Development of tokamak plasma vertical control system with neutral point taking into account

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1. Introduction

Since typical plasma in most of the existing tokamaks and future tokamak reactors, such as ITER, has a vertically elongated cross section, it is subject to vertical instability. Due to the size and therefore cost of such tokamaks, there will naturally be smaller margins in the poloidal field (PF) coil power supplies to provide the plasma stabilization by vertical feedback control system [1]. On the other hand, it is known, that the vertically elongated plasma has a neutral point (NP) in vertical direction [2, 3], above which the open loop plasma moves upward and correspondently the plasma moves downward if the plasma is located below NP.

Presented paper describes the design of linear models of T-15 tokamak vertically elongated plasma [4] (Fig. 1) together with development of vertical plasma control system. Here the connected in series fast poloidal field coils 10_{up} and 10_{dw} are used for plasma vertical control in present study. This system is optimized on the plasma position Z_p relatively NP location. Evolution of plasma is simulated with non linear tokamak plasma model implemented in DINA code [5].

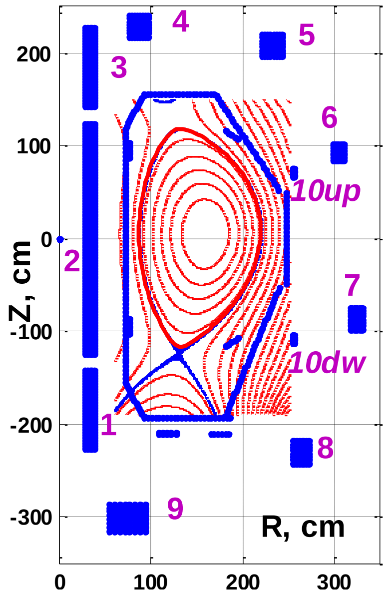

Fig. 1: Vertically elongated plasma in T-15

2. Linear plasma model

To develop control system to stabilize the plasma vertical position the linear model in following state space form

$$\begin{cases} dx(t)/dt = Ax(t) + Bu(t) \\ y(t) = Cx(t) + Du(t) \end{cases} \qquad (1)$$

was created. Linear models have been obtained with use of DINA code by two methods: 1) direct linearization of non-linear plasma model at specified time moment [6] and 2) identification of numerical experiments on plasma movement in vertical direction [7]. Here *A*, *B*, *C*, *D* are the matrixes of the model, *y* is the output vertical position displacement δZ, the variable *u* is the output voltage in the tenth PF coil. The vector *x* is the state variable, which for T-15 plasma in case of direct linearization of non-linear model includes the variations of currents δI in both active (10 pieces) and passive (54 pieces) coils. In canonical form the equation system (1) can be presented as

$$\begin{cases} d\delta I(t)/dt = A\delta I(t) + Bu(t) \\ y(t) = C\delta I(t) + Du(t) \end{cases} , \qquad (2)$$

where $A=-L^{-1}R$, $B=-L^{-1}$, D=0. Inductivity matrix L, resistivity vector R and matrix C are calculated during linearization.

Identification case of linear model was calculated by applying of nonzero signal in one input together with zero signals in other inputs. Taking corresponding output signals the transfer functions between applied input and the all outputs are created. Transfer matrix, which is connected with A, B, C and D matrixes in (1) as $H(s)=C(sI-A)^{-1}B+D$ (here s is the complex variable, I is the identity matrix) is calculated by repeating of such routine for the every input. Then the inverse problem is solved to reconstruct the state space form (1) for identification case of linear model.

