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I.A. Maione et al.

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A complete EM analysis of DEMO WCLL Breeding Blanket segments during VDE-up

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Within the EUROfusion consortium, a big effort is made in order to analyse the electromagnetic (EM) loads that act on the in-vessel components during normal and off-normal operations, being these loads an important input for their structural assessment of such components. With regard to the Breeding Blanket (BB) project, a global DEMO EM model, suitable to account for different blankets designs, has been developed in previous years with the capability to analyse EM transients in presence of both toroidal and poloidal magnetic field and considering materials with non-linear magnetic properties. Using the FE model based on the Water-Cooled Lithium Lead (WCLL) design, a VDE-up with a 74 ms current quench time was analysed. With respect to previous analyses, only focused on eddy currents (and thus, respective Lorentz forces), the present work reports a complete EM analysis of the BB segments that takes also into account the interaction of the BB magnetized material with the magnetic field (ferromagnetic forces) and the contribution of halo currents. Moreover, in order to follow the ongoing development of BB concepts, a comparison between the Single Module Segmentation (SMS) and Multi Module Segmentation (MMS) is also made, giving thus a complete view of the EM loads behaviour during the considered off-normal event.

Keywords: EU DEMO, blanket, WCLL, electromagnetic loads, vertical plasma disruption.

1. Introduction

DEMO (DEMO-nstration Power Plant) is a proposed nuclear fusion power plant that is meant to build upon the experience of the ITER experimental nuclear fusion reactor. While research is still ongoing to decide the exact parameters of the new machine to be used as a baseline for the design studies, it is normally assumed that DEMO will be a tokamak capable of producing at least 2 GW of fusion power on a continuous basis [1][2].

As a tokamak, DEMO is characterized by strong magnetic fields, produced by the superconducting coils systems, that confine the plasma particles to keep them away from the reactor plasma facing components. As a side effect, the generated magnetic field magnetises the structural components made in EUROFER97 [3] (i.e. the ferromagnetic material used for the main in-vessel components) generating ferromagnetic forces that act, thus, during all the operational states of the machine.

Moreover plasma Vertical Displacement Events (VDE) and disruptions, which consist in a violent and very rapid loss of the plasma confinement, can also arise in tokamaks. Due to the strong intensity of the magnetic field and plasma current, these events induce currents in the conductive structure that, interacting with the magnetic field, generate strong EM forces (Lorentz forces). Mainly two types of currents contribute to these loads: eddy currents, caused by the decay of the plasma current and the change of plasma shape, and poloidal halo currents (HCs), which flow through the structure wetted by the disrupting plasma when it gets in contact with the surrounding structures.

All these kinds of load have to be carefully assessed during the reactor design phase as they are usually design-drivers for the vessel and in-vessel components (breeding blanket (BB) modules, divertor, port plugs, fuelling, diagnostic systems, etc.).

The present work is aimed at completing the EM analysis of the BB segments started in [4], which was only limited to the Lorentz forces generated by eddy currents, evaluating the contribution of the ferromagnetic material and the HCs. In addition, following the ongoing studies inside the EUROfusion Work Package BB, analyses have also been carried considering two different BB configurations, i.e. Single Module Segmentation (SMS) and Multi Module Segmentation (MMS) [5].

2. Electromagnetic FE model overview

A complete description of the EM FEM model developed to perform the analyses has been already reported in [4] and, for this reason, only briefly summarized in the following.

The model represents a 20° sector based on the DEMO baseline 2015 design [6], implementing the Blanket system, divertors, vacuum vessel (VV), central solenoid (CS), poloidal field (PF) and toroidal field (TF) coils. Five BB segments, 2 inboard (IB) and 3 outboard (OB), have been developed considering the SMS WCLL design [7].

In order to reduce the model size and, thus, the computation time, the WCLL complex structure has been simplified homogenizing particular regions (e.g. FW with cooling channels). However, main regions as FW, BZ, BSS, CAPS and stiffening grids have been maintained in order to minimize the distortion of eddy current loops and ferromagnetic material distribution. A view of the internal segment structure is reported in Fig. 1.

