Fusion Engineering and Design 89 (2014) 115–121

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Thermo hydraulic and quench propagation characteristics of SST-1 TF coil

A.N. Sharma[a,*], S. Pradhan[a], J.L. Duchateau[b], Y. Khristi[a], U. Prasad[a], K. Doshi[a], P. Varmora[a], D. Patel[a], V.L. Tanna[a]

[a] *Institute for Plasma Research, Gandhinagar, India*
[b] *CEA Cadarache, 13108 St Paul lez Durance Cedex, France*

HIGHLIGHTS

- Details of SST-1 TF coils, CICC.
- Details of SST-1 TF coil cold test.
- Quench analysis of TF magnet.
- Flow changes following quench.
- Predictive analysis of assembled magnet system.

ARTICLE INFO

Article history:
Received 20 August 2013
Received in revised form 12 October 2013
Accepted 23 December 2013
Available online 25 January 2014

Keywords:
SST-1
TF coil
Quench
Normal zone
Gandalf
Two phase and supercritical helium

ABSTRACT

SST-1 toroidal field (TF) magnet system is comprising of sixteen superconducting modified ‘D’ shaped TF coils. During single coil test campaigns spanning from June 10, 2010 till January 24, 2011; the electromagnetic, thermal hydraulic and mechanical performances of each TF magnet have been qualified at its respective nominal operating current of 10,000 A in either two-phase or supercritical helium cooling conditions. During the current charging experiments, few quenches have initiated either as a consequence of irrecoverable normal zones or being induced in some of the TF magnets. Quench evolution in the TF coils have been analyzed in detail in order to understand the thermal hydraulic and quench propagation characteristics of the SST-1 TF magnets. The same were also simulated using 1D code Gandalf. This paper elaborates the details of the analyses and the quench simulation results. A predictive quench propagation analysis of 16 assembled TF magnets system has also been reported in this paper.

1. Introduction

Steady-state superconducting tokamak (SST-1) is designed for steady state operation, in both the single null and the double null configuration [1]. SST-1 has superconducting toroidal field (TF) and poloidal field (PF) magnet system. As a mandate of SST-1 mission, each TF coil is necessarily to be cold tested to its full operating conditions. This decision was reasonable as in a superconducting steady state tokamak configuration, the access to TF magnets for repair is very limited. The replacement of an assembled TF magnet may involve partial or full dismantling of the machine. Thus, each SST-1 TF magnet was consciously tested for its electromagnetic, thermal hydraulic and mechanical performances at its full operating current in either two-phase or supercritical cooling conditions and has been qualified prior to its assembly on SST-1 machine shell. Quenches observed during these single coil test campaigns were analyzed in detail in order to understand its thermal hydraulic and quench propagation characteristics. Some of the quenches have also been also simulated using 1-D code Gandalf [2].

2. SST-1 TF magnet system

SST-1 TF magnet system consists of 16 superconducting, modified ‘D’ shaped coils arranged symmetrically around the major axis spaced 22.5° apart. It is designed to give magnetic flux density of 3.0 T at plasma axis with ripple <2% within the plasma volume at its nominal operating current of 10,000 A. Each TF coil is made up of 6 double pancakes (DP) with each pancake having nine turns. The base conductor for these magnets is the cable-in-conduit

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[*] Corresponding author. Tel.: +91 79 23962164; fax: +91 79 23962277.
E-mail addresses: ansharma@ipr.res.in, aashoo.sharma@yahoo.com (A.N. Sharma).

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http://dx.doi.org/10.1016/j.fusengdes.2013.12.058

Table 1
Technical details of SST-1 TF magnet system.

Number of coils	16	Outer dimensions (radial)	1560 mm
Shape	Modified D	Outer dimensions (vertical)	2120 mm
Turn per coil	108	Average turn length	5500 mm
Double pancakes per coil	6	Weight of one TF coil	1920 kg
Rated current	10 kA	Centering force per coil	2.73 MN
Field at plasma axis	3.0 T	Tension in the coil	90–110 MPa
Maximum field	5.1 T	Total inductance	1.12 H
Maximum field ripple	<2%	Total stored energy	56 MJ
Bore dimensions (radial)	1190 mm	Dump time constant	12 s
Bore dimensions (vertical)	1746 mm	Peak dump voltage	±600 V

conductor (CICC) described in next section [3]. The main parameters of TF coils are summarized in Table 1. The winding pack is shrunk fitted into a SS316 L casing. All coils are connected in series and are protected against quench by suitable quench detection and protection system [4–6]. The straight legs of TF coils are wedged to form the inner vault to support the centering forces. The outer vault is formed by connecting outer inter coil structures (OICS) between the TF coils to resist the overturning torque experienced by the TF system from interaction with PF coils and plasma.

