ENERGY DISSIPATION OF COMPOSITE MULTIFILAMENTARY SUPERCONDUCTORS FOR HIGH-CURRENT RAMP-FIELD MAGNET APPLICATIONS

by

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ABSTRACT

Energy dissipation, which is also called AC loss, of a composite multifilamentary superconducting wire is one of the most fundamental concerns in building a stable superconducting magnet. Characterization and reduction of AC losses are especially important in designing a superconducting magnet for generating transient magnetic fields. The goal of this thesis is to improve the understanding of AC-loss properties of superconducting wires developed for high-current ramp-field magnet applications. The major tasks include: (1) building an advanced AC-loss measurement system, (2) measuring AC losses of superconducting wires under simulated pulse magnet operations, (3) developing an analytical model for explaining the new AC-loss properties found in the experiment, and (4) developing a computational methodology for comparing AC losses of a superconducting wire with those of a cable for a superconducting pulse magnet.

A new experimental system using an isothermal calorimetric method was designed and constructed to measure the absolute AC losses in a composite superconductor. This unique experimental setup is capable of measuring AC losses of a brittle Nb3Sn wire carrying high AC current in-phase with a large-amplitude pulse magnetic field. Improvements of the accuracy and the efficiency of this method are discussed.

Three different types of composite wire have been measured: a Nb3Sn modified jelly-roll (MJR) internal-tin wire used in a prototype ohmic heating coil, a Nb3Sn internal-tin wire developed for a fusion reactor ohmic heating coil, and a NbTi wire developed for the magnets in a particle accelerator. The cross sectional constructions of these wires represent typical commercial wires manufactured for pulse magnet applications.

Two types of field variation were of interest to this research: (1) a large peak-to-peak triangular cyclic field, and (2) a small sinusoidal wave-form (ripple) field superimposed on various large DC bias fields. The first field condition was used to simulate the ramp field operation of a pulse magnet. Superconducting wires were tested with and without transport current. The ripple field condition was adopted for approaching the ideal, constant critical current condition assumed in the existing AC-loss models. Only current-free wires were tested in this field condition.

In both test conditions, the AC losses must be calculated with a field-dependent critical current density profile which has not been explicitly included in the existing AC-loss models. The formulae of the existing hysteresis-loss and coupling-loss analyses were extended for the field conditions and the test wire cross sectional structures used in this work.
Single-strand AC loss test results were compared with analytical results using these modified loss models. Most calculated results agreed with the experimental data in two of the test wires. Existing AC-loss models were insufficient to explain the occurrence of a local maximum loss in a very low frequency regime in the ramp-rate dependent loss profile of the Nb₃Sn MJR wire.

An inter-bundle coupling loss model has been developed as the first analytical AC-loss model attempting to understand the loss mechanism of this newly found phenomenon. The proposed model has succeeded in explaining the occurrence of the local maximum loss at a slow ramp rate and simulating the trend of the loss profile as a function of the ramp rate. This was achieved by accounting for the collective coupling current effects caused by non-uniform cross sectional construction of the MJR wire.

The measured AC losses of single-strand carrying transport current are not consistent with the predictions by existing loss models, even when a field-dependent critical current density is applied in the calculation. The experimental results show that when a DC or an AC current is applied to a composite superconductor under ramp field condition, the additional AC losses caused by transport current are similar if \( I_{DC} = I_{AC,\text{max}} \). The test results also reveal that the total loss of a composite wire carrying large transport current may have a higher loss in a slowly ramped field than that in a fast one. This conclusion is just opposite to the general concept that high time-rate of field variation generates high AC losses. These new AC-loss properties of a current-carrying composite wire have been experimentally identified in all three types of test wire. These general phenomena may lead to a new area for future analytical work.

The United State Demonstration Poloidal Coil (US-DPC) is a prototype ohmic heating coil designed as a development step in pulsed superconducting magnet technology. One of the major goals of the US-DPC experiment was evaluating AC losses of the coil at ramp field operation up to 10 T at 10 T/s. AC losses measured in the large-scale US-DPC test were compared with those of constituent US-DPC wires tested in the laboratory-scale experiment. Due to the distinctly different field conditions of these two experiments, the comparison was mainly performed on the calculated AC-loss parameters. Good agreement in these AC-loss parameters was found. A prediction method for AC losses in a full-size cable has been developed out of the loss comparison process. The practical scheme uses the formulae applied in this work combined with the required parameters evaluated from the laboratory-scale single-strand experiments. This prediction method is one of the most important application of this thesis work.

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