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A novel design of feedback control system for plasma horizontal position in IR-T1 tokamak

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ABSTRACT

Determination of accurate plasma horizontal position during plasma discharge is essential to transport it to a control system based on feedback. By using the plasma-circuits linearized model, Proportional Integral Derivative (PID) based controllers and a first order transfer function representing the power supply (PS) dynamics of vertical coil system for IR-T1 tokamak, we analyzed step feedback response of the overall system of IR-T1 tokamak and corresponding Bode diagrams for two cases with and without the plasma resistance and the eddy currents distribution. Also we did experiments for determination of plasma horizontal displacement in this tokamak. This work is done by four magnetic probes that are installed on the circular contour of the tokamak. This data used as input to the feedback controller to validate the performance of it. Results of feedback response analysis show that the controller has good performance. Due to approximations in the controller design, construction, installation and implementation of the controller is necessary and this is the purpose of our future works.

1. Introduction

Plasma position control is a matter of significant concern for the next generation of large tokamaks. Control of plasma displacement has the important role in magnetic confinement of plasma in tokamak system. Control of plasma position in a tokamak is usually carried out on the basis of simple models [1–3]. They provide simulation environments that can be used to check the performance of a control system. Several linearized models have been proposed in the literature. Most of them are based on simplifying assumptions that dramatically reduce the dimensionality of the system [4,5]. The models initially used for plasma control included more or less detailed circuit equations for both active and passive conductors, but treated the plasma in an approximate fashion, often as a set of filamentary coils with a prescribed, usually rigid, motion [1,2]. The passive structures (like vacuum vessel) can also be schematized as a number of passive (short circuited) conductors. Putting together the linearized response of the plasma, Proportional Integral Derivative (PID) based controller and a power supply (PS) model for vertical field coil system, we can complete the behavior of the overall system. The paper has the following structure. Section 2 includes IR-T1 tokamak characteristics. In Section 3 we present the feedback design for application in plasma horizontal position control. PID controller and power supply design are represented in Section 4. In Section 5 the step feedback response of the overall system of IR-T1 tokamak and corresponding Bode diagrams for two different cases with and without the plasma resistance and the eddy currents distribution are presented. Description of the method for determination of plasma horizontal displacement by magnetic probes for IR-T1 tokamak will be presented in Section 6. This displacement is used as input to the feedback controller to validate the performance of it. In Section 7 the feedback response of the overall system of IR-T1 tokamak due to the displacement is represented. Section 8 is devoted to discussion of the results.

2. IR-T1 tokamak

IR-T1 is a small low beta and large aspect ratio tokamak with a circular cross section (see Table 1) [6–16]. In Fig. 1, we depicted IR-T1 tokamak components. In this paper we consider the flat-top phase of IR-T1 tokamak discharge for plasma horizontal position control. Vertical field penetration time is obtained by $\tau = \frac{\mu_0 L^2}{\eta}$; where η is the resistivity and L is length scale of magnetic field spatial variation. For IR-T1 tokamak, this time is approximately 1 ms and time scale of the vertical field power supply is approximately 50 ms. Also skin depth of eddy currents obtains by $\delta = \sqrt{\frac{2\eta}{\mu_0 \omega}}$; here

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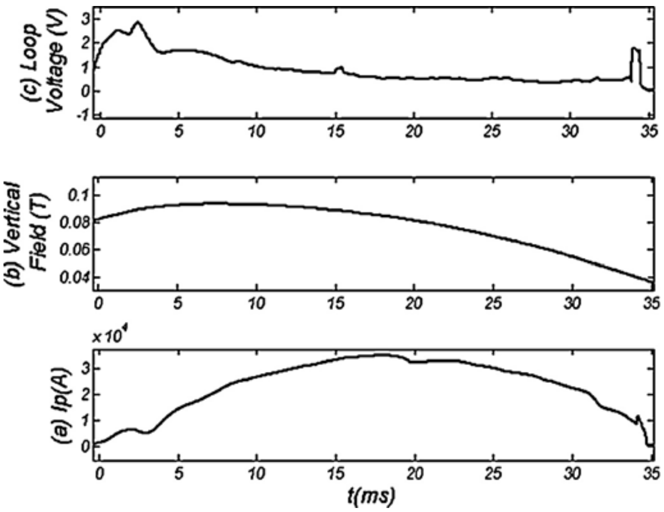

Fig. 1. IR-T1 tokamak components (top), and (a) plasma current, (b) vertical field, and (c) loop voltage.

