Study of ITER RWM control with semi-analytical models

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Abstract. This paper presents results of the study of resistive wall mode (RWM) control in ITER. The analysis is based on semi-analytical models developed by Y.Q. Liu and A. Bondeson using the code MARS-F for a set of ITER Scenario 4-type plasmas (9 MA, weak negative magnetic shear). A multiple input, multiple output, Linear Quadratic Gaussian (LQG) controller, assigning the voltage in the correction coils, was designed using these models for the control of RWMs in ITER plasmas with different degrees of instability. In spite of the screening effect of the vacuum vessel outer wall, the controller is able to suppress highly unstable RWM without using the second derivative of the measured poloidal magnetic perturbation. It was found that highly unstable RWMs can be stabilized with voltages about 300 V/turn. The effect of filtering of the diagnostics signal on the RWM control was studied with the goal to reduce AC losses in the superconducting coils. The cutoff frequency for a highly unstable RWM can be as low as 300 Hz without significant deterioration of the RWM control. It has been shown that the time delay in the power supply (2 ms) and the voltage rate limit (93 V/turn ms) only slightly affect the RWM control.

1. Introduction

The main approach to steady-state operation of the ITER is via negative or weak central magnetic shear plasmas with a high fraction of bootstrap current. These plasmas are characterized by high values of β_N limited by low-n kink modes. For each mode number n there are two critical values of β_N. The first value, $\beta_N(no\ wall)$, is the value of β_N when the modes become unstable without a stabilizing conducting wall. The second critical value, $\beta_N(ideal\ wall)$, higher than the first limit, is the value of β_N when the modes become unstable assuming ideal conductivity of the wall. If the value of β_N is somewhere between these two critical values, for a plasma without toroidal rotation, the mode is unstable. The instability growth time is determined by the time constant of the conducting wall, τ_w, which can be estimated in the cylindrical approximation using the formula $\tau_w \approx \mu_0 \sigma_w a_w h_w /(2m)$. Here σ_w, a_w, h_w, m are respectively, the wall conductivity, minor radius, thickness and the mode poloidal number. These modes are called resistive wall modes (RWM), and the degree of their instability is characterized by the growth rate and by a dimensionless parameter:

$$C_\beta = \frac{\beta_N - \beta_N(no\ wall)}{\beta_N(ideal\ wall) - \beta_N(no\ wall)},$$

showing relative proximity of β_N to the “ideal wall” limit.

A system of saddle coils, distributed in the toroidal direction on the plasma outboard side, can be used for RWM feedback stabilization. Control of RWM by saddle coils located outside the vacuum vessel was demonstrated at DIII-D. In the experiments, the RWM was stabilized during the period of about $50\tau_w$ [1].

The feedback control of RWM in ITER will be realized using the side set of the error field correction coils shown in Fig. 1. There are three pairs of toroidally opposite superconducting coils located outside the double wall vacuum vessel. The coils in a pair are connected for generation of magnetic field harmonic with the toroidal number $n = 1$. Each pair has an independent power supply. The coil maximum current is 280 kA·turn (10kA·28 turns); the voltage insulation limit is 360 V/turn (10 kV/28 turns); the inductance of a pair of coils is 50 μH/turn^2. About 120 kA·turn are required for correction of the error fields expected in ITER and more than 160 kA·turn are available for the feedback stabilization of RWM. The resistance of feedback circuit is determined by the resistance of busbars (4 mΩ). The time constant of the feedback circuit, about 10 s, is much higher than the time constant of the double wall vacuum vessel, $\tau_w \approx 0.2$ s. Therefore, the resistive voltage drop in the busbars can be neglected in the studies of RWM control.