The magnet winding pack is cooled by two phase helium or Supercritical Helium at 0.4 MPa and supply of 4.5 K. The nominal mass flow rate for each TF coil is 16 g/s. Cold helium is fed from the high field region of the magnet. For this purpose, inlet stubs have been welded to the double pancakes from the inner side of the winding pack.

Originally, it was envisaged to cool the TF casings with cold helium flowing in SS tubes soldered on the coil casings. However this idea was abandoned due to multiple leaks observed in these tubes. Indigenously developed SS316L single sided bubble panel type supercritical helium cooled radiation shields were developed to introduce case cooling. These were welded to the inner ring of the TF coil case. These panels were also cold tested along with the TF magnets and were found to be helium leak tight offering very low pressure drops. Fig. 1 shows a pair of TF coil with OICS, joints, manifolds and the super critical helium cooled radiation shield.

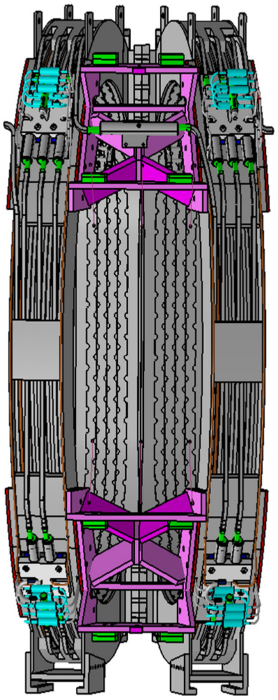

Fig. 1. SST-1 TF coil pair.

3. SST-1 CICC

SST-1 TF and PF magnets are made using identical NbTi/Cu based CICC. Its main features are given in Table 2. Each strand of CICC has about 1224 ± 30 hexagonal NbTi filaments. Its twist directions, in all stages, are anti clockwise (Z) and the pitches may vary within ±10% of the specified nominal values. The last stage bundled cable was wrapped with 25 micron SS 304 foil with 50% overlap. The void fraction in the cable space, measured at random intervals along the length of the cable was 40 ± 2%.

The choice of SS304L as the conduit material and its 1.5 mm thickness was motivated from the requirements that the conduit shall also be used as a load bearing structure inside the winding pack where the operating stresses may be as high as 300 MPa at cryogenic temperature. Structural analysis of TF coils under electromagnetic loads has been presented in [7].

Before mass production of SST-1 CICC by manufactures, a model coil (MC) test was done to validate the feasibility of using same type of NbTi based CICC for both TF and PF coil windings [8]. MC had double pancake type windings with hydraulic path lengths, flows and currents similar to SST-1 TF and PF magnets. Transient background fields were generated in longitudinal and transverse directions by separate solenoids. To validate CICC appropriateness for steady state operation of TF coils, MC was slowly charged up to 12,000 A corresponding to 6.2 T of maximum self field, with mass flow rate of 0.5 g/s. No quench was observed in this test. To demonstrate CICC suitability in all expected operational loads during different plasma operation stages and events like disruptions, background field solenoids were used to generate disturbances in parallel and transverse directions. Simultaneous ac parallel and transverse disturbances were applied to MC to simulate possible disturbances from feedback control coils during SST-1 operation. It was found that at 10 kA and 1.2 g/s CICC can withstand pulsed longitudinal disturbances up to 0.29 T as against the design value of 0.27 T corresponding to 330 kA plasma current is SST-1. CICC can withstand sinusoidal disturbances of amplitude more than 25 mT of 125 ms duration in any orientation. Fast ramp rate operational feasibility of CICC was demonstrated by charging MC with ramp rates corresponding to 2 T/s at mass flow rates of 0.8–0.9 g/s. Current sharing temperature was measured to be about 6 K at 10 kA (5.1 T) operation. Controlled quench tests using resistive heaters were done at different operating currents of 6–10 kA. The energy margin at 6 kA is about 0.75 MJ/m^3. Measured normal zone propagation speed was observed in between 1.3 and 2 m/s during these tests. Following the encouraging results as per the design values, SST-1 CICC mass production was allowed at the industry.

4. TF coils test program

In a tokamak configuration, access to TF magnets for repair is very limited and its replacement may involve partial or full dismantling of machine. So each TF magnet was tested for its electromagnetic, thermal hydraulic and mechanical performances at its