Simulation of EM loads acting on the plasma-facing units of ITER divertor cassette

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Abstract. Some aspects of electromagnetic (EM) simulation of the central divertor cassettes (CDC) in the ITER tokamak are described. The study is focused on EM loads anticipated on the plasma-facing units (PFU) of CDC. The paper is devoted to the EM simulations of the most dangerous scenarios associated with high mechanical stresses: fast downward vertical displacement events of Categories II and III with 36-ms linear current quench (FD VDE-II and FD VDE-III with 36-ms LCQ). The selected events have been analyzed using the original TORNADO code intended for simulation of transient EM processes in 3D solids using the finite element representation. Results of computations include evolutions of EM loads on PFUs in the form of integral EM forces and moments, their peak values and relevant time points.

1. Introduction

The ITER tokamak employs a modular divertor made of 54 cassettes mounted on the inner and outer toroidal rails inside the vacuum vessel. Divertor cassettes are arranged regularly around the vertical axis of the tokamak at the vacuum vessel bottom. Every cassette consists of the Cassette Body and Plasma Facing Components (PFCs) that include the Inner Vertical Target (IVT), the Outer Vertical Target (OVT) and the Dome. To protect the PFCs from the heat load produced by diverted particles, plasma facing units (PFU) are installed on the plasma-facing surfaces of the Vertical Targets (VTs) and the Dome. All PFUs are tungsten armoured and water cooled.

Based on results of numerous simulations, the divertor cassette design has undergone several modifications advancing to performance required for the expected heat load in ITER. Prediction of electromagnetic (EM) behaviour that can contribute substantially to heating and stress levels is crucial for confidence in the design.

Some aspects of the simulation of anticipated EM loads acting on PFUs of the Central Divertor Cassette (CDC) located in front of the lower port are presented. EM simulations have been focused on 10 off-normal operational events that include plasma current disruptions of I–III categories separately and in combination with the Magnet Fast Discharge of Category II (MFD-II).

This paper describes simulations of two scenarios of the plasma disruptions, namely, the Fast Downward Vertical Displacement Events of Category II (FD VDE-II) and of Category III (FD VDE-III) with 36-ms Linear Current Quench (LCQ). These scenarios produce the most dangerous loading on CDC PFUs. Input data for the simulations was retrieved from results provided by the plasma equilibrium code DINA.

The plasma disruption scenarios have been simulated with the use of the finite element EM code TORNADO [1] developed at Efremov Scientific Research Institute of Electrophysical Apparatus for
3D simulations of transient EM processes (EM transients) in massive conductive structures. The code utilizes the finite element (FE) approximation and is based on the T-Ω method [2–4] in terms of the vector of current density

\[ j = \nabla \times T, \]

and the vector of magnetic field intensity

\[ \mathbf{H} = \mathbf{T} + \nabla \Omega. \]

The results include time evolutions of the EM loads on CDC PFUs in the form of total integral EM forces and moments, their peak values and relevant time points.

2. 3D computational models

Accurate simulation of the EM response of the CDC components requires a 3D FE model describing the CDC and its conducting surroundings. Thus, a 10-degree sector of ITER machine has been taken for modeling, which contains CDC with adjacent divertor cassettes, the vacuum vessel lower port, mechanical attachments and neighbouring blanket modules #1 and #18.

The study was carried out with the use of two computational models: the 3D model of the entire CDC uses a coarse FE mesh and is applied for global EM analysis of the divertor cassette and the 3D model of the Dome uses a refined FE mesh to closely reflect its actual design.

Both models were built in the Global right-handed Cartesian coordinate system (GCS), as shown in Figure 1. The GCS origin coincides with the centre of the ITER machine. The Z axis is the vertical axis of the tokamak. The Y = 0 plane is the symmetry plane of the CDC.

![Figure 1. Simulated 10-degree sector of the ITER machine.](image)

The IVT and OVT of CDC are simulated in detail (Figure 2) using a refined FE mesh. The models of VTs include the steel support structures, upper and lower multilink attachments, all PFUs (16 for IVT and 22 for OVT), PFU legs and supports and the cooling pipes connecting the PFUs to the steel support structures.

To reduce the problem dimensions and the computation cost, the VT PFUs were modeled in a simplified way as a single continuous tungsten layer with a rectangular cross section with effective electrical properties. Figure 3 shows the simplified VT PFU model.

The Dome was modelled in detail taking into account its asymmetry relative to the Y = 0 plane (GCS), see Figure 4.

