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Design of The Magnetic System of Pakistan Spherical Tokamak (PST) for Steady State Operation

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Spherical Tokamak research gained attention due to natural elongation, high β (∝1/A) and being economical. Pakistan Spherical Tokamak (PST) is in the conceptual and physics design phase. It is a medium size tokamak and some of its basic parameters are; major radius R = 0.5 cm, minor radius a = 0.25cm, Aspect ratio A = 2.0, Elongation κ = 2.0, Toroidal Magnetic Field BT=0.5T. Purpose of this device is to explore plasma parameters for Steady State Operation in the limit of aspect ratio (A=2) for spherical tokamak. In addition to ohnic heating, ECR heating and LHCD will be implemented .There are mainly three coils systems in tokamak; central solenoid (CS) along with compensation coils (CC) used to produce toroidal E-field, poloidal field (PF) coils to keep the plasma in equilibrium and away from the tokamak walls, and toroidal field (TF) coils to stabilize the plasma. Toroidal magnetic field has importance due to the fact that volumetric fusion power density varies with ~ B^4. For the fixed safety factor, plasma confinement improves with toroidal magnetic field strength [1]. It means that high toroidal magnetic field is desirable for both fusion power and plasma confinement. The present study concentrates on the design of magnetic coils system of PST considering plasma equilibrium in tokamak.

For the design purposes MHD safety factor qa = 2.5 is considered which is above the disruptive Kink safety limit [2]. With this safety factor and toroidal field, the plasma current is estimated as 310 kA. Similarly plasma beta is estimated as 9%. Further to meet the volt-sec requirement, current in CS is estimated. Using all these parameters in TOKSCEN code, equilibrium is generated to estimate location, current and number of turns in compensation and poloidal field coils.

Demountable, water cooled, copper made, Toroidal field coils with twisted center stack are proposed which helps in easy joints and provide additional loop voltage for start-up. The twisted inner leg adds novelty in the toroidal coils design [3-4]. Demountable TF coil design gives installation, operational and maintenance flexibility [5]. Two different configurations of TF coils are used as case study. In one configuration single layer 16 turn equi-spaced coils are used whereas in other configuration 12 turn double layer equi-spaced coils (12x2) are used. The desired toroidal field at the center of plasma (R = 50 cm) is 0.5 Tesla. These coils are powered by an external capacitive circuit having combination for fast capacitor (capacitance of 95 mF) and slow capacitor banks (capacitance of 62 F). The coils material is considered to be OFHC copper rod (99.99 %). In this study the ripple factor is calculated using FEM method for both TF assemblies by varying location of outer limbs of TF from 80 cm, 85 cm, 90 cm, 95 cm and 114.5 cm. In the 12 coils assembly, turns are closely packed in pairs for the purpose to have larger space for diagnostics ports. Ripple factor at the equatorial plane is simulated and given in the table below:
Comparison of parameters of the TF coil magnet having 16 and 12 (pairs) turns respectively.
No. turns of TF Physical parameters 114.5 cm 95 cm 90 cm 85 cm 80 cm
16 coils (16x1)
δ at plasma centre 10-4 10-4 10-4 10-4 0.001
δ at plasma edge 0.002 0.0135 0.031 0.063 0.176
Inductance (mH) 0.219 0.149 0.143 0.136 0.130
Flux (Wb) 17.17 11.658 11.182 10.683 10.202
Resistance (mΩ) 0.231 0.208 0.201 0.194 0.191
Mass(kg) 4865 3736 3655 3584 3494
12 coils (12x2) δ at plasma centre 10-4 10-4 0.001 0.0016 0.0028
δ at plasma edge 0.0059 0.0445 0.078 0.144 0.300
Inductance (mH) 0.505 0.339 0.325 0.311 0.296
Flux (Wb) 26.324 17.658 16.911 16.203 15.443
Resistance (mΩ) 0.704 0.555 0.549 0.541 0.522
Mass(kg) 4076 3109 3055 3001 2929

Results of the simulation show that the ripple factor for 12 coils (12x2) is slightly higher than that for the 16 coils system due to more space between the coils. But its values lie within the safe limit means that 12x2 provide sufficiently low ripple factor which can significantly reduce the particle lose to the walls in the radial direction.
We can also observe that Ripple factor for both coils systems decreases significantly with increase in the radius of outer limbs. From the energy consumption point of view, the 12 coils (12x2) requires only 52 kA/turn current while for 16 coils (16x1), it is 78 kA/turn to produce 0.5 tesla magnetic fields at the plasma centre. For both coil systems current density is 1.3 kA/cm2.

Simulation results for the poloidal distribution of ripples for 16x1 and 12x2 show important features of spherical tokamak that ripple is maximum at the mid-plane. On the top and bottom side of coils ripple is very small in both cases due to the fact that near top and bottom side coils gets closer to each other.

Furthermore under same condition the current has longer flat top for 12 coils (12x2) system. Hence the 12 coils (12x2) system is relatively more suitable for PST.

The results of simulation for plasma equilibrium, and ripple factor will be presented for the optimization of coil currents and their position

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