Abstract

This thesis investigates the modelling and performance estimation of high-temperature superconductors in rotating electrical machines. Conventional ferromagnetic and superconducting materials are characterized, and methodologies are developed for accurate and time-efficient finite element modelling. These calibrated models are then used to evaluate the performance of HTS coils in armature windings of electrical machines.

This work uses finite element models employing the $T-A$ formulation with the thin sheet approximation to predict the performance of coated superconductors (Rare Earth Barium Copper Oxide tapes) in different operating conditions. Experimental activities were conducted on a 2^{nd} generation coated superconductor to calibrate and validate the electromagnetic models. The experimental setups for AC and DC supply measurements (77 K) were investigated and constructed.

Tests with DC supply were performed to measure the non-linear resistivity characteristic of the superconductors and their transition from the superconducting to the resistive state. Under AC supply, the hysteretic behaviour and AC loss characteristics of HTS materials were observed. Material parameters from these experiments were integrated into the models to represent superconducting behaviour accurately. The experimental and simulation results were used to develop an analytical method for transport loss estimation for superconducting tapes operating in the overcritical regime (I>I_c) when the superconducting layer manifests resistivity and losses in the copper stabilizing layers become impactful. A 2D $T-A$ electromagnetic multi-layered tape model was also proposed to estimate the coated conductor losses. Simulation results were compared to homogenized models, as well as analytical results and experimental data, showing good agreement for transport current and magnetization loss calculations. To better describe materials in electrical machine simulations, experiments were performed in different ferromagnetic samples at ambient and cryogenic temperatures to accurately characterize the properties of ferromagnetic materials in alternate operating conditions. The results were applied to calibrate multiphysics models of ferromagnetic cores in rotating electrical machines.

The measured material characteristics were applied to the 3D model of a case-study axial flux permanent magnet machine to estimate superconductor losses. Due to the different dimensional scales and non-linearities that have to be considered when modelling superconductors in complex electromagnetic devices, the simulations are highly demanding and, therefore, incompatible with electrical machine design methodologies. Hence, the synchronous machine 3D model was used to construct a 2D model of a machine slot for faster analyses in the superconducting tapes. The model is based on replicating the machine armature slot magnetic field in a 2D environment, where the superconductor formulations are added, significantly reducing model computation time and complexity. The proposed methodology was validated through comparison with a 3D model and analytical results available in the literature. The 2D model was used to estimate losses for spiral copper-plated striated coated conductor cables, which, due to their low AC losses, high current carrying capacity and mechanical flexibility, show promise for application in electrical machines. The losses in the SCSC cables are compared to those for REBCO tapes, and their applicability in electrical machine armature windings was demonstrated by the reduced impact of external field direction on cable losses. A complementary thermal slot model was developed to estimate superconducting armature windings' cooling requirements and efficiency. An experimental setup was designed to calibrate and validate the thermal model, showing good agreement between experimental and simulation results.