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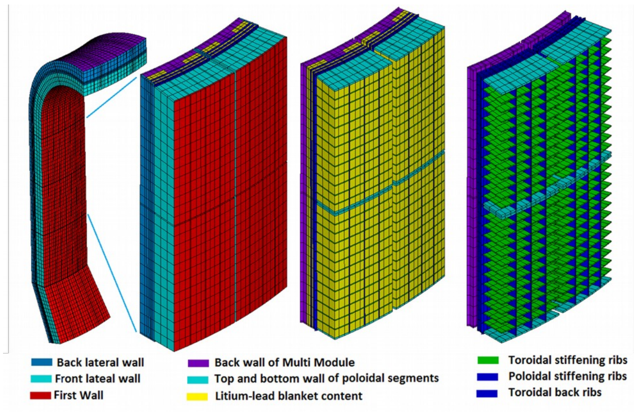

Fig. 1 Example of the internal segments structure implemented in the EM model. Different sketches of the IB central modules have been taken removing, from left to right, successively the FW and BZ content.

Analyses are performed using the ANSYS Emag commercial software. SOLID236 has been chosen as element type for all the defined materials allowing solving ferromagnetic problems in presence of discontinuities in the material properties at interfaces.

EM loads are calculated considering a VDE-up with a 74ms current quench time scenario analysed by means of the CarMa0NL code [8]. Both the poloidal and toroidal field variations due to the plasma movement and to the current quench are implemented.

3. Results

Force distribution as well as total force and moment acting on the whole blanket segments has been calculated and exported using APDL commands. In the following, forces and moments are reported with respect to the local Cartesian systems in agreement with those defined in [4].

3.1 Ferromagnetic loads

Ferromagnetic loads, as introduced before, are referred only to the contribution due to the magnetized material. They are calculated taking the output of the ANSYS EMFT macro [9], which allows summarizing the total forces on each segment, and subtracting the respective Lorentz forces.

The time evolution of ferromagnetic forces and moments has been found similar for all the segments and it is shown in Fig. 2 only for a reference case (namely, the IBL segment).

As a general comment, it is possible to state that, in comparison with the behaviour observed for the Lorentz loads, ferromagnetic components do not exhibit strong fluctuations during the considered plasma events, meaning that the magnetic field distribution produced by the plasma has a minor contribution in comparison to the coils field.

The ferromagnetic forces are mainly directed in the radial direction toward the inner leg of the TF coils due to a predominant 1/r toroidal magnetic field. Moreover, as reported in Table 1, IB segments are subjected to higher forces compared to OB segments despite their lower content of ferromagnetic material (4.72 m^3 and 8.27 m^3 for the IB and OB, respectively). This is a direct consequence of their dependence on the gradient of the magnetic field components as formulated, for example, in the approximated Kelvin's equation, $F = \mu_0(\boldsymbol{m}\cdot\boldsymbol{\nabla})\boldsymbol{B}$, where μ_0 is the vacuum permeability, $\boldsymbol{m}$ is the magnetic moment and $\boldsymbol{B}$ the magnetic flux density.

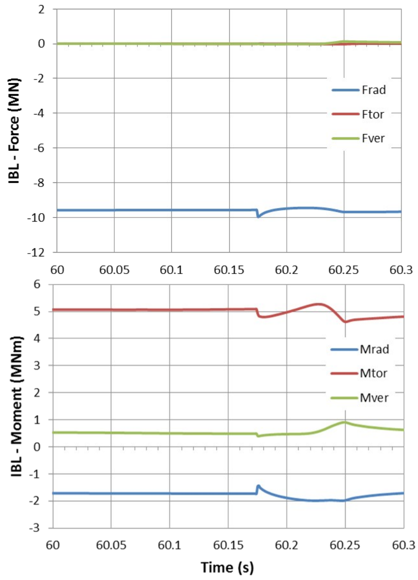

Fig. 2 Time behavior of the ferromagnetic loads for the IBL segment. Suffixes rad, tor, and ver are referred to the local coordinate system defined in [4].