η is resistivity of stainless steel and ω is eddy current variation frequency that is equal to plasma current frequency. For IR-T1 tokamak, we have approximate value $\delta \approx 2\text{cm}$.

3. Feedback control design based on plasma-circuits linearized model

The linearized response of the plasma includes describing the general response of the plasma to changes in the currents in the passive structures of the vessel and to changes in the currents in the active poloidal field (PF) coils. The plasma model which has been used in this analysis is:

$$\frac{dx}{dt} = Ax + Bu + E\frac{d\omega}{dt}\ , \mathrm{y} = \mathrm{Cx} + \mathrm{Du} + \mathrm{F}\omega \quad (1)$$

In which the internal state vector (passive, active and plasma currents) is $\boldsymbol{x} = \left[\delta \boldsymbol{I}, \delta \boldsymbol{I}_p\right]^T$ and the input vector is $\boldsymbol{u} = \left[\delta \boldsymbol{V}, 0\right]^T$. The quantities $\delta \boldsymbol{I}$, $\delta \boldsymbol{I}_p$ and $\delta \boldsymbol{V}$ represent linearized deviations about their nominal values and also $\boldsymbol{\omega} = \left[\delta\beta_p, \delta l_i\right]^T$. The matrices $\boldsymbol{E}$ and $\boldsymbol{F}$, determined using the system response to canonical disturbances. $\boldsymbol{E}$ and $\boldsymbol{F}$ matrices are not used in this present paper since we shall only

