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FUSION-9502; No. of Pages 12
ARTICLE IN PRESS

Fusion Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Design of a pulse transformer for the ohmic heating system of a small tokamak

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HIGHLIGHTS

- Design and dimensioning of a solenoid and magnetic core for tokamak operation.
- Mathematical model including core saturation and hysteresis.
- Ability to model the use of inductive energy storage via the solenoid.
- Experimental benchmark of model in a small prototype.

ARTICLE INFO

Article history:
Received 21 March 2016
Received in revised form 18 March 2017
Accepted 4 May 2017
Available online xxx

Keywords:
Pulsed power
Current pulses
Pulsed transformer
Plasma heating
Small tokamaks

ABSTRACT

A design methodology of the ohmic heating and plasma current induction system for a small tokamak is presented, capable of inducing in a preionized gas loop an average current of 50 kA over a 20 ms pulse. The design tool consists of a mathematical model that reproduces the transient behavior of a transformer when the primary current is generated by the discharge of a capacitor bank. The model utilizes linked and coupled magnetic fluxes between windings, and includes core saturation effects, as well as the hysteresis effect. A prototype transformer, with known parameters, was used to validate the model. This numerical tool was used in the conceptual design of the ohmic heating system; two combinations of feed circuit and construction parameters were tested, and best results were obtained when the primary solenoid was fed from the discharge of a 540 μF capacitor bank charged to 11.7 kV. The parameters of the solenoid were also determined, taking into consideration size and weight constrains; the best solenoid turned out to be a single-layer, 238-turn, 0.42 m diameter and 1 m long straight solenoid, made with 12 AWG magnet wire. The required steel core has a cross section of 0.1039 m^2 and a weight of 4 tons.

1. Introduction

Nuclear fusion, as an energy source, is much cleaner than its fission counterpart since the main resulting “ash” from the burn is helium, an inert gas. The energy density of the process is extremely high and since hydrogen and its isotopes (one of them natural for first generation fusion reactors) are the fuel, issues of uneven global distribution or scarcity are virtually nonexistent [1,2]. One of the most successful configurations to achieve controlled fusion in the laboratory is the tokamak, a device able to confine very high temperature plasmas using a toroidal magnetic field configuration. Presently, there is an ongoing activity at CICATA-IPN aimed at restarting an old tokamak machine decommissioned a long time ago, in order to make the field grow in the country and contribute to larger fusion programs providing a test bed of new ideas as it has been done in other small machines [3]; this conceptual machine has been named TPM-1U and its most important parameters are mentioned elsewhere [4,5].

In the early days of nuclear fusion research, the first years of the 1950s, Sakharov and Tamm had the original idea of a closed magnetic confined system with toroidal geometry [6]. Early on during the development of their concept, the need for a stabilizing poloidal field was discovered; at the time, Sakharov suggested either a current circulating in the confined plasma column or an additional conductor. In the end, circulating current on the plasma was deemed more attractive because in addition to generating stability, it was an excellent mechanism of plasma heating, the so-called ohmic heating, which was the only means available in the early tokamaks before the development of microwave heating and neutral beam injection. It was soon realized the importance of having good magnetic coupling between the primary winding and the

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http://dx.doi.org/10.1016/j.fusengdes.2017.05.018
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Please cite this article in press as: F. Ceballos-Soto, et al., Design of a pulse transformer for the ohmic heating system of a small tokamak, Fusion Eng. Des. (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.05.018

Nomenclature

a	Solenoid radius
A_c	Conductor cross section
A_n	Core cross section
B_{max}	Maximum magnetic induction
C	Charging circuit capacitance
D_{max}	Maximum solenoid core diameter
e_{sheet}	Silicon steel sheet thickness
f	Correction function for saturation effects
h_b	Solenoid height
i_p	Solenoid current (primary)
i_s	Plasma current (secondary)
K	Inductance reduction factor
L_p	Solenoid vacuum inductance
L_m	Solenoid magnetization inductance
L_{dp}	Leakage inductance of the primary winding
L_{ds}	Leakage inductance of the secondary winding
N_p	Number of turns in the primary winding
N_s	Number of turns in the secondary winding
R_p	Solenoid winding resistance
R_s	Plasma resistance
t_{pulse}	Pulse duration
v_p	Solenoid applied voltage
v_s	Loop voltage
μ_r	Material relative magnetic permeability
μ	Material magnetic permeability
ϕ_{max}	Maximum magnetic flux
λ_p	Primary linkage magnetic flux
λ_s	Secondary linkage magnetic flux

