

Effect of the Toroidal Field ripple on electromagnetic loads during disruptions

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1. Introduction

The Toroidal Field (TF) is the strongest magnetic field component in tokamak devices. It is produced by a dedicated set of windings (the so called TF coils), which ideally should generate a purely toroidal magnetic field decaying as $1/r$, r being the distance from the vertical axis. Due to the deviations from the ideal geometry of a perfect toroidal solenoid (segmentation, non-cylindrical geometry, misalignments etc.), both a toroidal non-homogeneity and a spurious poloidal component arise, giving rise to the so-called TF ripple. It is well known that even a small TF ripple may have a dramatic effect on plasma rotation [1] and on fast ion losses [2], potentially impacting plasma fusion performance. This is the reason why specific efforts are dedicated to the minimization of the TF ripple, both at design level [3] and with the introduction of ad-hoc solutions, like ferromagnetic inserts [4].

This paper focuses on the implications of the presence of TF ripple on the electromagnetic loads arising as a consequence of a disruption. During such events, significant amounts of current flow in the conducting structures surrounding the plasma, both induced by plasma current and position variations (eddy currents) and directly injected from the plasma to the structures and vice-versa (halo currents). Such currents interact with the magnetic field, giving rise to forces and moments on various parts of the device. In the following, we will show that the TF ripple is responsible for a vertical moment (i.e. describing a rotation around the vertical axis) on the conducting structures.

2. General considerations

Let us consider a thin wire γ (tangent $\hat{\mathbf{t}}$, volume V) carrying a current i , with two sides γ_1, γ_3 directed vertically at two symmetric toroidal locations $\phi_1 = -\phi_3$ and two sides γ_2, γ_4 directed toroidally, mimicking one eddy current loop induced in 3D structures during the disruption.

$$\hat{\mathbf{t}}_1 = \hat{\mathbf{i}}_z, \quad \hat{\mathbf{t}}_2 = \hat{\mathbf{i}}_\phi, \quad \hat{\mathbf{t}}_3 = -\hat{\mathbf{i}}_z, \quad \hat{\mathbf{t}}_4 = -\hat{\mathbf{i}}_\phi$$

The total moment with respect to the global origin acting on the wire is

$$\mathbf{M} = \iiint_V \boldsymbol{\rho} \times \mathbf{f} dV = \iiint_V \boldsymbol{\rho} \times (\mathbf{J} \times \mathbf{B}) dV = i \int_\gamma \boldsymbol{\rho} \times (\hat{\mathbf{t}} \times \mathbf{B}) dl$$

where ρ is the distance from the origin. The moment in the vertical direction is:

$$\begin{aligned} M_z &= \mathbf{M} \cdot \hat{\mathbf{z}} = i \int_{\gamma} (\boldsymbol{\rho} \times (\hat{\mathbf{t}} \times \mathbf{B})) \cdot \hat{\mathbf{z}} dl = i \int_{\gamma} (\hat{\mathbf{z}} \times \boldsymbol{\rho}) \cdot (\hat{\mathbf{t}} \times \mathbf{B}) dl = i \int_{\gamma} r \hat{\mathbf{t}}_{\phi} \cdot (\hat{\mathbf{t}} \times \mathbf{B}) dl \\ &= i \int_{\gamma} r \mathbf{B} \cdot (\hat{\mathbf{t}}_{\phi} \times \hat{\mathbf{t}}) dl \end{aligned}$$

where r is the distance from the vertical axis, $\hat{\mathbf{t}}_{\phi}$ is the toroidally directed unit vector. It should be noted that only the poloidal component of the magnetic field \mathbf{B} contributes to the vertical moment, since unit vector $(\hat{\mathbf{t}}_{\phi} \times \hat{\mathbf{t}})$ has zero toroidal component. We have:

$$M_z = i \int_{\gamma_3} r \mathbf{B} \cdot (-\hat{\mathbf{t}}_r) dl + i \int_{\gamma_1} r \mathbf{B} \cdot \hat{\mathbf{t}}_r dl = -i \int_{\gamma_3} r B_r dl + i \int_{\gamma_1} r B_r dl$$

If the poloidal magnetic field is axisymmetric or mirror symmetric ($B_r(\gamma_1) = B_r(\gamma_3)$), then the two terms cancel out and the vertical moment on the wire is zero. If the poloidal field is mirror antisymmetric ($B_r(\gamma_1) = -B_r(\gamma_3)$), then the two terms sum up and the vertical moment is different from zero. The PF coils provide an axisymmetric field, so they do not contribute to the vertical moment on the wire. Conversely, the TF coils generate a field which has a mirror antisymmetric poloidal component (one of the components of the so-called TF ripple) which produces a net vertical moment on the wire. Being the system isolated, on the TF coils an opposite vertical moment must appear, so that the total vertical moment is zero.