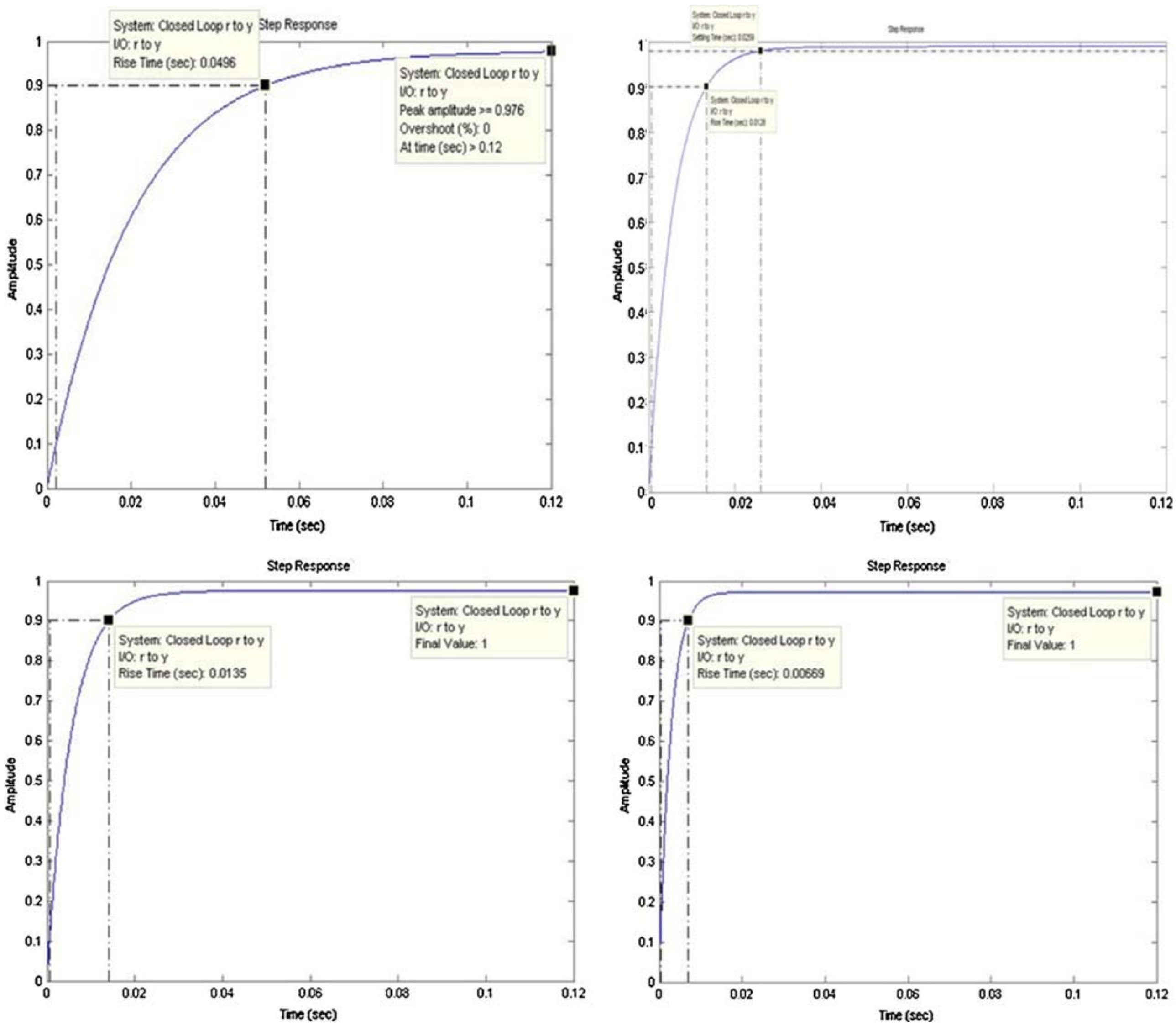

Fig. 2. Step closed loop response of the overall system of IR-T1 tokamak without the plasma resistance and the eddy currents distribution; top left: $a = 1$, top right: $a = 2$, bottom left: $a = 5$and bottom right: $a = 10$.

Table 1
Characteristics of IR-T1 tokamak.

Parameters	Value	Parameters	Value
R_0, Major radius (m)	0.45	B_0, toroidal field (T)	< 1
a, Minor radius (m)	0.125	I_p, plasma current (kA)	< 35
β_p, poloidal beta	1	II, toroidal current (kA)	~5
Electron Density	$0.7 - 1.5 \times 10^{13} cm^{-3}$	Discharge time	<35 ms

be considering external actions on the plasma via the coil voltage vector [17,18].

4. PID controller and power supply design

From the full order model that presented in Eq. (1), a reduced order model with one input (changes in the vertical field voltage) and one output (plasma horizontal displacement) was extracted and based on that a Proportional Integral Derivative (PID) based controller for vertical coil system of IR-T1 tokamak was designed. We have tested some common forms for PID controller and then we have chosen the following transfer function of PID controller for

