氏　　　名	BANSAL GOURAB
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論文審査委員	主　査　教授　　相良　明男 准教授　　柳　長門 教授　　三戸　利行 教授　　小川　雄一（東京大学） 准教授　　白井　康之（京都大学）

論文内容の要旨

Presently, well-established low-temperature superconductors (LTS), such as NbTi and Nb_3Sn, operating at ~ 4 K are being selected in the existing and near future fusion devices for producing high magnetic fields. However, LTS conductors possess low stability margin at 4 K due to the low specific heats of materials, which further degrades by non-uniform current distributions among strands. The future fusion energy reactors, such as the LHD-type force-free helical reactor (FFHR), cannot allow their huge magnets to quench, and thus, high stability conductors are required to secure safe operations. Compared to LTS, high-temperature superconductors (HTS) possess higher stability as they can be operated at elevated temperatures above 20 K, which assures higher specific heats. In addition, high critical current density is expected for HTS materials in high magnetic fields even at elevated temperatures. Moreover, lower refrigeration power is required due to elevated temperature operations. Owing to these advantages, HTS conductors are considered to be a potential candidate for fusion magnets. However, HTS conductors are presently available only in wire and tape forms, and there have been limited activities for developing large-current (> 10 kA) HTS conductors that can be used for magnet windings. Thus, in this thesis, feasibility studies of large-current capacity HTS conductors for fusion reactors have been conducted.

We hereby make a new proposal of simple stacking of HTS wires in the conductor form, and the focus of the research is on cryogenic stability of such conductors. Due to simple stacking of HTS wires, it is probable to observe inductance mismatching among wires, and therefore, non-uniform current distributions are supposed to be formed in the conductor. Non-uniform current distribution is a serious problem for the stability of LTS conductors, and it is also an important task to investigate similar effects on HTS conductors. In this respect, firstly, the present research was initiated by critically examining the stability of LTS cable-in-conduit conductors (CICC) with non-insulated strands by artificially introducing non-uniform current distributions. Secondly, the effect of non-uniform current distributions on HTS conductors was examined by utilizing an LTS/HTS hybrid conductor. Thirdly, 10 kA-class HTS conductors were fabricated and tested, extensively. Finally, the HTS conductor design studies for FFHR were conducted.

The stability margin was measured on a full-scale CICC with non-insulated NbTi/Cu strands by artificially introducing non-uniform current distribution in a controlled way. The conductor applied for the SST-1 tokamak (at IPR, India) was used, and the experiments were carried out at 4.2 K temperature and 6.1 T bias magnetic field. In the experiments, it was found that the stability margin of the conductor reduced significantly due to non-uniform current distributions, especially in the transition region between the well-cooled and ill-cooled regions. The limiting current, which separates the two regions, was also reduced. Numerical calculations were also carried out to simulate the experimental data of stability margin with uniform and non-uniform current distributions, and good consistency was observed.

In order to examine the effect of non-uniform current distributions on the stability of HTS conductors, a unique and innovative experimental method was proposed with an LTS/HTS hybrid conductor, which was the world first superconductor using both LTS and HTS together. In a hybrid conductor, layers of Bi-2223/Ag HTS tapes were soldered to form a stabilizer for the LTS wires. Once a normal-zone appears in the LTS wires, the transport current transfers into the HTS part from one layer to another and so on. This is supposed to be a case of extreme non-uniform current distribution in the HTS part. In the experiments at 4.2 K and 7 T, it was found that even with such an extreme non-uniform current distribution, the HTS part was stable and the conductor did not quench fully even though the transport current was close to the critical current of the HTS part in the hybrid conductor. These experimental results suggest that non-uniform current distribution should not be a problem for the stability of HTS conductors, which suggests that the freedom of conductor configuration can be increased for HTS conductors.

Thus, a large-current capacity HTS conductor was proposed, consisting of simple-stacks of HTS wires with presently available tape forms. This is regarded as a new but a controversial proposal, since simple stacking of superconducting strands without transpositions has never been allowed for LTS conductors. As a first step, a 10 kA-class (at 20 K, 8 T) HTS conductor was fabricated using Bi-2223/Ag tapes. The conductor was prepared by stacking HTS tapes in two bundles and then encasing them inside a copper jacket of 12 mm (width) × 7.5 mm (thickness). An innovative technique was applied to test the HTS conductor at different temperatures from 4.2 to 30 K. Thin stainless-steel heaters were attached to the conductor surface to elevate the temperature and the conductor was insulated by epoxy and GFRP to obtain similar conduction cooling conditions as in future magnets made of HTS conductors. The critical currents were measured, and the results were found to be close to the expectations by taking account of the self-field generated by the transport current in the conductors. This suggests no degradation in HTS conductors during the fabrication process. The stability margin of the HTS conductor was also measured at different temperatures. The conductor was found to be highly stable, as it was expected from the high heat capacity of the materials at elevated temperatures, and could not be quenched even with an energy input of several tens times higher than that required to quench LTS CIC conductors.

