Simplified modeling of tokamak plasmas in a computational electromagnetic environment

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Abstract

During the decade of the '90s much theoretical research and technical development was carried out in the area of correctly modeling eddy currents appearing in tokamak devices by using 3 Dimensional (3D) models. Further computer modeling must be undertaken taking into account the whole spectrum of aspects of plasma modeling in tokamaks: MagnetoHydroDynamic (MHD) description of plasma interacting with the plasma facing components (pfc) of a tokamak structure. However, a cornerstone on developing such an approach is a correct, although simplified, description of the problem in purely EM terms. A contribution toward this guiding line is the ambition of the author of this paper.

1 Introduction

At the beginning, some remarks on fusion and the environment will be given due to the fact that the title of the conference is ENERGY AND ENVIRONMENT. The fusion fuel cycle does not involve any input of radioactive material and does not generate radioactive waste directly. Radioactivity is present in the form of the intermediate fuel, tritium, and as radioactivity generated in structural materials by the absorption of neutrons. There is the freedom, by suitable choices of design and materials, to reduce the radioactivity to achieve low hazard potential. Studies in this area have been promising and the independent review prepared for the European Commission by the Fusion Program Evaluation Board was able to propose the following stringent targets as reasonable aims for the fusion program: “The worst possible fusion accident will constitute no major hazard to populations outside the plant perimeter that might result in
evacuation”. This paper concerning simplified modeling of tokamak plasmas in a computational electromagnetic environment must be placed in this context.

It is agreed that phenomena associated to ElectroMagnetic (EM) fields are among the most crucial for an efficient design of a fusion machine of tokamak type. Special attention must be paid in tokamak design to questions concerning plasma first wall interaction, when off-normal conditions appear during the operation. The physical mechanisms, describing these conditions, are by their nature very difficult to be approached by simplified models, as they combine neutron, heat, and electromagnetic fluxes, which have as consequence mechanical deformations of the structure. As examples of such a type of operating conditions can be mentioned the instabilities of plasma vertical position and the extinction of plasma current. These conditions have as a consequence an extremely rapid variation of the magnetic flux with final result the appearance of eddy currents in the conducting parts of the reactor. On the other hand eddy currents in conjunction with the total magnetic field produce a distribution of body EM force density at the metallic parts of the structure, whose hollow interior is occupied by plasma (the conducting material being considered linear). Hence, it is evident that these hazardous situations (known as plasma disruptions) must be avoided and this is one of the most crucial obstacles in developing a controlled thermonuclear fusion technology, which would at least partially replace other sources of energy. Plasma in tokamaks is magnetically confined. This result is obtained by exploiting the interaction of plasma with external magnetic fields of appropriate distribution. This could be considered, as the most convincing argument for scrutinizing thoroughly on the theory of EM fields related to plasma of a tokamak machine. Studying EM fields in such a configuration is jointly of crucial importance for the perception of plasma physical behavior (plasma equilibrium) and for the standardization of normal operating conditions of a fusion reactor, fact that will allow production in industrial scale of such a type of machine in the future [1, 19, 20, 21, 22, 28, 29].

EM fields in tokamaks appear to be of a frequency spectrum really vast. However, in a first approach, propagation aspects, presenting a minor contribution to the global plasma behavior, can be omitted. Hence, a quasi-static approach (low frequency approximation) is used for Maxwell’s equation describing EM fields in tokamaks in the sections that follow. However, in a more thorough approach in the future heating aspects related to the interaction of plasma and high frequency EM waves guided by appropriate wave-guides in the vacuum vessel should be included. Seeing a tokamak as an EM device three interacting systems can be distinguished [1, 19, 20, 21, 22, 28, 29]: plasma, coils, and the conducting structures. Hence, the importance of correctly modeling the EM forces, developed in the plasma facing conducting parts, due to the interaction of these three parts is essential for an efficient design of the tokamak machine. Both computer modeling and experiments are useful for identifying the behavior of every element of the tokamak in case of very rapid transients of magnetic fields and eddy current distribution in the metallic parts [2, 23, 24, 31]. The aforementioned transients may appear even during normal operating conditions (i.e. plasma stand-up and shutdown, shape / position control) but
mainly when accidental situations occur (e.g. transition of a super-conducting coil from the super-conducting state to the conducting one, plasma disruptions). As consequence induced currents and voltages in the conducting pans and coils appear. Eddy currents, in turn, produce EM forces, and other secondary phenomena related to their appearance. Field penetration delays, insulation and support damages, arcing, heat deposition can be mentioned as secondary phenomena of this type. To start with, a blanket without breeder material was considered. Readers interested in screening effects to EM field penetration in the tokamak structure due to the breeder existence may refer to \[21, 28\]. However, in \[21, 28\] less sophisticated disruption models were considered. A future more detailed analysis should take into account the breeder to investigate its screening effects.