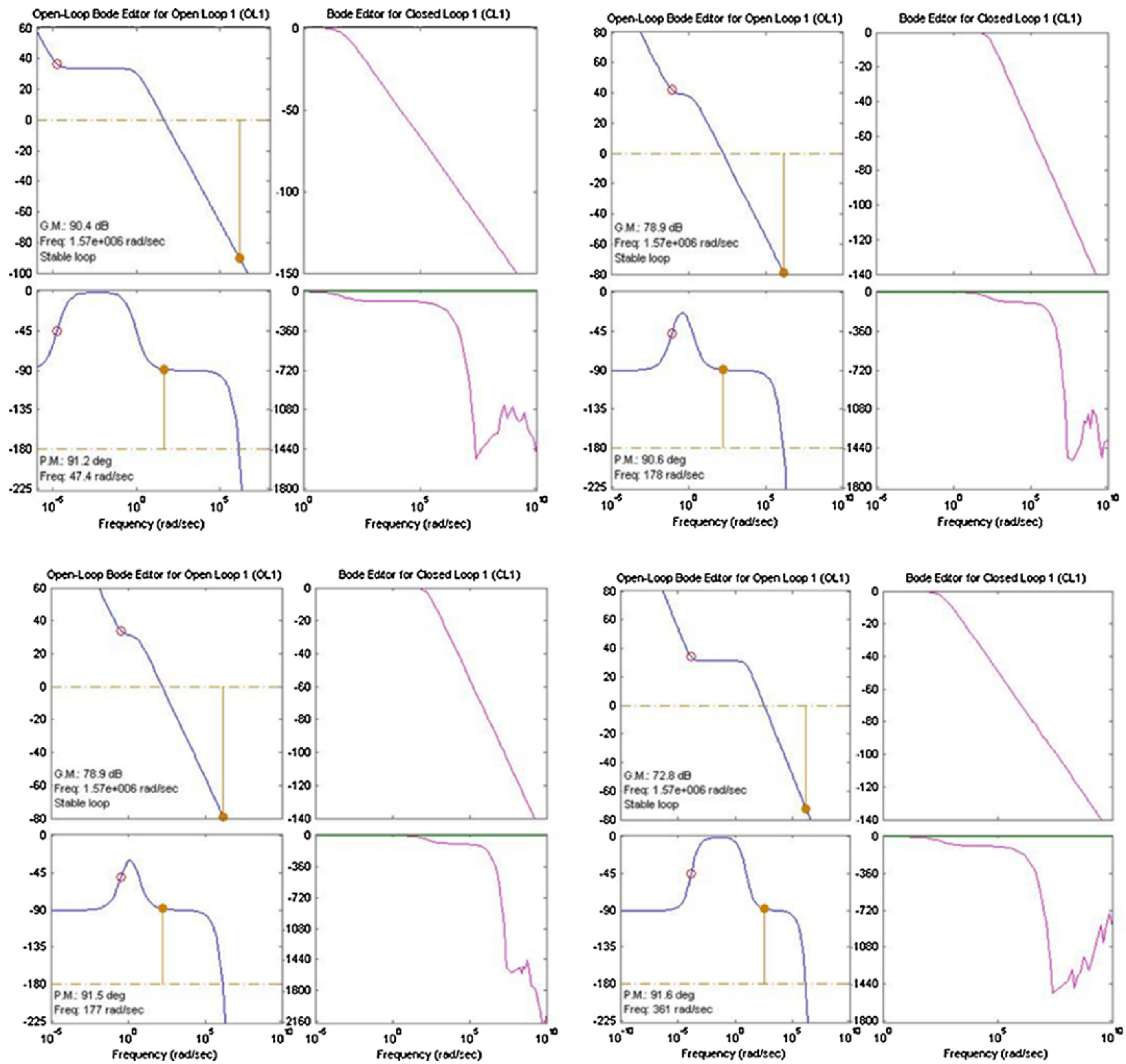

Fig. 3. Open loop and closed loop Bode diagram of the overall system of IR-T1 tokamak without the plasma resistance and the eddy currents distribution; top left: $a = 5$, top right: $a = 10$, bottom left: $a = 1$and bottom right: $a = 2$.

