Fusion Engineering and Design 100 (2015) 287–292

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Simulation study of induced EMFs and the suppression during SST-1 start-up

V. Jain*, D. Sharma, A. Vardhrajulu, C.N. Gupta, R. Srinivasan, R. Daniel

Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India

HIGHLIGHTS

- Induced EMFs study in PF coils during SST-1 start up using MATlab simulink.
- Integration of wave shaping network to generate practical OT current profile.
- This study would protect coil insulation with identifying RC circulating network.
- Study of MOV technique for circulation of current through RC.

ARTICLE INFO

Article history:
Received 11 February 2015
Received in revised form 11 June 2015
Accepted 18 June 2015
Available online 1 August 2015

Keywords:
SST-1
Induced EMF
Voltage suppression

ABSTRACT

Steady State Superconducting Tokamak (SST-1) comprises of various copper and superconducting coils for generating magnetic field for initiation, providing equilibrium and shaping of plasma in tokamak. In this paper, an attempt is made to study the induced EMF in superconducting poloidal field coils (PF coils) due to fast ramp down of current in ohmic transformer copper coils (OT coils) for SST-1 plasma initiation. The fast ramp down of current, from few kA to zero amperes in just 50–100 ms in OT coils, is required to achieve plasma breakdown and ramp up of plasma current in tokamak. However, it induces nearly 5 kV EMF in one of the SST-1 PF coils that can damage the coil insulation and also bias negatively the electronic switching of power supply. It is necessary to maintain induced EMF below 1 kV in all PF coils for safe operation of SST-1. The induced EMF up to 1 kV can be clamped without any need of protection and circulating current. If the induced EMF is in excess of 1 kV, then it has to allow the circulation of current through RC network for coil protection from overvoltage. These circulating currents in PF coils will affect the shaping of plasma. In this paper, the induced EMF in PF coils are simulated using MATlab simulink for a typical SST-1 current profile of OT coils. Further, this simulation study is used to design the protection system for PF coils. In this paper, the worst-case induced EMF scenario is considered by excluding the effect of passive elements like vacuum vessel and cryostat on mutual coupling parameters. However, the implementation of the EMF suppression scheme need more elaborated study with considering the accurate penetration depth of vacuum vessel, which will reduce the induced EMF in PF coils. The effect of circulating current on equilibrium and plasma shape is estimated and a scheme to correct this by driving current in one of the PF coils is developed.

1. Introduction

Plasma in SST-1 is initiated using ohmic transformer copper coils (OT coils) comprised of a central solenoid (TR1) and three pairs of coils (TR2 to TR4). These coils are arranged in different geometrical space around the tokamak vessel [1,2]. SST-1 has one mid plane superconducting coil (PF1) at the inboard side and four pairs of superconducting coils (PF2 to PF5). PF coils are used to provide shaping and equilibrium of plasma for SST-1 during steady state operation. The targeted plasma current in SST-1 is 220 kA. PF coil current is changed at slow rate to avoid quenching and hence, these coils are not used for plasma start-up. During the startup, a pair of vertical field copper coil (VF coil) is used to provide equilibrium for circular plasma. OT coils are used for plasma start-up which are charged up to 12 kA and then discharged rapidly by a wave shaping network and a current circulation system in order to initiate plasma in tokamak. Later, lower hybrid current drive (LHCD) will sustain the plasma current for steady state operation and PF coils

* Corresponding author.
E-mail address: vishal@ipr.res.in (V. Jain).

http://dx.doi.org/10.1016/j.fusengdes.2015.06.087
0920-3796/

will provide shaping and equilibrium. There are two transitions namely (1) ohmic current drive to LHCD for steady state operation, (2) VF coil to PF coils for providing plasma equilibrium. There are 16 superconducting toroidal field coils (TF coils) in SST-1 which are surrounding the tokamak vessel to produce the required toroidal field (up to 3 T) at the plasma center. The PF and TF coils are operated at 4.5 K and their performance reliability will depend on the cooling system [3,4]. OT coils of SST-1 has mutual coupling with PF coils [5] and hence, induced EMF are expected in these PF coils due to fast ramp down of current in OT. The mutual coupling between coils mainly depends on the geometrical closeness of PF coils to OT. Induced EMF in these coils can be harmful if it crosses the insulation limit of 1 kV. Under such condition, coils can be protected only by limiting induced EMF either by its suppression of EMF or by limiting the ramp rate of current in OT. Limiting the OT current ramp rate can affect the start up procedure of plasma in tokamak. Therefore, induced EMF suppression through some schemes is important in SST-1 to avoid huge stress on PF coils insulations and possible damages. The induced EMF in PF coils also negatively bias the power supply [6] which ultimately puts a constraint on power supply for operating the coil with a prescribed current profile. This will affect the plasma generation since the prescribed current profile in PF coils is crucial for maintaining appropriate shaping and equilibrium of plasma. The simulation study of this kind is necessary for designing power supply and obtaining the electrical parameters for practical purposes [7]. SST-1 PF system has flexibility to provide equilibrium over a wide range of plasma parameters [8]. VF coil is designed to provide equilibrium for ohmic phase (up to 100–200 ms) without considering circulating current in PF coils and this calculation has to be revisited in case of circulating currents.