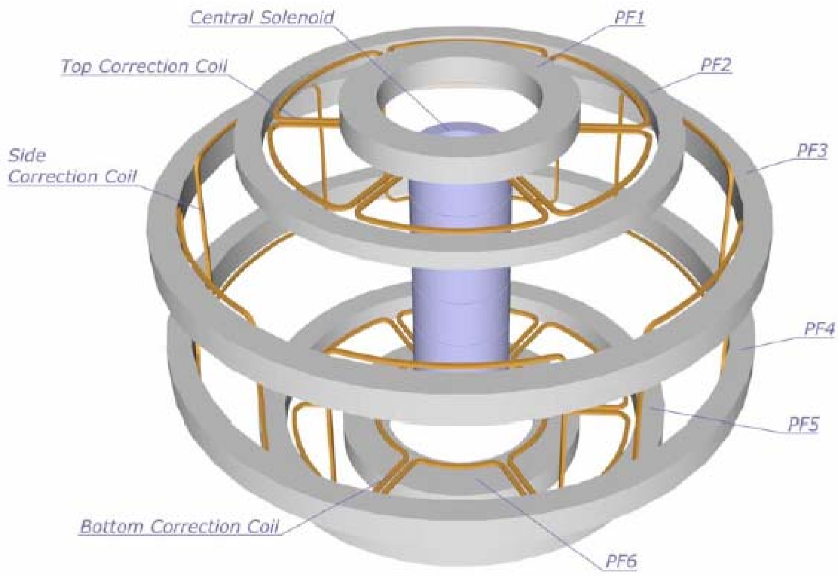

FIG. 1. ITER poloidal field coils and error field correction coils.

This paper presents the results of a study of RWM control performed using simplified analytical models (complex transfer functions) describing the RWM in a set of ITER plasmas. These models, developed by Y.Q. Liu and A. Bondeson, based on calculations using the MARS-F code [2] for ITER plasmas with different degree of RWM instability C_β, are described in section 2. A Linear Quadratic Gaussian (LQG) control algorithm, assigning voltage in the coils depending on the signals from the sensors measuring poloidal magnetic perturbation, was designed for RWM stabilization in the plasmas considered. This multiple input, multiple output, LQG controller is described in section 3. Section 4 presents the results of the study of RWM control with the controller, in particular, the coil voltage demand, acceptable value of the cut-off frequency in the filtering of RWM diagnostic signal, and the effect of the power supply time delay and voltage rate limit on the RWM suppression. Section 5 summarizes the results of the study.

2. Plasmas and Semi-Analytical Models of RWM

A typical representative of ITER steady state scenarios is the Scenario 4 [3]. This is a 9 MA highly shaped plasma with weak negative shear, producing about 300 MW of fusion power with $Q = 5$ for 3000 s ($R_p = 6.35$ m, $a_p = 1.85$ m, $\kappa_{sep} = 1.97$, $\delta_{sep} = 0.58$, $\beta_N = 2.57$, $l_i = 0.63$). A set of Scenario 4-type plasmas is considered in the studies of RWM control in ITER. These plasmas have the same current and shape, about the same profile of q, but different values of β_N. To carry out this β_N-scan, the plasma toroidal current was specified as:

$$j_{tor} = j_0 \left\{ \frac{R}{R_p} \alpha G(\psi_p) + \frac{R_p}{R} \left[H(\psi_p) - \alpha G(\psi_p) \right] \right\},$$

where ψ_p is the normalized poloidal magnetic flux, functions $H(\psi_p)$ and $G(\psi_p)$ are the same as they are in the Scenario 4 simulated with the transport code ASTRA [4] and j_0 is adjusted so that the plasma current is 9 MA [2]. Different values of β_N are obtained by varying the parameter α. The plasma with $\alpha = 1$ corresponds to the Scenario 4. For the set of Scenario 4-type plasmas, the "no wall" and "ideal wall" β_N limits for $n = 1$ kink modes, are about 2.5 and 3.6 respectively.

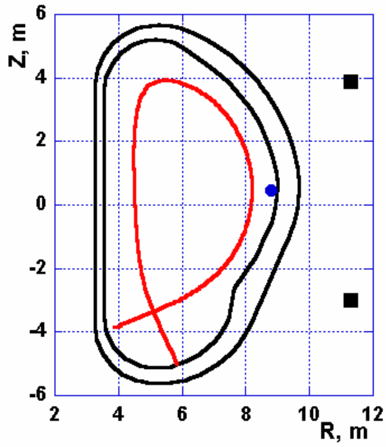

FIG. 2. ITER plasma, vacuum vessel, magnetic sensors (blue dot) and feedback coils (black squares) used in the studies of RWM control.

The semi-analytical models of RWM were developed by Y.Q. Liu and A. Bondeson using the MARS-F code [2]. This code uses an axisymmetric model of the vacuum vessel and an approximation of infinitely large numbers of the feedback saddle coils and magnetic sensors distributed in the toroidal direction. The sensors (shown in Fig. 2), located on the plasma side of the vacuum vessel inner wall, are assumed to measure the $n = 1$ component of the perturbed poloidal magnetic field:

$$B(t,\varphi) = B_0(t)\exp(i\varphi),$$

where φ is the toroidal angle.