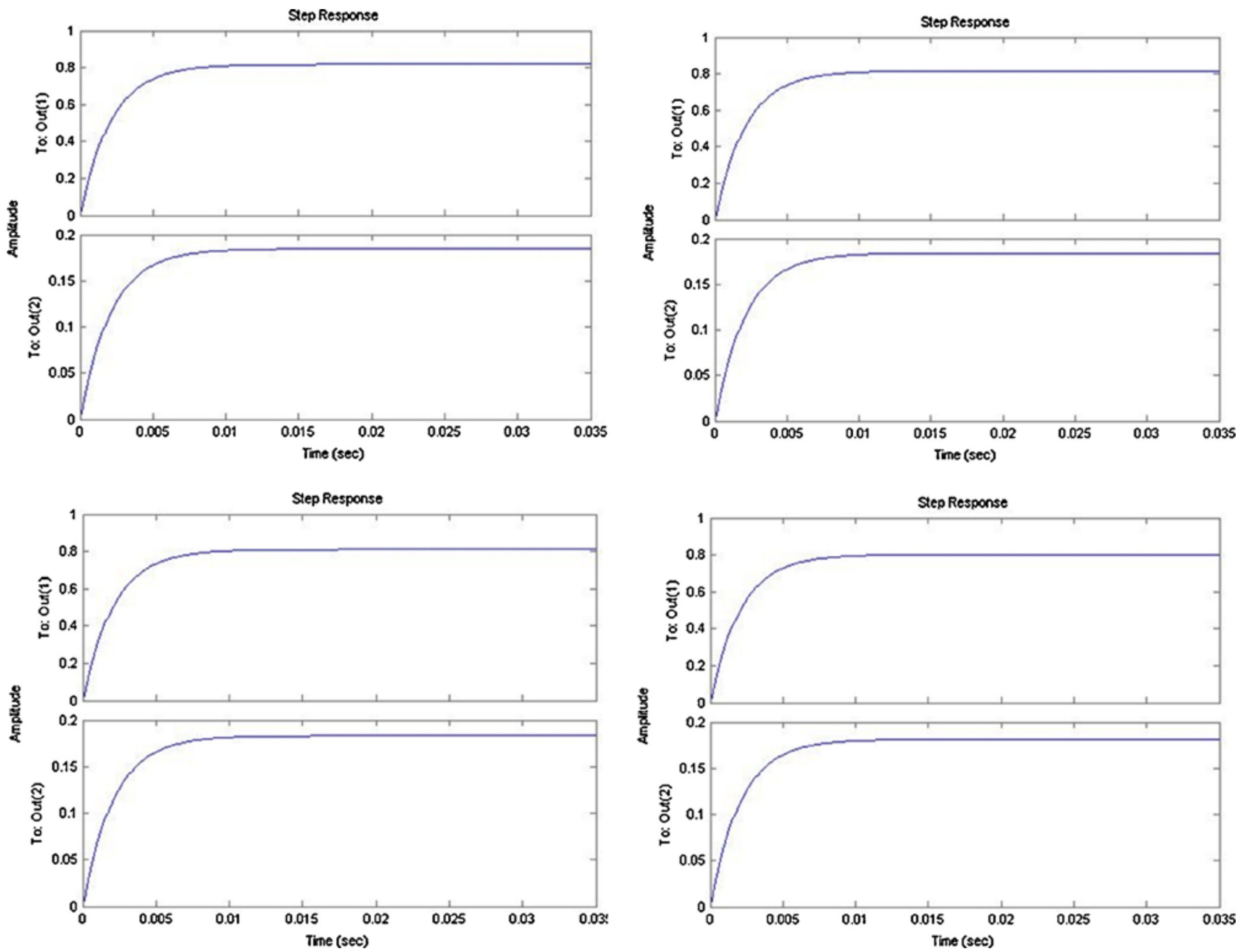

Fig. 4. Step closed loop response of the overall system of IR-T1 tokamak with the plasma resistance and the eddy currents distribution; top left: $a = 1$, top right: $a = 2$, bottom left: $a = 5$and bottom right: $a = 10$.

horizontal plasma position control (controller with filtered derivative) [19]:

$$G_{PID}(s) = K\left[1 + \frac{1}{T_i s} + \frac{T_d s}{1 + s\frac{T_d}{N}}\right]. \quad (2)$$

where K is the gain, T_i is the integral time and T_d is a time constant used to approximate the derivative action. To model the power supply (PS) of vertical coil system of IR-T1 tokamak, we are using only a first order filter, approximating the time delay and bandwidth of the PS. The proposed transfer function for PS system is:

$$G_v(s) \cong K_v \frac{e^{-T_v s}}{s + a} \quad (3)$$

where $K_v \simeq 1$ and $T_v = 1\mu s$ and a represent the pole of vertical coil system. With considering of Eq. (1) for plasma horizontal position controller design problem (without the matrices $\boldsymbol{E}$ and $\boldsymbol{F}$), the values of A, B, C and D for IR-T1 characteristics can be calculated by using the method proposed in Ref. [20]. With these values we can derive transfer function for the plasma response of IR-T1 tokamak. The blocks described above (plasma response model, PID controller and power supply model) put together and a closed-loop simulation will be carried out [18].

