Multimodal RWM feedback control in ITER

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Under specific circumstances, the plasma evolution in fusion devices can show unstable evolution modes. The growth time of these instabilities can be as fast as microseconds, making any active magnetic control action practically impossible. Conversely, in presence of a sufficiently close conducting wall, the plasma perturbation will induce eddy currents, counteracting the instability itself. This stabilizing effect lasts until the eddy currents decay; this intuitively explains why the growth rate can be slowed down to electromagnetic times, which are of the order of milliseconds or slower, so that an active stabilization is indeed possible. Such modes are hence called Resistive Wall Modes (RWMs).

It is usual practice to label the various possible instabilities in terms of the so-called toroidal mode number n (the Fourier harmonic index in the toroidal direction), such that the spatial dependence upon the toroidal angle φ of all plasma quantities is as $e^{jn\varphi}$.In Reversed Field Pinches many unstable modes with different n's routinely arise simultaneously. This is less common in tokamak devices, where the high toroidal field prevents many high-n modes to show up. In this paper, we will deal with the simultaneous evolution in ITER of two different instabilities: $n = 0$ (the so-called axisymmetric VDE, Vertical Displacement Event) and $n = 1$ (kink instability). We propose a feedback control architecture able to deal with this situation, and we design a controller consisting of two separate loops, so as to minimize the control effort and the interactions.

The system is modelled resorting to the CarMa code [1], a cutting-edge numerical model for the analysis of RWMs in presence of volumetric three-dimensional structures. Giving a finite elements discretization of the conducting domain, the basic equation is:

$$L^* \frac{dI}{dt} + RI + \frac{dU}{dt} = FV \tag{1}$$

where I is the vector of discrete currents induced in 3D structures, V is the vector of voltages fed to active conductors, L^* is a modified inductance matrix and R is a resistance matrix. The above model is able to rigorously take into account multiple toroidal mode numbers [1], by considering different plasma response matrices corresponding to different n numbers, computed with the CREATE-L code [2] for $n = 0$ and with the MARS-F code [3] for $n = 1$.

The ITER tokamak has been discretized with a 3D finite elements mesh, made of 4970 hexahedral elements, giving rise to $N = 4135$ discrete degrees of freedom. The plasma configuration considered is a Scenario 4, 9 MA configuration, with a normalized $\beta_N = 2.94$.

With a simple rearrangement of (1), we get the state-space model

$$\dot{x} = Ax + Bu\,, \quad y_m = C_m x \tag{2}$$

where the dynamic matrix A is given by $A = -(L^*)^{-1}R$, the state vector x coincides with the set of 3D currents I, the input quantities u are the voltages fed to the active coils. The outputs y_m are the magnetic field perturbations at given spatial points around the torus. These points are grouped in three equally-spaced poloidal sections, at $\varphi_1 = 0^o$, $\varphi_2 = 120^o$ and $\varphi_3 = 240^o$; the set of measurements in each of the three sections are indicated as y_{m_i}, with $i \in \{1,2,3\}$. We also consider the current i_{VS3} in the VS3 circuit and the 27 currents i_{ELM} in the ELM coils, grouped in 3 vectors of length 9 i_{ELM_1}, i_{ELM_2} and i_{ELM_3} relative to the current in the ELM circuits in three regions of the vessel (upper, center and lower). The average value of i_{ELM_i} along the toroidal angle will be denoted by $i_{ELM_{0,i}}$.

The dynamic matrix A has three unstable eigenvalues. The first (around $5.6s^{-1}$) corresponds to the $n = 0$ RWM (VDE). The other two have practically coinciding values (around $17s^{-1}$) and correspond to two $n = 1$ current density patterns (external kink), which are identical apart from a shift of $\pi/2$ in the toroidal direction.

The main requirement of the controller is the stabilization of the $n = 0$ and $n = 1$ modes. The aim is to enlarge the operating envelope, in terms of maximum disturbance (initial condition along the unstable modes) that can be rejected. The limitations are the maximum available voltages and currents.