If instead we consider one turn of a toroidal solenoid, mimicking a poloidal halo current pattern flowing partly in the plasma and partly in the structures, calling $(\hat{\mathbf{t}}_{\phi} \times \hat{\mathbf{t}}) = \hat{\mathbf{n}}$, we have:

$$M_z = i_{halo} \int_{\gamma} r \mathbf{B} \cdot (\hat{\mathbf{t}}_{\phi} \times \hat{\mathbf{t}}) dl = i_{halo} \int_{\gamma} r \mathbf{B} \cdot \hat{\mathbf{n}} dl = \frac{i_{halo}}{2\pi} \iint_{\Sigma} \mathbf{B} \cdot \hat{\mathbf{n}} dS = 0$$

where Σ is the closed surface (a torus) obtained by revolving γ around the vertical axis, thanks to solenoidality of \mathbf{B} , regardless of its symmetry. Splitting γ in a part in the plasma region and in a part in the structures, we have:

$$\begin{aligned} i_{halo} \int_{\gamma_{structures}} r \mathbf{B} \cdot \hat{\mathbf{n}} dl &= -i_{halo} \int_{\gamma_{plasma}} r \mathbf{B} \cdot \hat{\mathbf{n}} dl \\ M_{z,structures} &= -M_{z,plasma} \end{aligned}$$

If the plasma is in equilibrium, then it result $M_{z,structures} = M_{z,plasma} = 0$, otherwise a vertical moment over the structures may appear, exactly opposite to the one on the plasma.

3. Quantification in the ITER case

Here we quantify in the ITER case the effect qualitatively illustrated in the previous section.

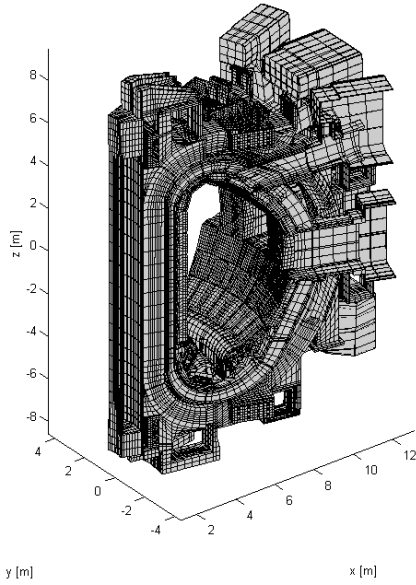


Figure 1. ITER geometry

slowly (in more than one second) and a huge halo appear (up to around 6 MA of toroidal halo current). Due to the mechanism described above, the TF coils experience a non-zero vertical moment (Fig. 2), of the order of 100 MN*m, which is almost perfectly compensated by the vertical moment on ex-vessel structures, which are those more involved by the TF ripple. The vertical moment on the vessel + in-vessel structure is not zero, because there is some current flowing in these structures and interacting with the TF ripple. However, its value is quite low because the vessel located in a region with a small ripple; in addition, the induced current is small, being the event under consideration slow. The residual discrepancy is due to imperfect imposition of equilibrium over plasma, as explained above, and to numerical errors. In table 1 we report the value of the vertical moment at $t=0.8622$ s over the ex-vessel structures, assuming different magnetic field components acting on them. Evidently, the vertical moment is due to the TF ripple. A mesh sensitivity analysis on the TF coil has been carried out. Three meshes have been considered, obtained by repetitively doubling the number of subdivisions in the poloidal direction. The vertical moment on the TF coil is practically identical.