5. Application to IR-T1 tokamak and related results

By using the approach presented in Ref. [21], the equations of plasma-circuits linearized model (plus linearized output equation) are given by:

$$L^*\delta\dot{x} + R\delta x + E\delta\dot{\omega} = B\delta u,\ \delta y = C\delta x + F\delta\omega, \quad (4)$$

where (as Section 3) x is currents vector includes active, passive (eddy) and plasma currents,R is resistance matrix for these components (active, passive and plasma), E and F are matrices related to time derivative of perturbation ($\omega = \left[\delta\beta_p, \delta l_i\right]^T$ is perturbation in our model) and perturbation itself, B is unity matrix, L^* is the modified inductance matrix (that is defined in Ref. [21]),u is input, y is output,C is state-to-output matrix and δ represents linearized deviation about nominal values. Eq. (4) can be written as:

$$\begin{pmatrix} L_a^* & L_{ae}^* & L_{ap}^* \\ L_{ea}^* & L_e^* & L_{ep}^* \\ L_{pa}^* & L_{pe}^* & L_p^* \end{pmatrix}\begin{pmatrix} \delta\dot{x}_a \\ \delta\dot{x}_e \\ \delta\dot{I}_p \end{pmatrix} + \begin{pmatrix} R_a & 0 & 0 \\ 0 & R_e & 0 \\ 0 & 0 & R_p \end{pmatrix}\begin{pmatrix} \delta x_a \\ \delta x_e \\ \delta I_p \end{pmatrix} + \begin{pmatrix} E_a \\ E_e \\ E_p \end{pmatrix}\delta\dot{\omega} = \begin{pmatrix} I \\ 0 \\ 0 \end{pmatrix}\delta u,\ \delta y = C\begin{pmatrix} \delta x_a \\ \delta x_e \\ \delta I_p \end{pmatrix} + F\delta\omega, \quad (5)$$