plasma column to achieve high values of plasma current. All the soviet tokamaks developed at the Kurchatov Institute, including the famous T-3 tokamak, did have an iron core to achieve good magnetic coupling between the primary "central solenoid" and the plasma column. While some of the contemporary large-size tokamaks have gone via the air core route (Alcator-Cmod, TFTR, JT-60), some of them have opted for an iron core (JET, T-15, HT-7) [7]. In the realm of small tokamaks, many of the most successful ones such as COMPASS [8], CASTOR [9], STOR-M [10] and ISTTOK [11] are all tokamaks that incorporated an iron core. The addition of an iron core improves this coupling between the primary windings and the plasma; however, the core needs to be carefully designed and dimensioned, since the volt-seconds requirement of the discharge will tend to saturate the core and generate stray magnetic fields [7], as well as accounting for how its presence affects the overall magnetic field environment around the tokamak and hence the plasma equilibrium [12].

One of the key elements in the design of the small machine is the induction system, responsible for inducing a high current in the plasma, which creates the confining helical field when superimposed with the externally generated toroidal field, and also heats the plasma by Joule effect. The generation of this plasma current is achieved by the transformer effect: when a solenoid magnetically connected to the plasma receives a time-dependent current pulse, a magnetic field is generated according to Faraday's law; this magnetic flux travels on a silicon steel core to the secondary winding (the plasma) and a loop voltage is established. Since the plasma is short-circuited, a current is induced in it according to Lenz's law, also time dependent and limited by the plasma resistivity, which starts dropping as the temperature increases. The heat generated by Joule effect is transferred to the plasma, and in large machines the current is such that temperatures of millions of degrees Kelvin are routinely achieved in large modern devices using additional forms of plasma heating (electromagnetic waves and neutral beams) [13]. The tokamak transformer, in charge of both inducing the plasma current that creates the helical field and heat the plasma to high temperature via the Joule effect, can be designed with either an air-core or an iron-core. The main difference between the two alternatives is the amount of magnetic coupling between the central solenoid of the tokamak and the plasma loop. Recent studies have focused on the importance in working on the saturation region of iron cores, allowing to achieve the necessary plasma currents even without a central solenoid, utilizing external coils to achieve ohmic heating of the plasma; in this cases, the design of the transformer is even more critical and needs [14–16].

2. System requirements and restrictions

The goal of the ohmic heating system (OHS) described in the previous section is to achieve an average of 50 kA plasma current for the duration of a 20 ms pulse; such target values for plasma current and pulse length would put TPM-1U on par with other tokamak machines of similar size operating around the world [3]. This value of plasma current gives a magnetic safety factor of $q = 4$ at the expected plasma edge location for a central toroidal field of 0.5 T, which would make the confined plasma stable [17]. The con-

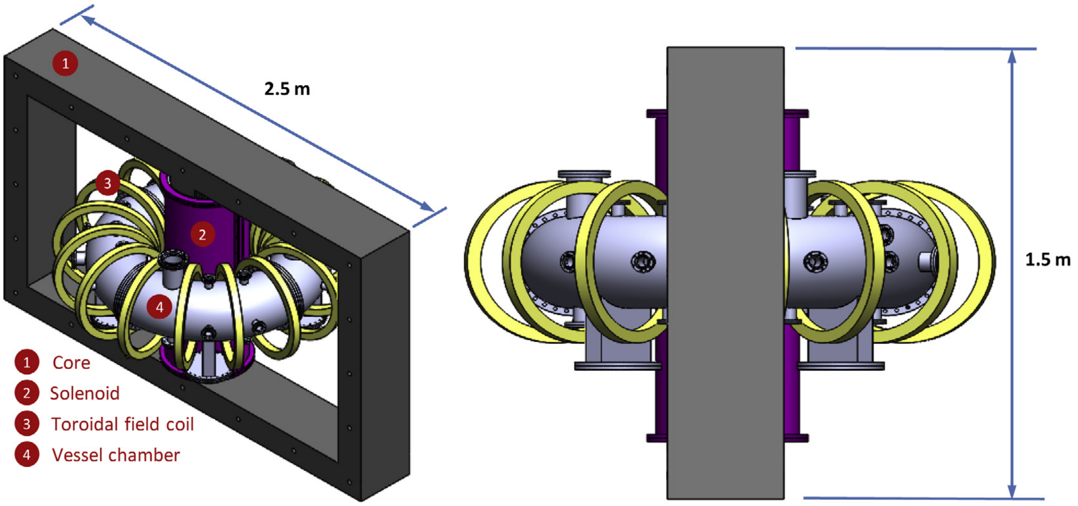

Fig. 1. Main components of the TPM-1U tokamak.

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