Table 1 Force and moment components acting on IB and OB segment before the plasma disruption (t = 60 s).

	Frad (MN)	Ftor (MN)	Fver (MN)	Mrad (MNm)	Mtor (MNm)	Mver (MNm)
IBR	-9.578	0.002	0.006	-1.714	5.070	0.530
IBL	-9.591	-0.008	-0.021	1.536	5.107	-0.579
OBR	-3.517	1.140	0.273	-1.726	0.491	-0.318
OBC	-5.059	0.033	-0.509	0.662	-2.683	-0.005
OBL	-3.535	-1.180	0.214	3.681	0.116	0.386

In addition, as a consequence of a non-symmetric distribution of the radial force with respect to the geometrical centre of the segment, a total toroidal moment (Mtor) is generated in the local coordinate system. Due to the BB design, this effect is more evident in the IB segments than in the OB segments (see Table 1).

On the other side, as effect of the ripple, disuniformity in the toroidal force distribution is also produced. This is noticeable in the OB region where the ripple is more pronounced and Frad is smaller for OBR and OBL due to the "smoother" field gradient in the region under the TF coils. As a side effect, the variation of the field distribution due to the ripple causes an increase of the other force components, i.e. Ftor and Fver, and consequently also of the other moment components, i.e. Mrad and Mver.

3.2 Halo contribution

The EM analysis of the WCLL SMS model in presence of Halo currents has been performed assuming a

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peak of 7MA and a poloidal current distribution along the FW obtained from the CREATE simulation [10]. The HC have been assigned to FW nodes using the “F” ANSYS command and assuming a uniform current distribution in toroidal direction as shown in Fig. 3.

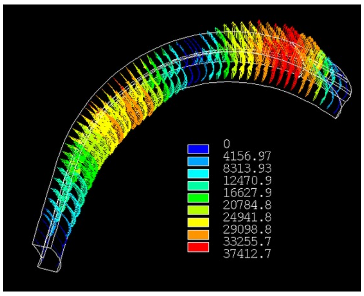

Fig. 3 Example of the imposed halo current density in the wet area.

In order to perform the simulation, the EM model developed for the previous analysis has been modified setting a finite conductivity for the plasma regions identified in Fig. 4 allowing the flow of a fictitious plasma current.

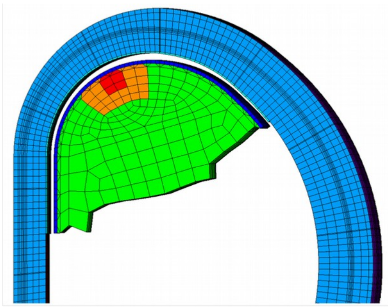

Fig. 4 The plasma conducting region (in red, orange and blue) implemented in the model for the HCs EM analysis. The wetted area is in blue.

That, together with the application of Volt constraints (“CP” command) on the FW and plasma side, allows the halo current loop to close in order to ensure ***div·J****=0* for the imposed current (see Fig. 5).

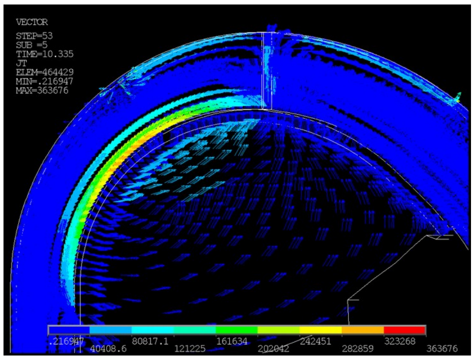

Fig. 5 Distribution of the halo currents flowing into the BB and the plasma. The model assumes a finite conductivity for the plasma region.