The controller design is conceptually divided in two parts, one for each n value. We denote with u_i, $i \in \{1,2,3\}$ the voltages applied to the non-axisymmetric coils in the upper, center, and lower region of the vessel, respectively. These voltages have been decomposed as:

$$u_i = \Theta \cdot \begin{pmatrix} u_{Ai} \\ u_{Bi} \end{pmatrix} + u_{i0}\,, \quad i = 1,2,3\,, \Theta = \begin{pmatrix} \cos\eta_1 & \sin\eta_1 \\ \cdots & \cdots \\ \cos\eta_9 & \sin\eta_9 \end{pmatrix}. \tag{3}$$

The u_{Ai} and u_{Bi} components are used by the $n = 1$ mode stabilization controller, whereas the u_{i0} terms are used by the $n = 0$ mode stabilization controller in the attempt of minimizing the amplitude of the $i_{ELM_{0,i}}$ currents. The reason for the decomposition of the inputs as in (3) is that the u_{Ai} and u_{Bi} terms counteract the $n = 1$ perturbation without stimulating the $n = 0$ mode. Analogously to the inputs in (3), the estimated vertical position z_i in the generic poloidal section

i, with $i \in 1,2,3$ has been approximated as $z_i = z_0 + z_A \cos\varphi_i + z_B \sin\varphi_i$, where z_0 is the average vertical position along the toroidal angle, calculated as $z_0 = \frac{z_1+z_2+z_3}{3}$.

In each section z_i is given by a suitable combination of magnetic measurements. Hence, z_A and z_B are given by ($M^\dagger$ indicates the Moore-Penrose pseudoinverse of the matrix M.)

$$\begin{pmatrix} z_A \\ z_B \end{pmatrix} = M^\dagger \begin{pmatrix} z_1 - z_0 \\ z_2 - z_0 \\ z_3 - z_0 \end{pmatrix}, M = \begin{pmatrix} \cos\varphi_1 & \sin\varphi_1 \\ \cos\varphi_2 & \sin\varphi_2 \\ \cos\varphi_3 & \sin\varphi_3 \end{pmatrix} \tag{4}$$

The controller design is split in the design of two separate stabilizing controllers, for the $n = 0$ and $n = 1$ modes respectively. The $n = 0$ controller has been designed as

$$u_0 = k_1 \dot{z}_0 + k_2 i_{VS3}\,, \quad u_{i0} = k_3 i_{ELM_{0,i}}\,, \quad i = 1,2,3 \tag{5}$$

where the gains k_1, and k_2 in (5) have been chosen using an approach similar to the one described in [4]. The gain k_3 has been choseen via a trial and error approach in order to reduce the axysimmetric currents flowing in the ELM coils. Indeed, when only a $n = 0$ perturbation is present, this current is caused by the inductive coupling between the plasma, the other conducting structures, and the ELM coils.

The $n = 1$ controller has been designed as a state feedback controller, where the control matrix has been chosen in order to take into account the saturation of the ELM coil voltages. The needed state observer has been designed as a Kalman filter with diagonal covariance matrices whose non zero elements are tuned on the base of a trial and error procedure.

The first simulation refers to a VDE event consisting of a 10 cm displacement along the unstable $n = 0$ mode. Using $u_{i0} = 0$, $i = 1,2,3$, i.e. without the decoupling action, the $n = 0$ controller gives rise to high currents in the ELM coils (Fig. 1) as compared to the case of decoupling action present (Fig. 2).

The second case (Fig. 3) refers to a disturbance along the $n = 1$ mode corresponding to a 1 cm displacement at the toroidal angle φ_1. Evidently, the decomposition of the inputs to the plant and of the outputs produces very little influence of the $n = 1$ loop on the $n = 0$ mode.

