

Optimization of the PF coil system in axisymmetric fusion devices

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ABSTRACT

The tokamak is nowadays the most promising fusion device for the plasma confinement and the production of fusion energy. It exploits magnetic fields to confine plasma inside a torus shaped chamber. The magnet system of a tokamak device is mainly composed by Toroidal Field (TF), Central Solenoid (CS) and Poloidal Field (PF) coils. In this paper, a new approach is described for the optimization of the PF coil system. The proposed procedure allows to optimize the number, position and dimension of the PF coils reducing, at the same time, currents and forces on the coils while fulfilling the machine technological constraints. The method exploits the linearized relation between the plasma-wall gaps and the PF coil currents. The procedure effectiveness has been tested on the PF coil system of the ITER tokamak and exploited for the design and optimization of the PF coil system for the next generation tokamak DEMO, as shown in the last section of the paper.

1. Introduction

Nuclear fusion is one of the most promising way of obtaining energy supply in a clean and in principle inexhaustible way. The most advanced devices for hot nuclear fusion are tokamaks, toroidal axisymmetric structures where the plasma is magnetically confined due to the interaction with magnetic fields produced by the currents flowing in suitable coils placed around the chamber. The main project in this field is ITER [1], an experimental reactor that is under construction in France. At the same time, the pre-conceptual design phase towards the realization of DEMO [2,3], the first reactor producing net electricity for the grid, is already started.

The design of the CS/PF coil system of a tokamak is a complex problem due to the nonlinear relation between the plasma shape variation and the currents in the CS/PF coils. Moreover, a set of linear and nonlinear technological constraints related to the maximum current density, magnetic fields and vertical forces on the coils has to be satisfied. The previous considerations make the optimization of the number, position and dimension of the PF coils a challenging task in the design of the next generation fusion reactors. Different methods have been proposed in the literature for the optimization of the currents of the PF coils while keeping their positions fixed ([4–7]). Other methods try to optimize also the coil positions using nonlinear optimization procedures based on Newton's methods ([8–10]) or genetic algorithms [11].

In this paper, an optimization procedure of the PF/CS coil system is

proposed. Given a reference plasma scenario, the procedure focuses on the most critical configurations, typically those at start (SOF) and end of flat top (EOF), assuming that all the remaining equilibria are less demanding in terms of forces, currents and fields. This assumption should therefore be verified a posteriori. The procedure is able to optimize PF coils number, position and dimension guarantying all the machine technological constraints. This approach is an extension of the procedure used for the optimization of the PF coil currents in existing devices [12,13]. It is based on the linearization of the Grad-Shafranov (GS) equation for the plasma magneto-hydrodynamic (MHD) equilibrium evaluation around the desired plasma equilibrium ([14,15]); then an iterative quadratic optimization problem with linear and quadratic constraints is solved. In previous studies (e.g., [16]), the PF coil system optimization problem was mainly formulated as a LQ minimization problem. Such a formulation allowed taking into account the linear constraints only. The novelty introduced in this paper is the formulation of the problem as a quadratic minimization problem that allows taking into account also quadratic constraints, mainly related to the vertical forces acting on the coils.

The proposed solution, which dramatically simplifies the nonlinear computations needed for tokamak design, is currently being exploited for the optimization of the PF coil system in next generation tokamaks such as DEMO and DTT [17]. The present study arises from the need for a tool able to optimize the PF coil system reducing, at the same time, currents and forces on the coils. Since it is uncertain whether the conventional divertor solution, based on the single null magnetic

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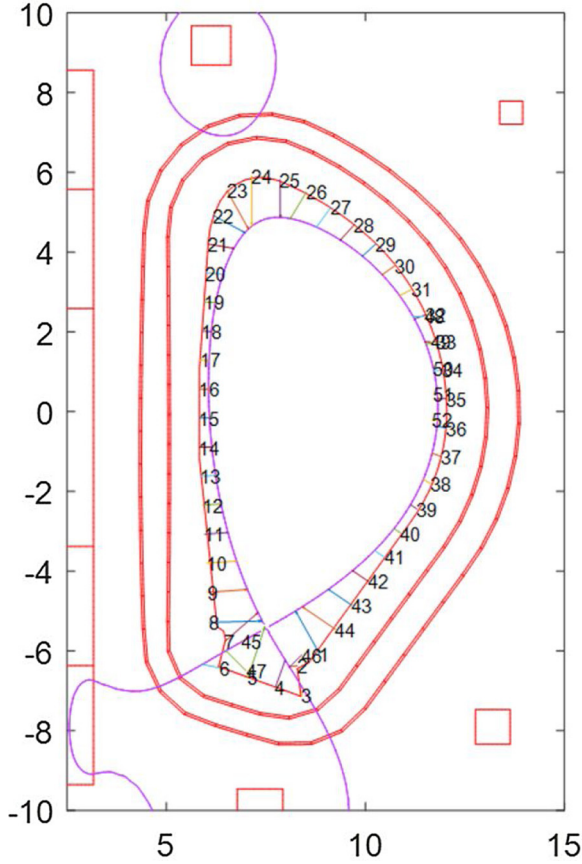


Fig. 1. DEMO SN equilibrium with indication of the gaps.