In Fig. 6 the EM loads (Lorentz force and moment) produced by the halo currents are shown. The evaluation of these Lorentz EM loads has been carried out neglecting the effects of plasma and PFCs poloidal field as well as the field perturbation produced by the TFV and PFV during plasma disruption. However, considering their minor contribution to these EM loads respect to the TF coils field contribution, the error is considered negligible for such analysis.

The graphs show that HC loads have their maximum at 60.235 s, in agreement with the implemented data. Due to the interaction of the poloidal currents, flowing mainly in the FW, and the toroidal magnetic field, radial and vertical forces are generated. Their maximum value is found in the IB segments (0.53 MN and 0.67 MN for Frad and Fver respectively). As consequence of the position of the wetted area respect to the origin of the local coordinate system, a high component of the toroidal magnetic moment (Mtor) is also originated.

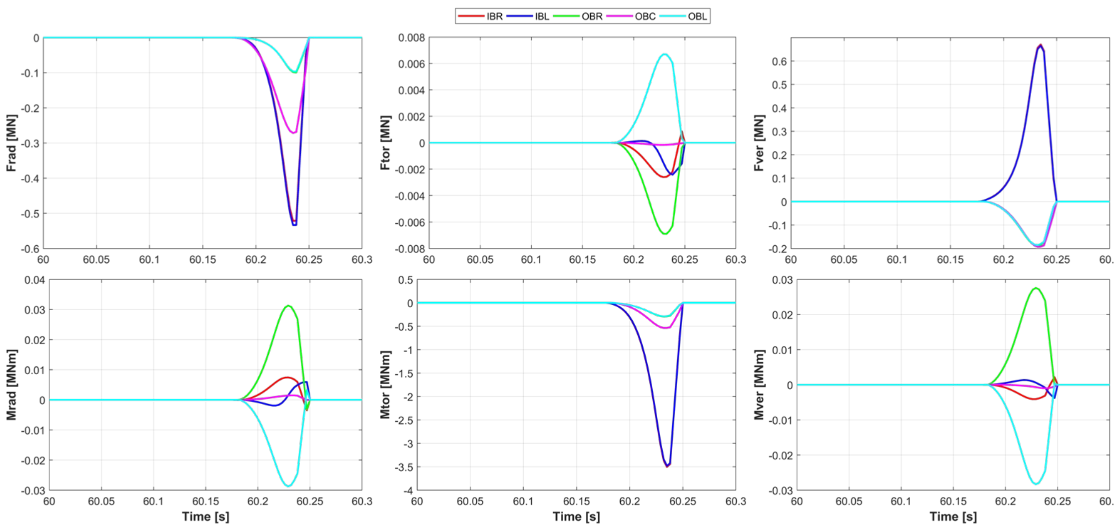

Fig. 6 Time behaviour of the IB and OB electromagnetic loads due to the halo currents.

4. Comparison between SMS and MMS

Changes in the design of the BB segments can be critical for the evaluation of EM loads since they modify

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the paths of currents flowing in the structure as well as the ferromagnetic material distribution.

Regarding the SMS and MMS configurations, the main difference from the EM point of view is given by the gaps between modules introduced in the MMS configuration. On the basis of previous analyses and theoretical considerations, these gaps are not expected to change significantly the ferromagnetic forces (being the amount and distribution of EUROFER only slightly different in the two configurations), nor the eddy currents due to the current quench (CQ) (flowing principally in the radial-toroidal segment cross section and thus only marginally affected by the MMS gaps). However, for what concern the impact on the poloidal eddy currents, mainly generated by the plasma movement and the toroidal flux variation during the thermal quench (TQ), no references are available. For this reason, an analysis of the MMS configuration has been performed.

To this purpose, the model developed in [4], referred to the SMS configuration, has been modified allowing a transformation from the SMS to the MMS configuration by means of a suitable ANSYS APDL routine that change the material properties of the elements corresponding to the MMS modules gap. The results, together with that obtained for the SMS configuration, are shown in Fig. 7. Graphs related to MMS and SMS configuration are drawn using solid and dashed line respectively. Results are only limited to ferromagnetic and eddy currents loads; no HCs are considered in this comparison.