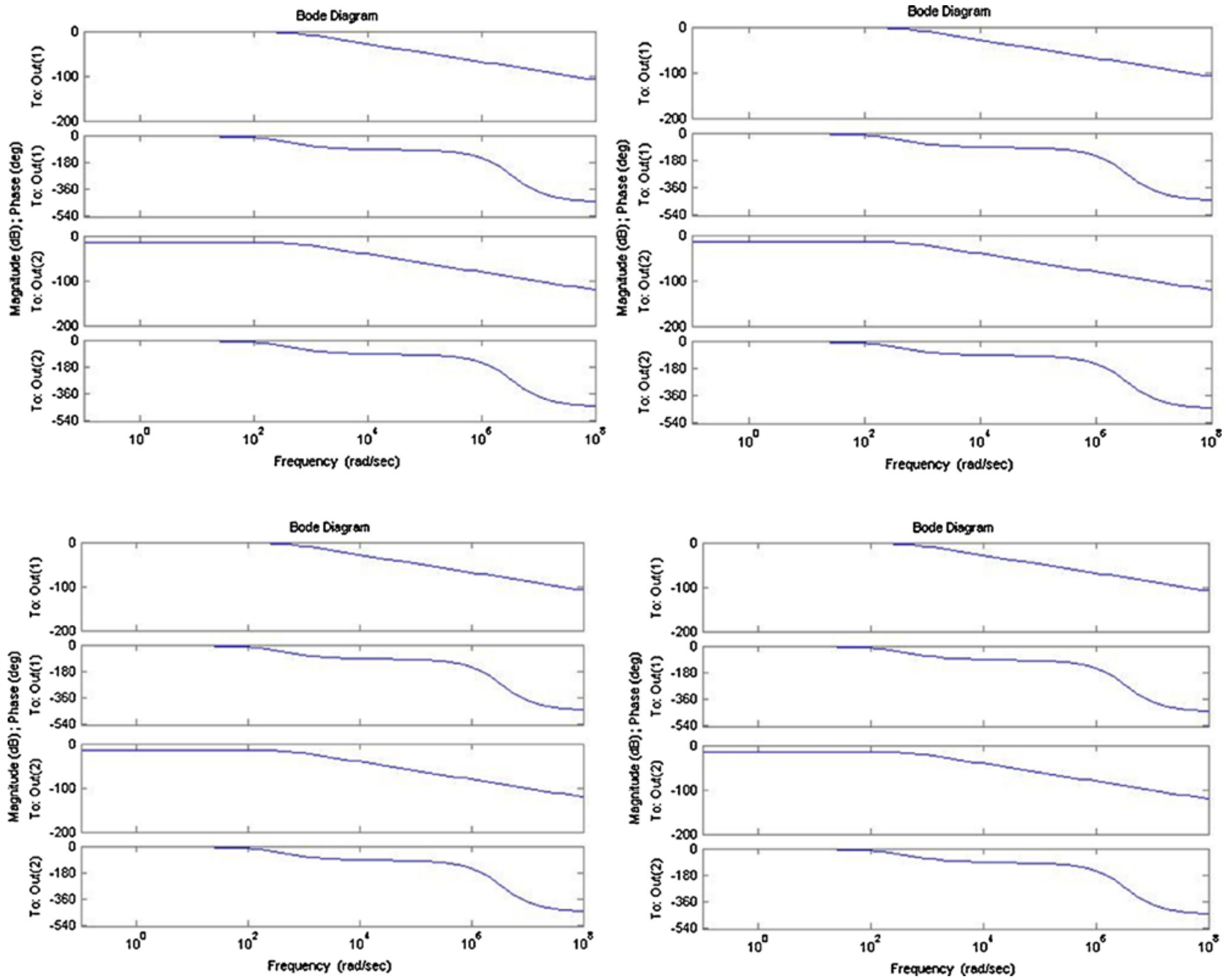

Fig. 5. Closed loop Bode diagram of the overall system of IR-T1 tokamak a with the plasma resistance and the eddy currents distribution; top left: $a = 1$, top right: $a = 2$, bottom left: $a = 5$and bottom right: $a = 10$.

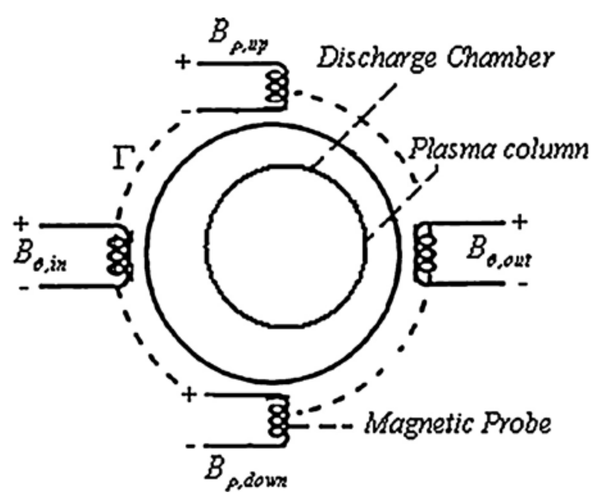

Fig. 6. Positions of the four magnetic probes on the outer surface of the IR-T1 tokamak chamber.