References

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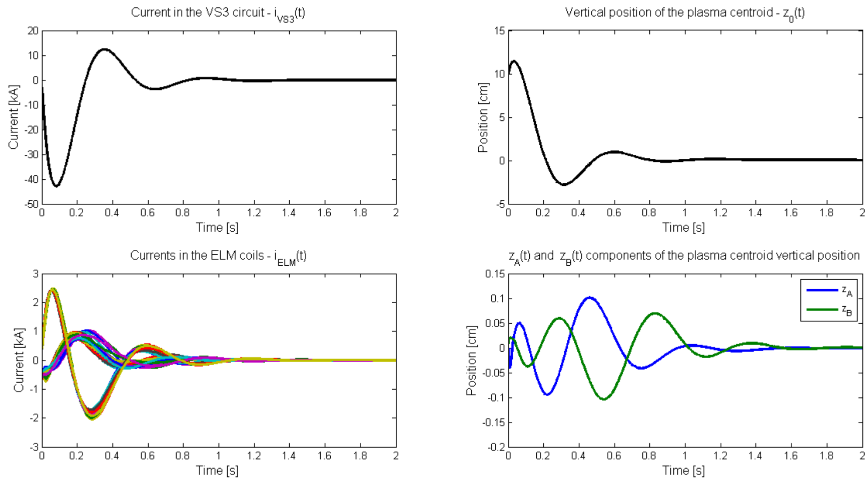

Figure 1: Closed-loop response to a 10 cm VDE (no decoupling).

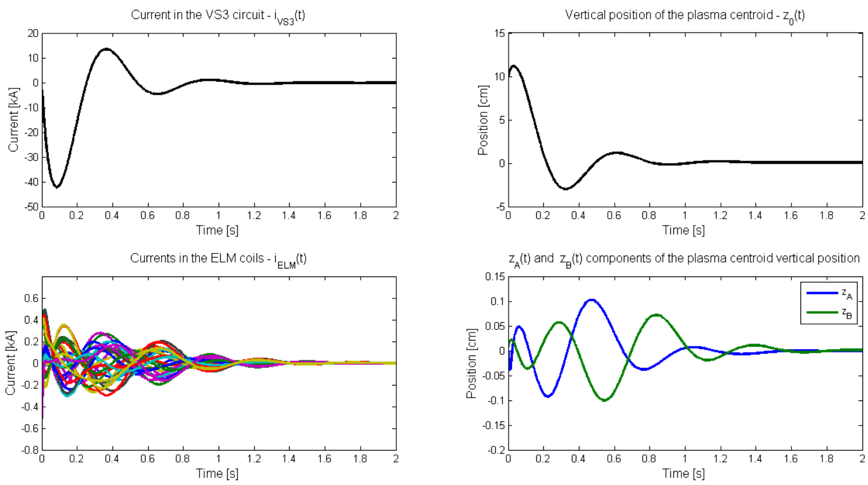

Figure 2: Closed-loop response to a 10 cm VDE.

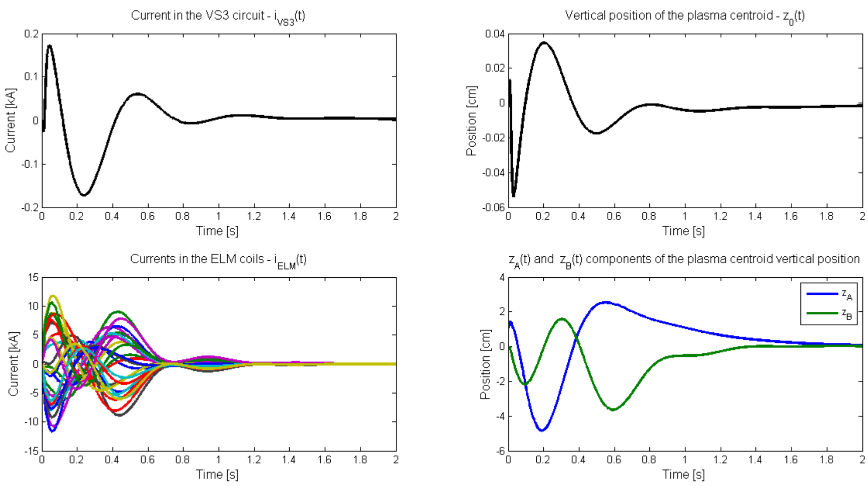

Figure 3: Closed-loop response to a 1 cm displacement along the $n = 1$ mode.