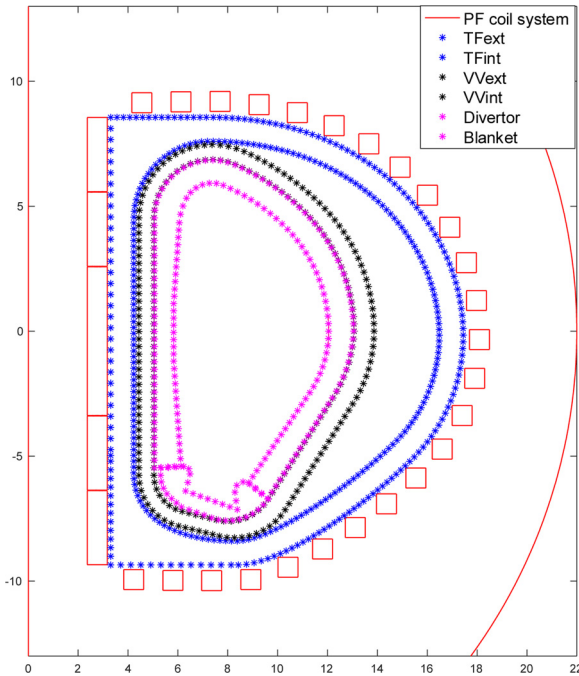


Fig. 2. Redundant PF coils systems compatible with the 2017 DEMO device geometrical description.

configuration also adopted for ITER, will extrapolate to the considerably more severe exhaust requirements in DEMO, several non-conventional magnetic configurations (e.g. snowflake divertor, X divertor, double nulls) as well as liquid metal divertor targets are

considered as alternatives. In this framework, a versatile tool fulfilling different aims, depending on plasma configuration, could be crucial.

The paper is organized as follows: Section 2 defines the problem highlighting the importance of the plasma linearized model; Section 3 describes the proposed optimization procedure; in Section 4 the optimization method is applied on the PF coils systems of DEMO and ITER devices. Finally, some conclusions are drawn in Section 5.

2. Preliminaries

The definition and optimization of plasma configurations requires nonlinear equilibrium codes able to solve the Grad-Shafranov equation and linearized MHD equilibrium models describing the approximated plasma response to variations in the CS/PF coil currents. In the following, a brief description of the plasma modelling is presented.

2.1. Plasma modelling

A tokamak can be seen as a system consisting of the plasma, the passive structures and the active circuits; the 2D FEM code CREATE-NL [18] is designed to solve numerically the Grad-Shafranov equation, which describes the behavior of such a system under the hypothesis of axial symmetry. The output of the code is a static plasma equilibrium. Both CREATE-NL and CREATE-L [19] can be used to obtain a linearized model by means of two different linearization procedures, numerical and analytical in a neighborhood of the equilibrium point, respectively. The general form of a linearized model can be derived from the input variables:

- $\delta \mathbf{x}(t) = [\delta I_{CS/PF}(t) \delta I_e(t) \delta I_p(t)]^T$ is the current vector which includes external currents and plasma current;
- $\delta \mathbf{w}(t) = [\delta \beta_p(t) \delta l_i(t)]^T$ is the disturbance vector where β_{pol} and l_i are parameters related to the plasma internal distributions of pressure and toroidal current density, respectively. This choice is made according to the assumptions and the analyses described in [19,20].

The main output variables are:

- $\delta \mathbf{y}(t) = [\delta \psi(t) ; \delta B_{pol} ; \delta \psi_b(t) ; \delta g(t)]^T$ is the output vector including poloidal magnetic fluxes per radian $\delta \psi(t)$ and poloidal magnetic fields δB_{pol} measured by the diagnostic system. $\delta \psi_b(t)$ is the magnetic flux per radian at the plasma boundary and $\delta g(t)$ are the plasma wall gaps at different poloidal locations of the first wall/divertor (Fig. 1).

Linearization around equilibrium quantities X_0 , W_0 and Y_0 yields:

$$\delta \mathbf{y}(t) = \mathbf{C} \delta \mathbf{x}(t) + \mathbf{F} \delta \mathbf{w}(t) \quad (1)$$

where:

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$$\delta \mathbf{x}(t) = \mathbf{X}(t) - \mathbf{X}_0, \delta \mathbf{w}(t) = \mathbf{W}(t) - \mathbf{W}_0, \delta \mathbf{y}(t) = \mathbf{Y}(t) - \mathbf{Y}_0;$$

- $\mathbf{C}$ and $\mathbf{F}$ are model matrices $\mathbf{C} = (\partial \mathbf{Y} / \partial \mathbf{X})_W$ $\mathbf{F} = (\partial \mathbf{Y} / \partial \mathbf{W})_X$.

Resorting to the linearized Eq. (1), small variations of the currents in the CS/PF coils ($\delta I_{CS/PF}$) are related to small variations of the plasma shape (δg) through a coefficient matrix ($\mathbf{C}_G$):

$$\delta g = \mathbf{C}_G \delta I_{CS/PF}. \quad (2)$$

Although the relation between the variation of the gaps and the PF currents is not linear, if the plasma boundary does not change too much, a linearization in (1)-(2) represents an important tool for the optimization of the PF coil system for a given set of plasma configurations.

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