The Dome PFUs are mounted on three water manifolds: the Inner Particle Reflector Plate (IPRP) manifold, the Umbrella manifold and the Outer Particle Reflective Plate (OPRP) manifold. Two design options have been modeled for the Umbrella manifold:
(i) the Umbrella manifold is designed as a solid conducting structure with eddy currents passing in the toroidal direction and
(ii) the Umbrella manifold has a poloidal slit in its central plane that divides the structure in two electrically insulated parts thus preventing the eddy current flow in the toroidal direction. Such design is expected to significantly reduce the radial and vertical EM moments on the Dome.

Figure 2. FE models IVT half (on the left) and OVT half (on the right).

Figure 3. FE model of IVT PFU (zoomed).

Figure 4. FE model of the Dome.
3. EM loads on CDC PFUs

Two EM transients with different symmetry conditions have been simulated for both selected plasma events, FD VDE-II and FD VDE-III with 36-ms LCQ:

- The first process is caused by halo current and variations of the toroidal magnetic flux.
- The second process is also associated with variations of the poloidal magnetic flux and it is caused by variations of the toroidal plasma current, its shape and position.

Evaluation of EM loads anticipated on CDC PFUs has been performed in two stages. First, distributed EM loads in the form of eddy current, EM fields and forces were simulated for every type of EM transients individually. Then, the obtained EM loads were superimposed with respect to the magnetic interaction between eddy currents and fields. The resulting loads were used as inputs for the subsequent stress analysis of the entire CDC and its Dome.

The simulations have revealed that the highest EM loads are expected on the extreme PFUs of the vertical targets and the Dome manifolds and are associated with interaction between the total poloidal current and the toroidal field. The total poloidal current is composed of two components distributed in a distinctive manner with respect to different symmetry planes of the PFCs.

The symmetrical component of eddy current associated with the current and the toroidal magnetic flux produces near-equal integral EM loads on CDC PFUs. The peak EM loads occur in the middle of the plasma current disruption when the halo current through CDC is maximum.

The integral EM loads due to the anti-symmetrical eddy current associated with the poloidal magnetic flux have opposite directions at the extreme PFUs. These EM loads tend to fall to zero when approaching the symmetry planes of the VTs and the Dome. The peak loads occur at the end of the plasma current disruption reaching much greater values than the EM loads from the symmetrical eddy current.

Peak values of the integral EM loads on PFUs are listed in Tables 1 and 2. PFUs are numbered right to left if viewed from the GCS origin. The torques acting on PFUs of the Dome are presented for the points located between the multilink attachments.

### Table 1. Maximum EM forces on most loaded PFUs of VTs.

| PFU        | $F_x$, kN | $F_y$, kN | $F_z$, kN | $|F|$, kN |
|------------|-----------|-----------|-----------|-----------|
| IVT, PFU #1 | -93.3     | 12.0      | 92.5      | 123       |
|            | (527 ms)  | (528 ms)  | (529 ms)  | (528 ms)  |
| IVT, PFU #16 | 94.6     | -7.87     | -94.8     | 127       |
|            | (527 ms)  | (497 ms)  | (529 ms)  | (528 ms)  |
| OVT, PFU #1 | 14.6      | 15.4      | 102       |
|            | (528 ms)  | (529 ms)  | (523 ms)  | (528 ms)  |
| OVT, PFU #22 | 104      | -5.75     | -17.5     | 104       |
|            | (528 ms)  | (496 ms)  | (523 ms)  | (528 ms)  |
4. Conclusions
For both simulated plasma disruption scenarios, the highest EM loads are expected to take place on the extreme PFUs of the VTs and the Dome collectors. These loads are associated with interaction between the total poloidal current and the toroidal field.

The symmetrical component of eddy current produces a uniform toroidal distribution of the integral EM loads on CDC PFUs with their peaks in the middle of the plasma current disruption.

In contrast, the EM loads on CDC PFUs due to the anti-symmetrical eddy current demonstrate a non-uniform distribution in the toroidal direction. These EM loads reach their maximum at the end of the plasma current disruption.

The simplified model of PFUs enables a quite accurate evaluation of the total transport current passing through PFUs in the poloidal direction and, therefore, acceptable results for the EM forces. However, the estimate of current distribution over the PFU cross section in this approximation is rather rough, which results in an inaccurate evaluation of the anticipated torques.

The EM analysis has revealed that the latest changes in the Dome design lead to significant increase in integral EM loads as compared to the 2012 design option:
- a 24% rise of the radial moment \( M_x \);
- a 40% rise of the toroidal force \( F_y \) and vertical moment \( M_z \).

A poloidal slit introduced in the updated Dome design in the central plane of the Umbrella would provide electrical break thus reducing the integral EM loads:
- radial moment \( M_x \) 1.8 times;
- toroidal force \( F_y \) and vertical moment \( M_z \) 2 times.

The results of the study suggest that the preferable design option is the Umbrella with the electrical break enabling the decrease in EM loading on the Dome.

The views and opinions expressed in this article do not necessary reflect those of the ITER Organization.

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