As outcome of the analyses, no significant differences have been found between the EM loads of the two configurations confirming, from one side, the initial hypothesis on eddy currents forces due to the CQ and ferromagnetic forces. On the other hand, loads generated by poloidal eddy currents (e.g. Frad during the TQ) maintain their intensity. This result, not at all obvious, can be explained considering that MMS gaps do not act as lamination in transformers: poloidal eddy current loops are not really "cut" by MMS gaps, but only directed toward the BSS (welded to the BB modules). Evidently, this effect is not enough to substantially change the generated loads.

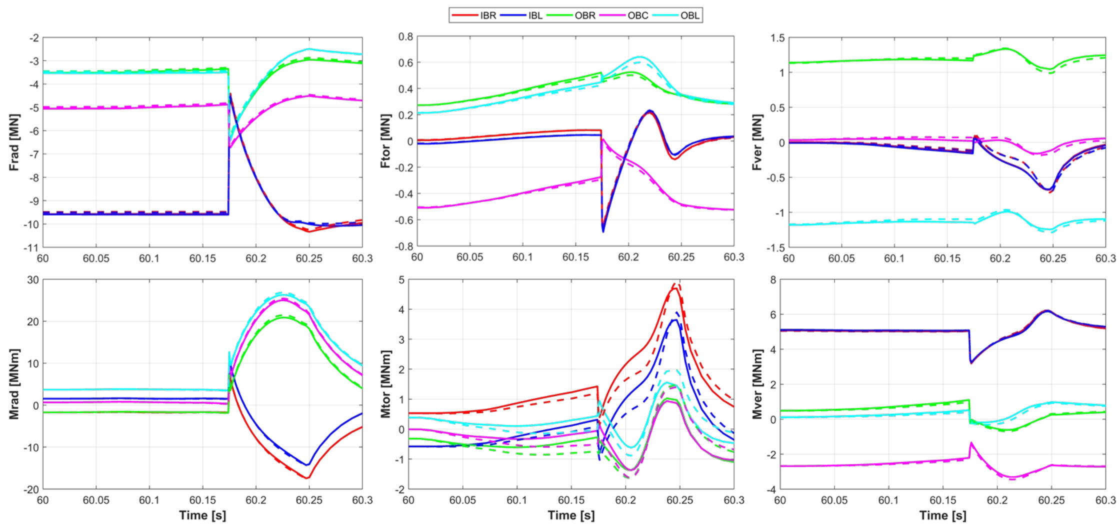

Fig. 7 Comparison between the total (eddy current + ferromagnetic) EM loads on the MMS (solid) and SMS (dashed) configuration.

5. Conclusion

The work herein presented is part of a series of EM activities carried on in the framework of EUROfusion Work Package BB with the aim of analysing the behaviour of the main EM loads acting on BB segments generated by normal and off normal events. In particular this study has been focused on ferromagnetic and halo current contribution to the total EM loads during a plasma VDE-up completing the analysis reported in [4].

Results have shown that ferromagnetic forces are slightly affected by the plasma behaviour. They are mainly directed in the radial direction toward the inner leg of the TF coils and reach values around -9.5 MN and -5 MN for the IB and OB segments respectively. Considering that such forces act on the ferromagnetic in-vessel components during all the plasma operational states (not only during an off-normal event), they cannot be considered negligible and, in fact, have been found important, for example, for the design of the BB-VV attachment system, as well as for the structural assessment of the BB segments [5].

On the other and, EM loads due to halo currents have only a modest contribution. Forces remain below 1 MN and the only relevant moment, in local coordinate system, is Mtor due to the concentration of halo currents in the top region of the BB segments. It reaches values of -3.5 MNm for the IB segments.

Moreover, in line with the design of BB concepts, two different segment configurations, i.e. MMS and SMS, have been analysed in order to underline possible advantages/disadvantages with respect electromagnetic

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events/conditions. In this case, no particular differences have been found.

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