Location of the toroidal elements of the feedback coils is shown in Fig. 2. Currents in the upper and lower elements are represented as:

$$J_{upper}(t,\varphi) = -J_{lower}(t,\varphi) = J_0(t)\exp[i(\varphi - \varphi_0)] \equiv J(t,\varphi),$$

where φ_0 is the toroidal phase of the currents.

The currents in the feedback circuit vary according to the applied voltage, $V(t,\varphi)$, produced according to a control algorithm:

$$L_f \frac{\partial [J(t,\varphi)]}{\partial t} = V(t,\varphi), \text{ or } j(s) = \frac{v(s)}{sL_f},$$

where $j(s)$ and $v(s)$ are the Laplace transformations of the functions J and V, L_f = 50 μH/turn^2 is the inductance of a pair of the ITER side correction coils.

The semi-analytical model of RWM based on the MARS-F calculations operates with a complex transfer function, $P(s)$, between $j(s)$ and the Laplace transformation of the function B:

$$b(s) = b_0 P(s)\, j(s)\,,\;\; j(s) = L\big[J(t,\varphi)\big],\; b(s) = L\big[B(t,\varphi)\big].$$

Here b_0 is a normalization constant defined as the maximum value of the radial component of the magnetic field produced on the sensors by the unit current in the feedback coils. The transfer functions $P(s)$, without the effects of the ITER blanket modules and plasma rotation, are found to be:

$$P(s) = \frac{12.68 - 0.0585i}{s - 10.25} + \frac{0.4149 + 0.0053i}{s + 5.239 + 8.191i} + \frac{-13.71 - 0.3617i}{s + 48.64 - 5.851i} \qquad \text{for } C_\beta = 0.37,$$

$$P(s) = \frac{15.02 - 0.452i}{s - 16.42} + \frac{0.446 - 0.271i}{s + 6.484 + 1.596i} + \frac{-15.77 - 0.005i}{s + 47.40 - 2.202i} \qquad \text{for } C_\beta = 0.52,$$

$$P(s) = \frac{17.57 - 1.032i}{s - 32.80 - 1.016i} + \frac{-12.86 + 1.792i}{s + 38.19 + 3.963i} + \frac{-5.255 - 1.069i}{s + 41.47 - 22.96i} \qquad \text{for } C_\beta = 0.67,$$

$$P_1(s) = \frac{19.63 - 1.153i}{s - 59.78 - 2.144i} + \frac{-24.62 + 2.186i}{s + 46.10 - 0.979i} + \frac{3.596 - 1.064i}{s + 61.89 + 33.62i} \qquad \text{for } C_\beta = 0.83.$$

3. RWM Controllers

The transfer functions $P(s)$ are used here for the design of ITER controllers. The controllers were validated in simulations of the suppression of RWM using the following approach. The RWM evolves free ($V \equiv 0$, $I \equiv 0$) starting from a small value of B ($B << B_0$). The feedback stabilization is switched on, when the maximum signal on the probes increases to a given level B_0.

The goal of control is to suppress B. In the simulations, the value of B_0 was chosen as 1.5 mT, which is about by a factor of 3 higher than the background noise expected on the ITER sensors in the steady state scenarios. The background noise is defined as all signals on the sensors measuring $n = 1$ mode of the poloidal field, except for the signals from RWM and ELMs. (The ELMs are not expected in ITER steady state scenarios.)

In [2], the studies of ITER RWM control were performed with the feedback gain, G, defined as:

$$v(s) = -\frac{L_f}{b_0} G(s) b(s), \quad G(s) = (K_2 s + K_1)\,\frac{(1 + T_d s)}{(1 + T_d s / \xi)}\,.$$

This control algorithm is characterised by four parameters (K_1, K_2, T_d and ξ). It was shown that for stabilization of highly unstable RWMs (C_β close to 1), the term proportional to the second derivative of magnetic field on the sensors (e.g. the term proportional to s^2) is required in the feedback gain. According to the analytical study [5], the second derivative, d^2B/dt^2, helps in compensation of the screening effect of the vacuum vessel outer wall. It was shown that with the voltage limit foreseen for ITER (about 300 V/turn), good control performance can be achieved for C_β up to about 0.6, while with less stringent requirements on the control performance, a plasma with C_β up to about 0.8 can be stabilized.

