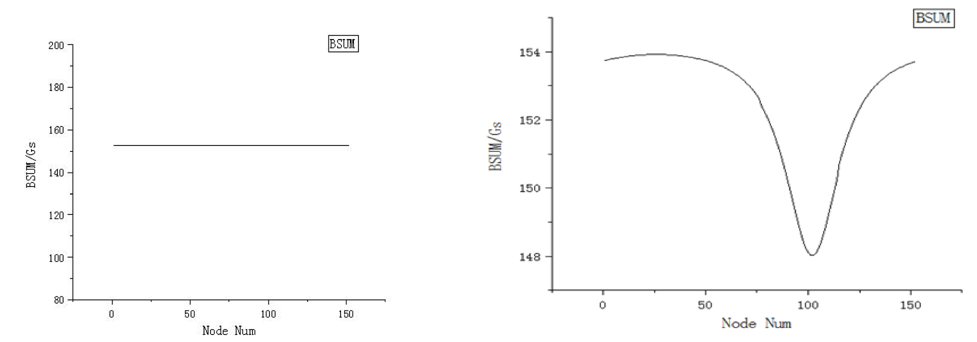
3. Magnetic field signal calculation based on the model

- ◆ The feasibility of proposed method was verified by the numerical simulation based on the second stage of cable. There are total 9 strands, including 3 Cu stands and 6 Sc strands. Each strands carried out 10A current. Magnetic field intensity was calculated in two different cases. One case is no strand breakage in the cable. The other case is one strand breakage among the 9 strands. Magnetic field intensity and corresponding curve were calculated. According to the simulation results, it can be deduced that obvious changes of the magnetic field intensity were obtained which was caused by the strand breakage. More than 2Gs changes could be got when the magnetic probe was applied within 5mm around the cable.



(a) no strand breakage (b) one strand breakage (c) Magnetic field intensity curve

Fig. 5. Magnetic field intensity calculation results



(a) No breakage strand **(b) one breakage strand**

Fig. 6. Magnetic field intensity curve for strand breakage

4. Reconstruct current source from simulated magnetic field

- ◆ An inversion method which reconstructs the internal current distribution by measuring the magnetic field distribution around the cable was developed and applied.
- ◆ A numerical code has been developed for the reconstruction of inner currents.
- ◆ The model used for each second stage cable is equivalent to one cable with the diameter 4.64mm as shown in Fig.7.
- ◆ 4 kinds of wire breakage patterns:

{I}={10,10,10,10,10}A, with no strand breakage
{2}={10,0,10,0,10}A, with two strand breakage
{3}={10,0,0,10, 0}A, with three strand breakage
{4}={10,6,4,8,5}A, with random current value

The broken lines with circle signs are the preset current values while the cross signs are the reconstructed ones. Important information could be found that the reconstructed currents are in good agreement with the true values, which reveals the validity of the method and the code.

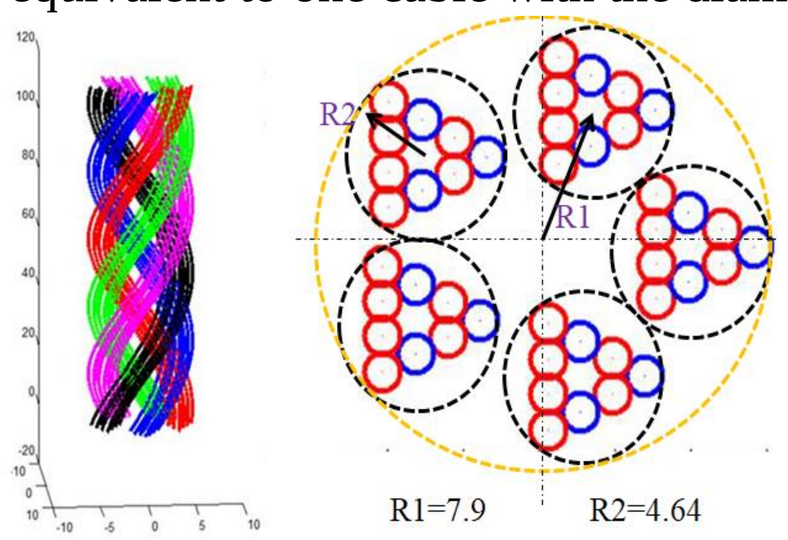


Fig. 7. Equivalent model of the third stage

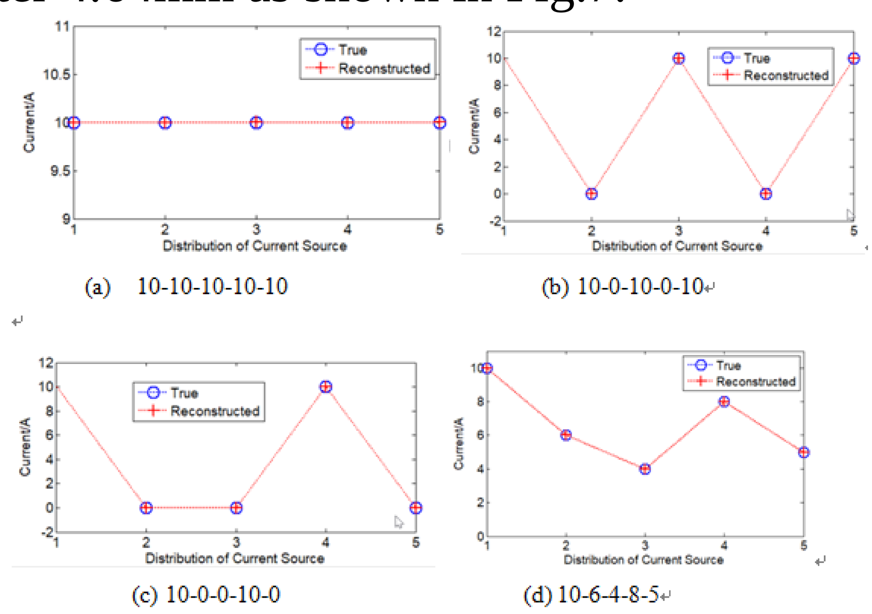


Fig. 8. Results of the current reconstruction

5. Results and Conclusions

Based on the described method and the models established, the feasibility and efficiency of the proposed method are demonstrated through the numerical simulations results. The inner current values in the third stage cable can be properly reconstructed. And the reconstructed currents are in good agreement with the true values. The whole investigations in relation to rate of strands breakage have shown the feasibility by the use of the magnetic field changes.

Future work will involve experimental verification with more practical CICC samples. It mainly includes 3 stage cable sample and the full-size sample. The improvement of de-noising technique will be developed as well in the next work.