A simulation study to quantify the induced EMF in PF coils is performed by considering the practical OT current ramp down. A wave shaping network comprises of switching units which are turned on or turned off at different interval of time is used to simulate the required current ramp down in OT from 12 kA to zero in few tens of milliseconds. A proper mechanism has to be adopted to suppress induced voltage in PF coils.

In one of such techniques, anti-transformer is used which has its primary connected to OT and secondary connected to PF coil that needs to be powered by the power supply. Induced EMFs in secondary of this anti-transformer is almost equal in magnitude and of opposite phase to induced EMF in PF coil. Hence, the algebraic sum of induced EMF across the power supply terminal is nullified. However, this technique cannot limit the induced EMF in PF coil below the safe limit of 1 kV. Further, the huge size of anti-transformer puts a constraint on infrastructure.

In this paper, the MOV (Metal Oxide Varistor) surge protection scheme in PF coil has been studied. In this scheme, a surge current is rapidly circulated through a RC network connected across the PF coils through a thyristor that is triggered through MOV for induced voltage above the trigger limit of MOV. Hence, this circulating current will ensure the voltage across the coil within safe limit. However, the circulating current will affect the magnetic topology and also put a magnetic stress on PF coils [9].

Section 2 of this report describes about SST-1 plasma equilibrium in presence of circulating current. Section 3 of this report gives idea about wave shaping network and current waveform through OT. Section 4 shows the comparison of OT current waveform with the designed practical current profile in SST-1. Section 5 describes the Induced EMF profile in all PF coils in order to give idea about the peak induced voltage in case of no suppression. Section 6 describes about two different suppression techniques. Section 7 elaborates about the selection of MOV parameters for simulation purpose. Finally discussions on results are presented.

Table 1
Plasma parameters for equilibrium in Fig. 1.

Output	Fig. 1(A)	Fig. 1(B)	Fig. 1(C)
R_0 (m)	1.077	1.064	1.063
A (m)	0.207	0.194	0.193
β_p	0.13	0.14	0.16
δ	0.075	0.143	0.140
k	1.042	1.228	1.170
l_i	0.78	0.83	1.15

2. SST-1 shaped plasma equilibrium in presence of circulating current

The earlier study of SST-1 plasma equilibrium during steady state operation is reported in [8]. In this calculation, circulating current is not considered as these coils are energized only during the LHCD phase. In the present situation, Due to reduced allowable limit on induced EMFs in PF coils, the circular plasma equilibrium during ohmic phase has to be constructed along with circulating currents. For this study, only PF4 is used to drive a prescribed current so that the circular plasma equilibrium can be achieved even with circulating currents in other PF coils.

A typical 100 kA plasma scenario is considered for this study. The PF3 coil coupling with OT is very significant and expected to carry large current. A parametric study is carried out with this coil by changing PF3 coil current and finding the requirement on PF4. This has clearly showed that up to 0.5 kA per turn of circulating current in PF3, the circular equilibrium can be achieved only with VF coils as planned earlier. If the circulating current is more than 0.5 kA, a reasonably small current in PF4 can bring back the plasma equilibrium. Fig. 1(A) corresponds to case with no circulating currents. Fig. 1(B) shows the scenario in presence of circulating current and the plasma shape is elongated one. Fig. 1(C) shows the circular plasma by driving 5 kAt current in PF4 along with circulating current in PF3 of about 2 kA per turn. Table 1 shows plasma parameters for this equilibrium. Hence, the voltage suppression scheme should ensure the current limit as well the voltage limit.

3. Circuit model for OT coils driver current

In SST-1, OT acts like driver for plasma generation and therefore, OT parameters has to be included into the electrical model to produce the experimental current profile as accurately as possible. For this reason, wave shaping network is built and its performance is compared with practical OT coil current waveform in SST-1.

The position of TR coils, PF coils and VF coils in SST-1 are shown in Fig. 2(A). TR coils comprises an OT system.

TR and VF coils are copper coils. The OT system is charged up to 12 kA typically and operated regularly. The TR1 and TR2 coils are efficiently coupled with PF3 due to close proximity and this can be seen in Fig. 2(A). Simulation with 12 kA charging current profile in OT, shown in Fig. 2(B), is generated by wave shaping network (Fig. 3). The operation of wave shaping network in simulation is described as follows:

1. The direct switch is opened at 1.25 s with bypassing the DC power supply with another switch (not shown in figure) for starting the current ramp down in OT. This current ramp down is governed by the resistor and self inductance of SST-1 OT coil (Table 2) and capacitor (1000 μF) for first 10 ms.
2. After 10 ms, three resistors (0.2, 0.5 and 0.38 Ω) immediately take over the current from capacitor. These resistors are bypassed one by one at specific time interval in order to get the specified ramp down of current close to practical current profile of SST-1 OT.