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Power dissipation and energy transfer during testing of the ITER toroidal field model coil

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Abstract

The testing of the ITER toroidal field model coil (TFMC) in the background field of the EURATOM-LCT coil took place in autumn 2002 at the TOSKA facility of the Forschungszentrum Karlsruhe in the framework of the ITER R&D programme. The maximum currents in the two coils, in combined operation, were 16 kA in the LCT coil and 80 kA in the TFMC, respectively. The heat load of both coils, including the eddy current losses in the passive structures and the joule losses due to the joint resistances, was removed by a secondary loop of forced flow supercritical He. About 2% of the stored energy was transferred to the cryogenic system after all the safety discharges of both coils together. Most of the energy (about 98%) was extracted and transferred to the dump resistors of both coils, located outside the vacuum vessel. A computer code, based on the full inductance and resistance matrices, has been developed with SIMULINK^{TM}. After validation with experimental data the code has been used to perform circuit analysis and to evaluate the power dissipation and energy transferred to the cryogenic plant and to the external power circuits.

Keywords: Power dissipation; Eddy currents; Safety discharge; LCT; TFMC; SIMULINK model

1. Introduction

Toroidal field model coil (TFMC) is a large race-track shaped model coil of 31 tonnes of weight and 98 turns, built to test the design principles of the ITER TF coil system [1]. The coil is made of circular Nb_3Sn forced-flow (FF) cable in conduit conductor inserted in a thin steel jacket placed into spiral grooves of 316NL stainless steel radial plates (Fig. 1) to form five double pancakes inserted in a case made also of 316LN stainless steel sheet 70–90 mm thick. The EURATOM-LCT coil is a “D-shaped” coil of 39 tonnes of weight, made of 588 turns of flat FF cooled NbTi cable in conduit conductor and seven double pancakes inserted in a 316NL stainless steel case 35–50 mm thick.

The TFMC coil is fed by two ac–dc converter power supplies, nominal currents 30 and 50 kA and ±35 V nominal voltage, connected in parallel [2]. Two especially designed He FF cooled current leads, installed into two separate vacuum vessel extensions, positioned

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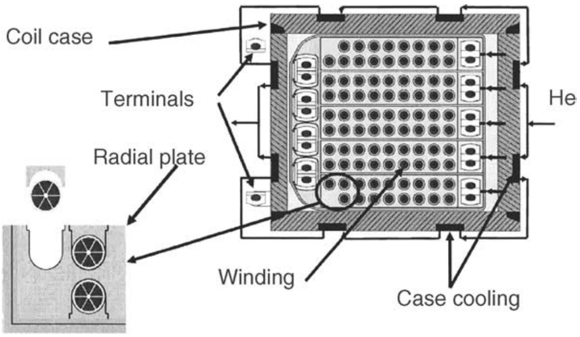

Fig. 1. TFMC cross-section.

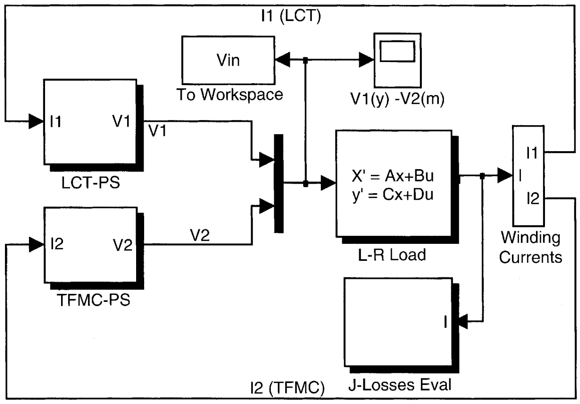

Fig. 2. SIMULINK code block diagram.

vertically, connect the power supplies to the coil via flexible cables and water-cooled bus bars. The LCT coil is fed from a similar power supply with nominal current of 20 kA through two current leads, mounted in horizontal position.

Eddy currents are generated during transients in the passive structures (e.g. stainless steel radial plates and coil cases), which are magnetically coupled to the coil windings, leading to eddy current losses [3]. Eddy current losses are also generated during current flat top due to the ripple of the power supplies [4].

A 2 kW He refrigerator was used to cool down the test configuration and the four current leads to 4.5 K. At the start of the cool down the cooling power was around 7 kW and decreased at the end to 2 kW. At the end of the cool down the secondary cooling loop was pressurised to supercritical conditions. An additional refrigerator of 500 W was used to provide additional cooling for the operation of the LCT coil up to 16 kA [1].

The evaluation of the eddy currents and the corresponding joule losses in the two coil cases and in the TFMC radial plates has been performed with an "ad hoc" computer code based on the full inductance and resistance matrices. Two lumped parameter models have been used also to simulate the power supplies and their current controllers. The outputs of the code have been compared with experimental data, obtained from current, voltage, temperature and pressure transducers, both during transient and steady state conditions. The code has been used to simulate various operating scenarios and joule losses transferred to the cryogenic plant, to the water-cooling plant and to the external power circuit during inverter mode and fast discharges.

2. SIMULINK code

The computer code, developed with SIMULINK^{TM}, is based on four main modules (Fig. 2): the Electric Load, consisting of coils, current leads, dump circuits and busbar systems; the two Power Supplies modules (LCT-PS and TFMC-PS), inclusive of their current controllers, and the joule Losses Evaluation module that calculates the power and energy losses on the passive elements.

2.1. Electric load

The horizontal axes of the two coils are not parallel to each other but they form an angle of 4.5°. The absence of ferromagnetic materials in close proximity and the hypothesis that the two coils do not move justify the use of a linear time-invariant model (LTI) for the two coils. Denoting with $I_1(t)$ the current in the LCT coil winding, $I_2(t)$ the current in the TFMC coil windings, $I_3(t)$, $I_4(t)$ and $I_5(t)$ the eddy currents in the LCT coil case, in the TFMC plates and in the TFMC case, respectively, and with $V_1(t)$ and $V_2(t)$ the voltages of the 20 and 30//50 kA power supplies, the electric load can be represented by the following linear differential equation:

$$L\frac{\mathrm{d}I(t)}{\mathrm{d}t} + RI(t) = V(t) \quad (1)$$

where $I = [I_1, I_2, I_3, I_4, I_5]^T$ is the vector of currents, $V = [V_1, V_2]^T$ the vector of the power supply voltages, L the inductance matrix (5×5) and R the resistance