2 Results

The following reference disruption scenarios have been considered:

- model P1: linear current decay in 25 ms for an elliptical cross-section plasma (slow current quench).
- model P2: linear current decay in 25 ms for a rectangular cross-section plasma (slow current quench).
- model P3: vertical displacement over 2 m in 25 ms (pure VDE).
- model P4: vertical plasma motion of 2 m in 25 ms super-posed to a slow current quench (1 MA/ms).
- model P5: VDE (2 m in 25 ms) followed by a fast current quench (5 MA/ms).
- model P6: linear current decay in 5 ms for an elliptical cross-section plasma (fast current quench).
- model P7: linear current decay in 5 ms for a rectangular cross-section plasma (fast current quench).

Models P1, P2, P6 and P7 concern plasma disruptive instabilities known as static disruptions, whereas P3, P4 and P5 simulate plasma VDE accidental events known as dynamic disruptions. To start with, a blanket without breeder material was considered. Fig. 1 shows the FEM model created by PATRAN for a blanket portion (10° sector).

The output of modeling was induced eddy currents distribution in the blanket sector, as a three-component current density vector in the center of each element, for a sequence of pre-defined instants. Furthermore: ohmic power dissipated in the structure because of the eddy currents, magnetic energy associated to eddy currents and body forces were computed in various instants. Body EM force distribution is given in the form of element forces by unit volume. Body EM force distribution and eddy currents are given locally, at the center of each element of the model, as shown for example in figs. 2. The resultant EM forces in the blanket structure were also computed for all the instants of computation. Figs. 2a, 2b, 2c and 2d show eddy current density distribution and related forces pattern for the cases of a slow current decay without plasma motion (P1), for the case of a pure VDE (P3), for the case of a VDE with a slow current quench (P4) and for the case of a VDE followed by a rapid quench (P5) (Important remark:
for model P5 the current scale was divided by two in order to make it possible for the drawing to be contained in one page - see Histogram 1). In principal, eddy currents are induced in such a way, that their pattern of flow be toroidal. In fig. 2b an interesting feature is to be remarked: a pure VDE provokes eddy currents induction in both senses of toroidal direction (positive and negative Y), whereas in the other scenarios eddy currents induction is done only in one sense of the radial direction (even in the cases of models P4 and P5, in which the effect of the current quench is clearly pre-dominant).

Figure 1: Discretization in elements of ITER’s blanket (portion of 10°).

Figure 2a: Eddy currents and electromagnetic forces pattern for the model P1 at the time instant 25 ms.

Figure 2b: Eddy currents and electromagnetic forces pattern for the model P3 at the time instant 25 ms.
Figure 2c: Eddy currents and electromagnetic forces pattern for the model P4 at the time instant 25 ms.

Figure 2d: Eddy currents and electromagnetic forces pattern for the model P5 at the time instant 25 ms.

