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Multi-scenario electromagnetic load analysis for CFETR and EAST magnet systems

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HIGHLIGHTS

- A multi-scenario force-calculating simulator for Tokamak magnet system is developed using interaction matrix method.
- The simulator is applied to EM analysis of CFETR and EAST magnet system.
- The EM loads on CFETR magnet coils at different typical scenarios and the EM loads acting on magnet system of EAST as function of time for different shots are analyzed with the simulator.
- Results indicate that the approach can be conveniently used for multi-scenario and real-time EM analysis of Tokamak magnet system.

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ABSTRACT

A technology for electromagnetic (EM) analysis of the current-carrying components in tokamaks has been proposed recently (Rozov, 2013; Rozov and Alekseev, 2015). According to this method, the EM loads can be obtained by a linear transform of given currents using the pre-computed interaction matrix. Based on this technology, a multi-scenario force-calculating simulator for Tokamak magnet system is developed using Fortran programming in this paper. And the simulator is applied to EM analysis of China Fusion Engineering Test Reactor (CFETR) and Experimental Advanced Superconducting Tokamak (EAST) magnet system. The pre-computed EM interaction matrices of CFETR and EAST magnet system are implanted into the simulator, then the EM loads on CFETR magnet coils at different typical scenarios are evaluated with the simulator, and the comparison of the results with ANSYS method results validates the efficiency and accuracy of the method. Using the simulator, the EM loads acting on magnet system of EAST as function of time for different shots are further analyzed, and results indicate that the approach can be conveniently used for the real-time EM analysis of Tokamak magnet system.

1. Introduction

Accurate and quick analysis of the electromagnetic (EM) load on Tokamak main components is very important during not only Tokamak engineering design phase but also operation phase for ensuring the safety of the device. An approach for EM analysis of the current-carrying components in tokamaks has been proposed recently [1–3]. According this method, the interaction matrices for main Tokamak current-carrying components, which reflect parameters of pair-wise load interactions between separate coils at unit current, are calculated in advance. Considering the linear relationship between the currents and corresponding EM loads, the EM loads can be obtained by a linear transform of given currents using the pre-computed interaction matrices. The interaction matrices, which are fundamental scenario-invariant properties of the system, enable immediate purely-algebraic calculation of all individual EM load between the components by given currents. The reduction of the computational complexity and time to milliseconds makes this technique possible for use in real-time simulator[1–3].

We have explored on the application of the new approach for EM load assessment of EAST magnet [4]. The application validated the efficiency and accuracy of the new method, and results indicate that the interaction matrix, as a scenario-invariant property of the system, can be developed to use for multi-scenario and real-time analysis of the EM loads for tokamak current-carrying components.

As a continuation of the work in [4], a multi-scenario and real-time force-calculating simulator for Tokamak magnet system is developed by Fortran programming in this paper. Then we apply the simulator to EAST and CFETR magnet system separately. The EM loads on CFETR magnets are evaluated at three different sce-

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Table 1
Specified quantities as parameters of interactions.

Parameter	Description	The load on:	The load from:
F_R	Radial force	TF	TF
$F_{tor}^{(1)}$	Out-of-plane force	TF	TF
M_y	Moment of the out-of-plane force about the main axis	TF	TF
F_{y-hlaf}	Vertical total force on the upper-half coil	TF	TF
$F_{tor}^{(2)}$	Out-of-plane force	TF	CS/PF/Plasma
M_x	Overturning moment of the out-of-plane force about radial axis	TF	CS/PF/Plasma
F_v	Vertical total force	CS/PF/Plasma	CS/PF/Plasma
F_{hoop}	Hoop force	CS/PF/Plasma	CS/PF/Plasma

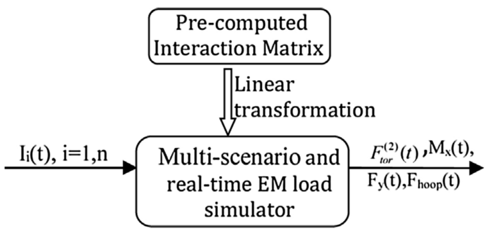

Fig. 1. Breakdown of simulating process.