Having observed the encouraging results of 10 kA-class HTS conductors, the 100 kA-class HTS conductor design was initiated as an option for the LHD-type fusion energy reactor FFHR. An innovative idea of having rather thin layers of HTS wires within the conductor with stainless-steel jacket is proposed. By having such a configuration, the bending strain can be minimized to be ~0.05% level so that the winding of coils using these conductors is feasible. Moreover, the problem of error magnetic field generated by shielding currents in the HTS tapes and/or by the occurrence of non-uniform current distribution among tapes due to inductance mismatching is considered to be equivalent as the shift of current centers in the conductors. If the HTS part can be confined in thin layers, the current shift is supposed to be in an acceptable level within the tolerance of winding accuracy. As a conclusion, it has been found that HTS conductors can be feasible to be used for fusion energy reactor magnets, though a number of issues associated with their development should be solved one by one.

論文の審査結果の要旨

Bansal Gourab 氏は、ヘリカル型核融合エネルギー炉 FFHR の大型超伝導マグネットに用いることを想定した大電流容量高温超伝導（HTS）導体の開発をめざした研究を行った。近年、HTS 線材の開発が急速に進んでいるが、代表的なビスマス 2223 およびイットリウム系に特有なテープ形状の線材を用いた 10 kA を超えるコイル巻線用大電流容量導体はまだ開発例がない。特に、本研究では新しい試みとして、テープ線材を単純に積層するという導体構造を提案している。これによりセラミック系の酸化物超伝導材料を用いながら機械的に強固で製作性の良い導体が構成できると考えられる。ただし、これは、従来の低温超伝導（LTS）導体ではまったく選択できない発想であり十分な検証を必要とする。実際、LTS 導体では、極細多芯フィラメントで作った素線を撚り合わせ、各素線を導体の２次元断面内で万遍なく配置（トランスポーズ）することによって電流分布を均一化する工夫を行っており、これによって初めて安定な通電が保証できる。フィラメントのないテープ線材を単純積層した導体構造では、線材間で電流分布の不均一が生じると考えられ、それが安定性の劣化を起こすことが懸念される。

そこで、本研究では、まず従来の LTS 導体において電流分布の不均一が冷却安定性に対して与える影響について詳しく調べるところから研究を開始した。このためにケーブルインコンジット型強制冷却導体を用いて人為的に電流分布の不均一を導入する実験を行ったところ、電流分布が不均一になるほど安定性が低下することについて、その関連性を大型導体として世界で初めて定量的に明確にすることに成功した。一方、HTS 導体では動作温度を高く設定できるため、導体の構成材料自体が有する大きな比熱によって本質的に安定性が高いと期待できるが、実際にこのことを検証することは重要である。そこで、HTS 導体を実際に製作する前にこのことを確かめるため、LTS／HTS（Bi-2223）ハイブリッド導体という世界で初めて提案した導体を活用することによって、HTS 部分に対して極端に不均一な電流分布を与える実験を行った。この導体では、積層した HTS 線材間の接触抵抗を小さくする構造を採用していることもあり、電流分布の不均一に起因する不安定性が生じないことを確かめた。この実験結果をもとに単純積層構造の大電流容量 HTS 導体が構成できる可能性を提案し、導体設計の自由度が上がることを示した。次に、実際に 10 kA 級の HTS（Bi-2223）導体サンプルを試作し、温度を 4.2 ～30 K の範囲で可変にする工夫をして特性試験を行った。その結果、素線の特性をもとに磁場分布を正確に考慮して予測される臨界電流まで安定に通電でき、導体製作に伴う劣化が生じないこと、また、局所的な熱擾乱を与えるヒータを用いて安定性試験を行ったところ、ヘリウムで直接冷却された LTS 導体に比べて一桁以上大きなパワーを入れてもクエンチが生じないことを観測した。

最後にこれらの結果をもとに、FFHR を想定した 100 kA 級導体の設計を行った結果、優れた特長を有する従来にない発想の導体構造が設計できることを示した。ステンレス製の厚肉ジャケットの中にテープ形状のイットリウム系線材を高さ方向に

薄く積層した構造とすることで、コイル巻線時に想定される歪みを最小限に抑える設計となっている。一方、線材内および線材間に誘起される磁気遮蔽電流が誤差磁場として及ぼす影響について検討を行ったところ、実効的な電流中心の移動による磁場変化が必要磁場精度に対して小さく、許容範囲内であることを示した。また、導体は間接冷却によって十分に冷却できることも計算で示している。今後の HTS 導体の研究としては、これらの項目についてさらに具体的な実験や数値計算を通して詳細な検討を行うことにより、最適な導体およびコイル構造を提案していくことが課題として考えられ、本研究によりその方向性を示すことができている。

以上の結果はいずれも新規性および発展性が高く、本論文は学位論文として十分価値があると判断し、審査委員全員一致で合格とした。