It is apparent, that a very strong edge effect at the open bottom blanket region is present. A rationale for this type of pattern is, that the structure, in this way, finds a means of equilibrating eddy currents / EM body force density distribution of the upper blanket region. Consequently, elements in the bottom part of the structure have to sustain a current / force equal to the distributed current / force of the elements of the upper part. In Histogram 1 is presented local maximum eddy current density value for different models, studied for modeling various cases of disruption. Two distinct cases were modeled, using elliptical plasma cross-section, the first with a picked radial current density profile: \( \alpha = 3 \), the second with a flat profile: \( \alpha = 0 \). In the case of a pure current decay (static
disruption), the eddy current values for P1 and P6 (elliptical plasmas) are different from those obtained in model P2 and P7 (rectangular plasma sections), corresponding to the same disruption. Maximum induction of eddy currents is observed, when an elliptical plasma cross-section with $\alpha = 3$ (P1 and P6) is used. Furthermore, it is observed that in all the accidental events, the maximum eddy current appears at the end of the current quench. Another meaningful observation is, that fast current decays have as consequence stronger induction of eddy currents, than that produced by slower ones. However, there is no proportionality. If, for instance, current quench rate is multiplied by a factor of four, this does not imply a multiplication of the induced eddy currents by four. Finally, as far as it concerns simple dynamic disruption events, by comparison of models P2 and P3, it can be concluded, that a pure VDE (P3) induces higher currents than a pure quench. On the other hand, by comparison of models P3 and P4, it can be concluded, that the effect of a VDE at constant plasma current is potentially more dangerous than that of a motion with a current decay. The result is even stronger, in the case of a current quench, which occurs abruptly at the end of the displacement (P5). In this case, high eddy currents values can, clearly, be attributed to the rapid quench, as it happens in the case of model P7.

![Histogram 1: Extreme values for eddy currents as given by the code CARIDDI (MA/m²).](image-url)
In Histograms 2 and 3 the resultant EM forces in a $10^\circ$ sector, in the X, Y and Z directions, acting onto the four materials of the blanket, are presented. The values are computed by CARIDDI, taking into account the interaction between the toroidal eddy currents and the total magnetic field, the imposed one plus that, which is produced by eddy currents. In case of flat radial current density profile plasmas, the following remarks can be made: Clearly, resultant EM forces in models P1 and P2 are comparable (a slight discrepancy is, just, attributed to the fact that, in these models, the rectangular cross-section is slightly bigger, than that of the elliptical one. In static disruption accidental events (models P1 and P2), the pre-dominant EM force component, is of the order of 1 MN and appears to be oriented toward the radial (X) direction. When pure VDEs are studied (model P3), however, the pre-dominant EM force component, exerted to the blanket, is the vertical one (oriented toward the Z direction). This resultant force of EM origin (whose order is of 2.3 MN) presents a downward direction, because a downward VDE is modeled and is applied to the back plate of the OB component. When VDEs are followed by rapid switch-off of plasma currents (as it happens in model P5), results comparable to those of static disruptions, presenting a rapid current quench rate (model P6), are observed. In these cases resultant forces of EM origin are of almost the same magnitude. It is noticed, that force components of EM origin oriented toward the toroidal direction are always quite small, mainly when pure VDEs occur. Hence, as far as blanket modules are concerned, strongest forces are produced by rapid quenches of plasma currents. Consequently, special attention must be taken to the direction of EM forces.

**Histogram 2:** Total EM force (MN) analyzed in axial (X), toroidal (Y) and poloidal (Z) direction as given by the code CARIDDI for a portion of $10^\circ$.  

![Histogram 2](image-url)
Histogram 3: Total EM force (MN) analyzed in axial (X), toroidal (Y) and poloidal (Z) direction as given by the code CARIDDI for a portion of 10°.

3 Conclusions

Apparently, static and dynamic disruptions look not to provoke the same type of behavior on the tokamak in-vessel region. As far as it concerns eddy currents, this is very clear: they appear an inversion of sign along the vertical direction, when a VDE occurs. Furthermore, EM forces appearing on the blanket present in principal a very strong component toward the radial direction, when a static disruption occurs, whereas they present a very strong component toward the vertical direction in case of a dynamic disruption. Another interesting characteristic to be taken into account in the design phase of the ITER project is that numerical modeling gives a pattern, which presents an edge effect. Something else, to be noted, is, that current quench rate (from 1 to 5 MA/ms) presents a tremendous impact on induced currents value. It is an astonishing element of this study, that this impact is not apparent, as far as it concerns the distribution of the EM force volume density. This is due to the fact, that eddy currents (having a flow pattern essentially toroidal) and toroidal magnetic field (having considerable value) vector product is zero. As stressed in other parts of this paper, the models considered are quite simplified. A more precise description of a tokamak EM behavior should take into account the effects due to vacuum vessel, the poloidal field coils and the shielding blanket. Finally, it must be stressed that, MHD-type software codes, specially prepared for studying plasma equilibria and identifying operating scenarios, will have to be interfaced to the EM ones in order to obtain a rigorous and robust model for VDEs.

References

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