We studied the RWM control in ITER with a Linear Quadratic Gaussian (LQG) controller. The controller has six inputs and two outputs. The inputs are real and imaginary components of B_ϑ, dB_ϑ / dt and $\int B_\vartheta dt$. The controller outputs are real and imaginary components of the coil voltage V. The controller was designed assuming the ideal power supply (that is without voltage limit and time delay).

4. Studies of RWM Control with LQG Controller

The LQG controller was validated in the simulations of suppression of RWMs having different degree of instability C_β. An example of the suppression of highly unstable RWM ($C_\beta = 0.83$) with $B_0 = 1.5$mT is shown in Fig. 3. The solid lines are the real components of B, J and V, the dashed lines represent imaginary components of these functions. It is shown that the highly unstable RWMs ($C_\beta \approx 0.8$) can be stabilized with voltage 300 V/turn. In spite of the screening effect of the vacuum vessel outer wall, the LQG controller is able to suppress the highly unstable RWM without using the second derivative of B. This is important for the reduction of noise in the closed feedback loop and reduces AC losses in the superconducting feedback coils.

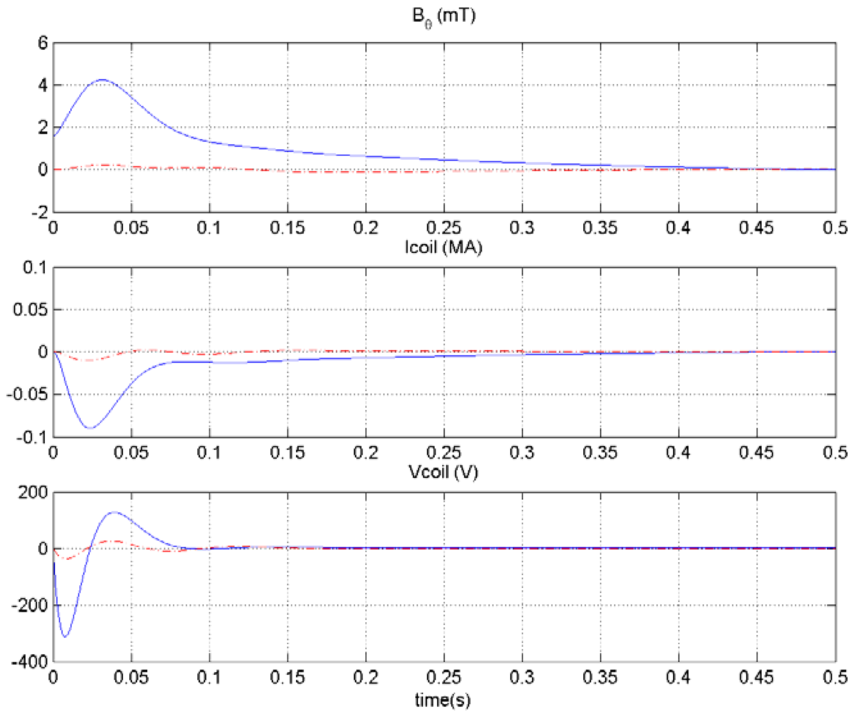

FIG. 3. RWM suppression for the plasma with $C_\beta = 0.83$. LQG controller, no filtering, $B_0 = 1.5$ mT.

The RWM control with filtering of B was also studied using the LQG controller with the goal to reduce the AC losses. Low-pass elliptic filters were assumed in the studies. The Bode diagram for these filters is illustrated by Fig. 4. It was shown that for a moderately unstable RWM ($C_\beta \approx 0.5$) the critical value of the cut-off frequency (when the system loses control) is about 30 Hz. Filtering with the cut-off frequency higher than the critical value by a factor of 2 does not lead to significant deterioration of the RWM control. For a highly unstable RWM ($C_\beta \approx 0.8$), the critical value of the cutoff frequency is 150 Hz. The filtering at 300 Hz only weakly deteriorates the controller performance.