To choose the linear model for design of vertical position controller the comparison simulations of plasma evolution during several vertical displacement events (VDE) were carried out with use of three cases of linear simulation models and the non-linear plasma simulation model. Such VDEs were triggered by disturbance of voltage in one PF coil shown in Fig. 1 while the voltages in other coils were equal zero. Time averaged relative difference between Z coordinate of plasma axis simulated with linear and identification plasma models for each case of PF coil disturbance are shown in Fig. 2 where N_{coil} is a number of active coil. Here the three linear plasma model simulation cases are considered: 1) direct linearization of non-linear model with assumption of zero plasma resistance R_p, 2) direct linearization of non-linear model with assumption of T-15 plasma resistance equal R_p= 2.3280 mΩ and 3) identification case of non-linear model. One can see firstly that the including of plasma resistance in linear model decreases an error in response of non-linear plasma simulation and secondly the modeling results of plasma movement during VDE with use

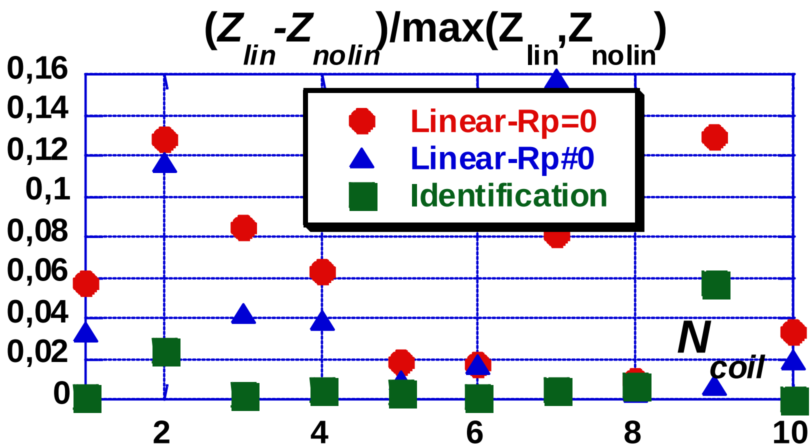

Fig. 2: Relative difference between Z coordinate of plasma axis simulated with linear and non-linear plasma models for each case of PF coil disturbance

of identification case is much closer to the non-linear modeling ones. Thus the plasma vertical controller for T-15 plasma movement was designed on the base of identification case of non-linear model.

3. Design of vertical plasma position control system

Design of T-15 plasma position control system is based on LQ-controller [8], in which the control signals are calculated as $u = -Kx$, where matrix K is defined from minimizing of functional $I = \int_0^{+\infty} \left(x^T Q x + u^T R u + 2x^T N u \right) dt$. Here Q, R are the diagonal weighting matrixes, matrix N is selected to provide the acceptable control time and magnitude of the contrable impact. The ratio between the elements of R matrix determines the distribution of control in the coils. The relationship between the elements of Q matrix determines the difference between the deviations of the corresponding elements of the vector x from zero.

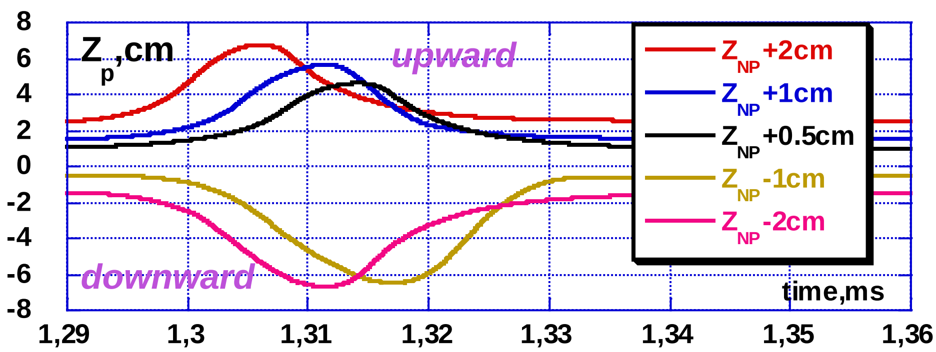

Fig. 3: Several upward and downward scenarios with plasma vertical position stabilization in T-15