Specifically, we refer to a detailed mesh of the ITER active and passive structures (Fig. 1), routinely used for the simulation of disruptions [5,6]. Plasma evolution is simulated with DINA code and the mesh includes a 3D description of TF coils and their ripple. A number of disruptive events have been considered. First, we concentrate on the “VDE DW slow” event described in [5,6], in which the plasma moves in the downwards direction, hitting the structures in the divertor region; the plasma current quenches quite

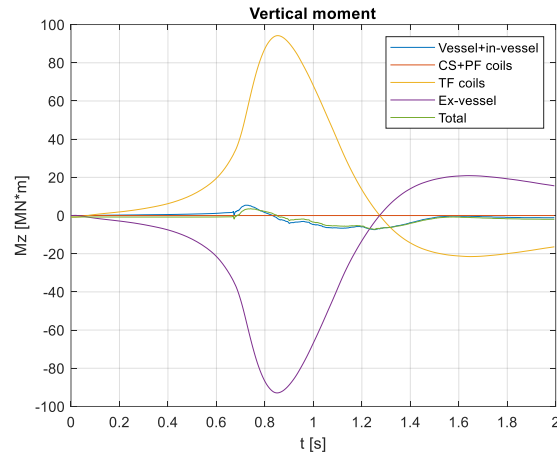


Figure 2. VDE DW slow: Vertical moment

Total field	Field due to PF coils	Field due to TF coils	Ideal 1/r toroidal field
-92.62	$8.43 \cdot 10^{-3}$	-92.65	$-1.43 \cdot 10^{-15}$

Table 1. Vertical moment [MN*m] on ex-vessel structures due to various magnetic field contributions

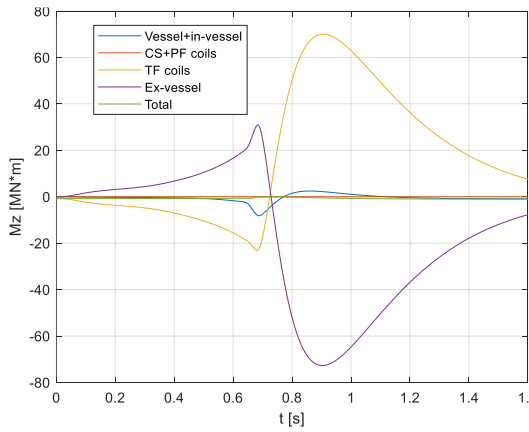


Figure 3. VDE UP fast: Vertical moment

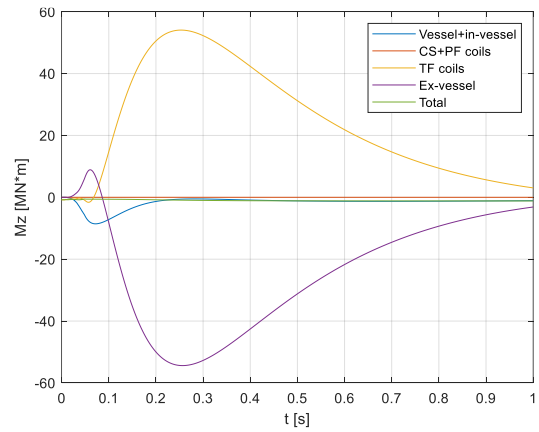


Figure 4. Major Disruption: Vertical moment

Similar results have been obtained for different disruptive events. Figure 3 reports the vertical moment for the VDE UP fast event described in [5], which is complementary with respect to the previous case, since the plasma moves in the upwards direction, the current quench is much faster (36 ms) and the toroidal halo current is much smaller (2 MA).

The overall vertical moment is of the same order of magnitude (around 70 MN*m maximum). The effect of the vessel is more relevant in this case, since the event is faster and hence the current induced in the vessel is higher. The overall vertical moment balance is better than in the previous case, also because the halo current is lower and hence the inexact imposition of plasma equilibrium is less relevant. The same conclusions can be drawn from the analysis of a Major Disruption (Fig. 4), i.e. an event in which the disruption occurs on a centred configuration, before the VDE can develop. For this case, Fig. 5 shows the vertical moment acting on the vessel and in-vessel component, whose maximum value is of the order of 10 MN*m, compensated by ex-vessel structures and magnets.

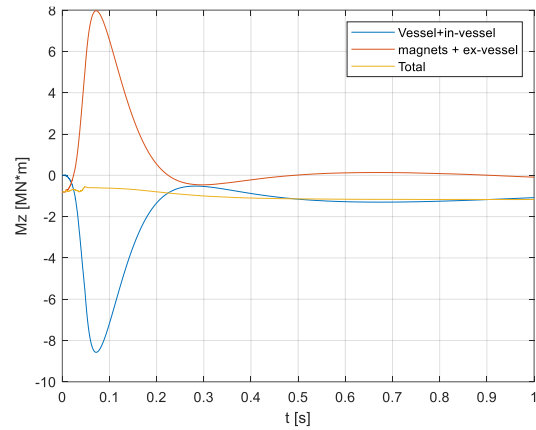


Figure 5. Vertical moment on vessel and ex-vessel

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