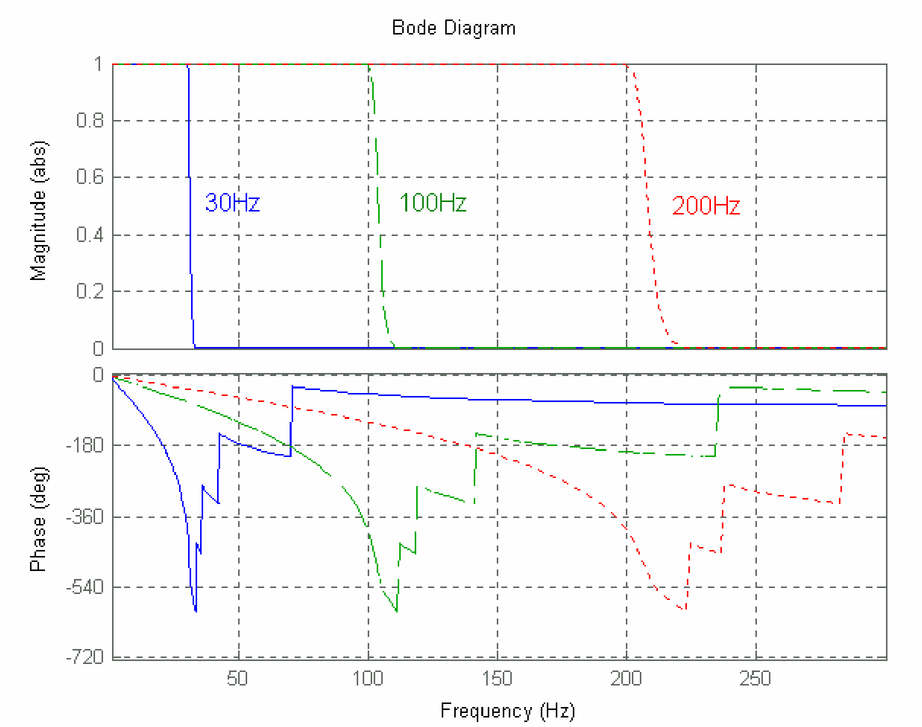

FIG. 4. Bode diagrams of the low-pass elliptic filters with different cutoff frequencies.

A sensitivity study was performed for the highly unstable RWM ($C_\beta = 0.83$) with a goal to assess the effect of uncertainty in the parameters b_0 and B_0 on RWM control and to justify the voltage insulation limit 360 V/turn for the side correction coils. The voltage limit of 300 V/turn was considered in the simulations of RWM suppression. As indicated above, the parameter b_0, the normalization constant in the definition of $P(s)$, is the maximum value of radial component of the amplitude of magnetic field produced by the feedback coils (2D model) on the probes (2D model), when the coil current amplitude J_0 is 1 MA·turn. The current of 1 MA·turn in a pair of ITER side correction coils (3D model) produces a radial field 0.1 T on the sensors shown in Fig. 2. Therefore, the value 0.1 T/MA·turn can be used as the upper estimate for the parameter b_0 in the 2D models. The analytical study, performed in the cylindrical approximation [6], considers the effect of the gap between adjacent coils. For the case of the ITER side correction coils (20% gaps in the toroidal direction), the analysis predicts the reduction of b_0 by about 35%. Taking this into account, the sensitivity study was carried out using two assumptions: $b_0 = 0.1$ T/MA·turn and $b_0 = 0.05$ T/MA·turn. The RWM detection level, B_0, in the sensitivity study was taken 2, 3 and 4 times higher than the expected level of the noise on the poloidal field sensors (0.5 mT). The results of the study are summarized in Table 1. The table shows the maximum values of the coil voltage, V_{max}, current, I_{max}, and poloidal magnetic field on the sensors, B_{max}, arising in the simulations of RWM control. One can see, that the voltage limit 300 V/turn opens the possibility of stabilizing highly unstable RWMs ($C_\beta \approx 0.8$). However, an increase in the voltage above 300 V/turn requires the corresponding enhancement of the coil current and, as a consequence, a larger number of turns in the side correction coils. This requires more space and it is not feasible. It should be also noted that the lower detectable limit of RWM (B_0 in these simulations) reduces the voltage demand.

TABLE 1. RWM CONTROL WITH BASIC LQG CONTROLLER AND IDEAL POWER SUPPLY.

	b_0 = 0.1 T/MA turn		b_0 = 0.05 T/MA turn	
	B_0 = 1.5 mT	B_0 = 2.0 mT	B_0 = 1.0 mT	B_0 = 1.5 mT
V_{max}, V/turn	300	300	300	300
I_{max}, MA turn	0.09	0.125	0.125	**0.350***
B_{max}, mT	4.3	6.8	3.4	11.1

* *the present design limit is 0.28 MA turn*

Preliminary studies of the RWM control were also performed with a simplified model of the power supply. In particular the effect of time delay in the power supply on the RWM control was analyzed. The power supply model is schematically shown in Fig. 5.