4. Simulation results

Described in previous section plasma vertical position controller was used to study the T-15 plasma stabilization during both upward and downward VDEs with different set points of Z plasma position relative to Z_{NP}, which is ≈ 0.5 cm for T-15 plasma. The five plasma stabilized scenarios in vertical direction were considered with following set points of Z: $Z_{sp1} = Z_{NP}+2$ cm, $Z_{sp2} = Z_{NP}+1$ cm, $Z_{sp3} = Z_{NP}+0.5$ cm, $Z_{sp4} = Z_{NP}-1$ cm, $Z_{sp5} = Z_{NP}$ -2 cm. The initial Z positions of plasma in the beginning of these scenarios are chosen to be equal correspondently Z_{p01} = 2.5 cm, Z_{p02} = 1.5 cm, Z_{p03} = 1.1 cm, Z_{p04} = -0.5 cm, Z_{p05} = -1.5 cm (see Fig. 3). The time moment t_c when the plasma vertical position stabilization is

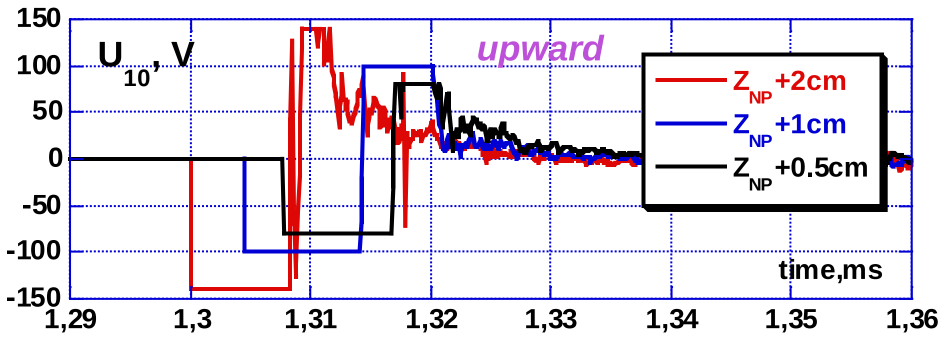

Fig. 4: Waveforms of voltages in 10-th P F coil during plasma position control in considered upward scenarios

switched on is defined when during VDE the value of $abs(Z_p(t_c)\text{-}Z_{p0}) \geq 2.5$ cm. At that time moment the voltage on 10-th PF coil is applying. The level of voltage U_{max} is chosen to have the minimum its value to change the direction of uncontrolled vertical movement. In Fig. 4 the waveforms of U_{10} are presented for all considered upward plasma movement VDE scenarios. One can see that the closer plasma is located to NP the smaller $|U_{max}|$ value is necessary to suppress the plasma vertical velocity. Such effect seems to be more effective in the case of plasma vertical movement towards X-point location (see Fig. 5). That means that the power supply of plasma vertical control system is lower if the controllable plasma is located closer to NP.

5. Conclusions

Simulation results of sensitivity study of plasma position control in T-15 have shown that the maximum value of voltage in control poloidal fields coils is decreasing if the plasma at the start of VDE locates closer to the neutral point. In that case there is possibility to decrease the power supply of plasma vertical control system. Such effect is more effective in the case of plasma vertical movement towards X-point location. This study is carried out with vertical control system based on T-15 plasma linear model designed with identification method of linearization obtained with use of DINA code.

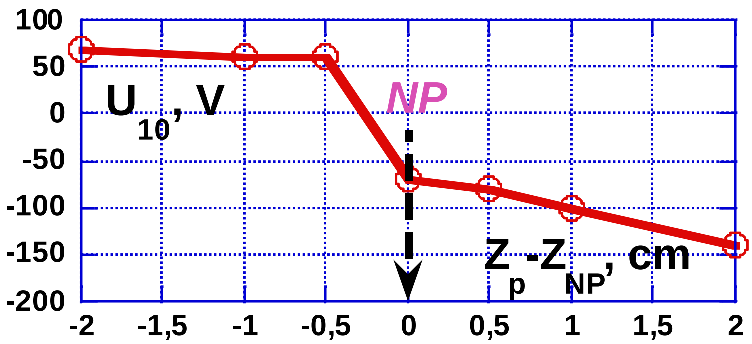

Fig. 5: Maximum value of voltage in 10-th PF coil depending on initial plasma position corresponding NP location

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