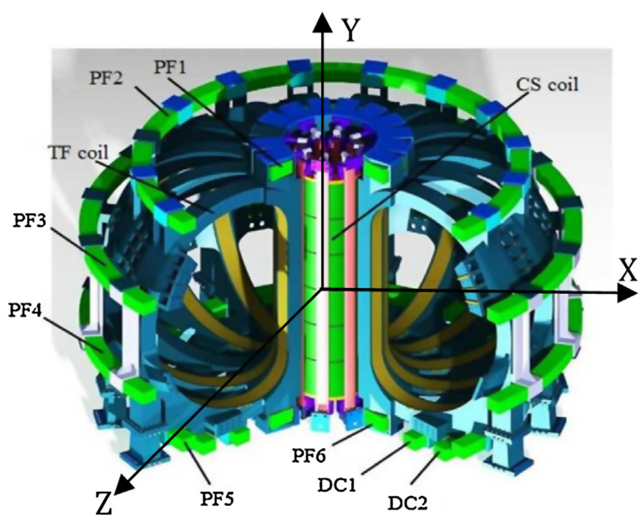

Fig. 2. Overview structure of the CFETR tokamak magnets.

narios in Section 3. And the real-time load results such as the net vertical forces acting on the stack of EAST central solenoid coils are analyzed in Section 4.

2. Method

According to the method present in[1–3], the Lorentz forces acting on any current-carrying component of the system can be calculated as product of the current in loaded structure, source currents and the interaction matrix, of which the currents consolidate the information on magnitudes of currents in the conductors, and the interaction matrix consolidates the information about the geometrical configuration of the current paths:

$$\vec{F_i} = I_i \sum_{j=1}^{n} I_j \vec{G_{ij}} \quad (1)$$

The interaction matrix $\vec{G_{ij}}$is by definition a matrix of linear transform between currents and forces. It can be used for the direct calculation of all individual forces in the system and their subtotals by known currents using simple single-step linear matrix operation. Interaction matrix is calculated at unit current in all element conductors. Therefore, this matrix does not depend on any particular combination of current magnitudes and represents a fundamental attribute of the system of conductors.

Suppose all the conductors of the Tokamak magnet system are loaded with unit current (1MA) separately. Since the magnetic fields are different everywhere, we can split the conductors into several segments, then the Lorentz force acting on conductor i due to the magnetic field produced by conductor j (all with unit current) can be calculated by:

$$\vec{G_{ij}} = \frac{\mu_0}{4\pi} \iiint_{V_j} \iiint_{V_i} \frac{\vec{j_i} dV_i \times (\vec{j_j} dV_j \times \vec{r_{ji}})}{|\vec{r_{ji}}|^3} \quad (2)$$

where $\vec{j_i}$ and $\vec{j_j}$ are separately the current density vector, dV_i and dV_j are the element volume of conductor i and j.

And according to [1], there are mainly 8 parameters which can characterize all principal aspects of the load interactions between Tokamak magnet coils – integral estimates of the corresponding systems of distributed forces, as listed in Table 1. The magnet system has been split into three parts, concerning different generic configurations: (1) CS/PF-to-CS/PF interactions; (2) TF-to-CS/PF interactions; (3) TF-to-TF interactions. Plasma is taken as an additional toroidal coil.

Based on this technology, with the pre-computed interaction matrix, a multi-scenario and real-time force-calculating simulator for Tokamak magnet system is developed by Fortran programming. As shown in Fig. 1, once the interaction matrix of any Tokamak magnet system is calculated and implanted into the simulator, given the currents waveform, the EM load acting on magnet system as function of time for different shots can be calculated.

Then the simulator is applied to EM analysis of CFETR and EAST magnet system. The multi-scenario and real-time EM loads acting on magnet coils of CFETR and EAST are evaluated separately.

3. Multi-scenario EM analysis for CFETR magnet system

3.1. CFETR magnet system introduction

CFETR which is being designed by the China National Integration Design Group, is a next-generation engineering reactor. The mission of CFETR is as follows: (1) ITER-like; complementary with ITER; (2) Fusion power 50–200 MW; (3) Duty cycle time (or burning time) ~ (30–50%); (4) Tritium should be self-sufficiency by blanket.

Table 2
Design parameters of CFETR TF coils.

Number of Coils	/	16
Number of turns per coil	/	132
Operating current	kA	67.4
Magnetic field at the plasma center(B_t)	T	5
Maximum field at the coil(B_{max})	T	10.6