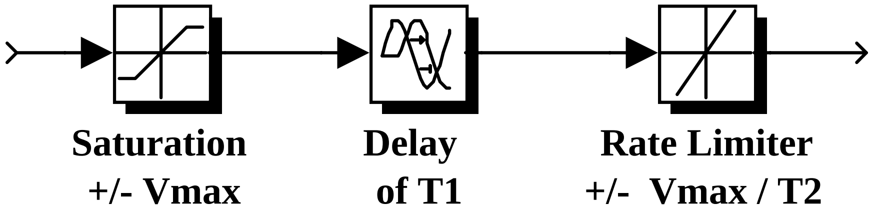

FIG. 5 Simplified model of the power supply.

The reference values of its parameters are as follows: V_{max} = 350 V/turn, T_1 = 2 ms, T_2 = 3.75 ms. The simulations were carried out for B_0 = 1.5 mT with the basic LQG controller, designed assuming the ideal power supply ($V_{max} = \infty$, T_1 = 0, T_2 = 0). The plasmas with different degree of RWM instability were considered (C_β = 0.37, 0.52, 0.67 and 0.83); the diagnostic signal was not filtered. It was shown that the power supply time delay of 2 ms and the voltage rate limiter of 93 V/turn·ms only slightly affect the RWM control. In addition to the above study, which was performed with the reference values of T_1 and T_2 for the highly unstable RWM (C_β = 0.83), we also studied its control with the power supplies having higher values of T_1 and T_2. Two cases of the power supply model were considered: Case 1, V_{max} = 350 V/turn, T_1 = 2.5 ms, T_2 = 3.75 ms, and Case 2, V_{max} = 350 V/turn, T_1 = 5 ms, T_2 = 15 ms. The simulations have shown that the basic LQG controller (designed assuming T_1 = 0) suppresses the RWM with the power supply Case 1, whereas it cannot suppresses the RWM if the power supply Case 2 is used. To suppress the RWM using the power supply Case 2, a new LQG-controller was synthesized, taking into account the power supply delay T_1 = 5 ms. This new controller can suppress the RWM using the power supply Case 2. However, the settling time of the RWM control becomes enhanced and it requires higher current. The results of simulations, the maximum values of the coil voltage, V_{max}, current, I_{max}, and poloidal magnetic field on the sensors, B_{max}, arising in the simulations of control of the highly unstable RWM (C_β = 0.83), are summarised in Table 2.

TABLE 2. RWM CONTROL WITH DIFFERENT MODELS OF POWER SUPPLY.

Controller	Designed for T_1=0	Designed for T_1=0	Designed for T_1=0	Designed for T_1=5ms
Power supply	Reference	Case 1	Case 2	Case 2
B_{max}, mT	5	5.2	RWM is unstable	16.4
V_{max}, V/turn	330	338	RWM is unstable	307
J_{max}, kA·turn	111	119	RWM is unstable	231

5. Conclusion

The control of RWM in ITER Scenario 4-type plasmas was studied using semi-analytical models of RWM developed Y.Q. Liu and A. Bonderson using the MARS-F code [2]. On the basis of these models, we produced the LQG controller, which was used in the studies of RWM control in ITER. In spite of the screening effect of the vacuum vessel outer wall, the controller is able to suppress highly unstable RWM ($C_\beta \approx 0.8$) without using the second derivative of n = 1 mode of the poloidal magnetic field. It has been shown that it is possible to suppress highly unstable RWM by the side correction coils within the voltage of about 300 V/turn. The studies justified the choice of the 10 kV voltage insulation limit for these coils and assessed the acceptable cut-off frequency in the RWM diagnostics filtering. The frequency is 60 Hz for a moderately unstable RWM ($C_\beta \approx 0.5$) and 300 Hz for a highly unstable RWM ($C_\beta \approx 0.8$). It has been shown that the reference values of the power supply time delay (2 ms) and the voltage rate limit (93 V/turn ms) only slightly affect the RWM control. Further studies of the ITER RWM control are required. In particular, they should take into account more realistic 3D models of the side correction coils.

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