where subscripts a, e and p are related to active, passive and plasma components. By ignoring $\boldsymbol{E}$ and $\boldsymbol{F}$ matrices in this paper, we studied two cases. In first case we neglect the plasma resistance and the eddy currents distribution. Then Eq. (5) transforms to:

$$\delta\dot{x}_a = -\left(L_a^* - \frac{L_{ap}^* L_{pa}^*}{L_p^*}\right)^{-1} R_a \delta x_a + \left(L_a^* - \frac{L_{ap}^* L_{pa}^*}{L_p^*}\right)^{-1} \delta u, \begin{pmatrix} \delta y \\ \delta I_p \end{pmatrix} = \begin{pmatrix} C \\ -L_{pa}^*/L_p^* \end{pmatrix} \delta x_a \quad (6)$$

For this case, we have model with linearized deviation of vertical coil current from equilibrium value (δI_v) as the state vector and change in vertical field voltage as the input (δu). Here we have a voltage driven model [18,21]. Comparison of Eq. (6) with Eq. (1), give us unknown values A, B,C and D for voltage driven model (as we cited in Section 4). In Fig. 2 we have presented step closed-loop response of the overall system of IR-T1 tokamak for first case. After choosing the PID controller transfer function (Eq. (2)) and optimizing the parameters of controller, in the next step for tuning and good performance of the overall feedback response of the system, we optimized the pole of the vertical field power supply. In other words, we investigate the PS dynamic performance in the overall system dynamic. We imply that the parameters of PID controller design optimized to have best performance for any value of poles. We choose four different values for a of the PS system to find opti-

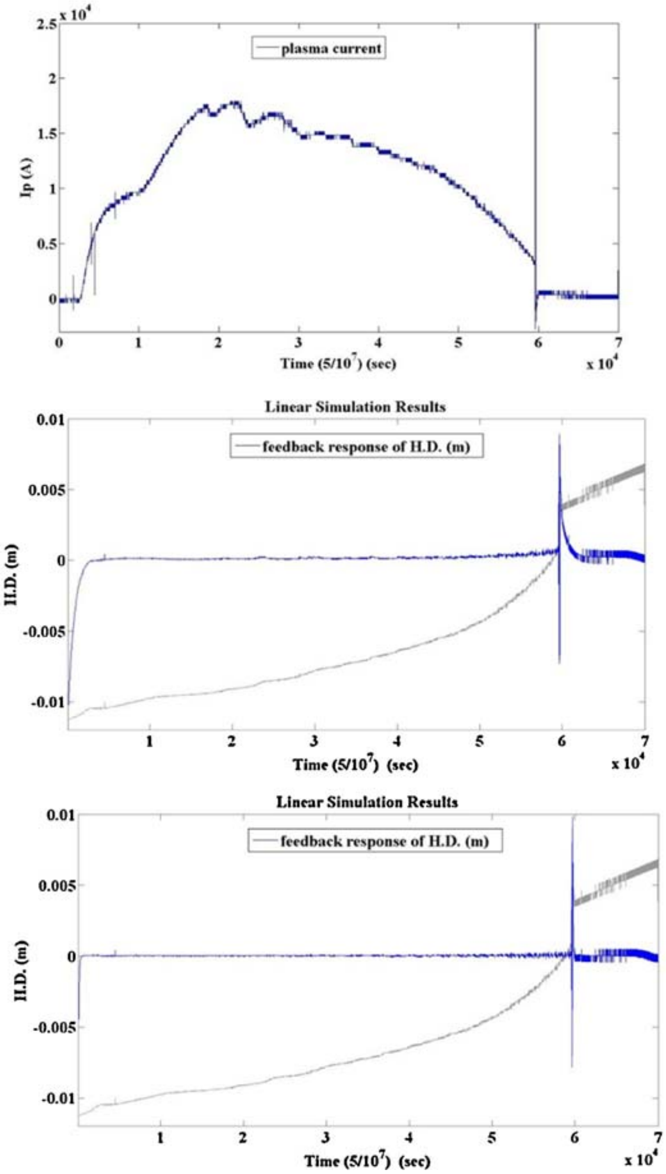

Fig. 7. From top to bottom respectively: Plasma current, Horizontal displacement (H.D.) and its feedback response for V = 2.80 kV with pole = 1, and pole = 10. The whole time interval is 35 ms.

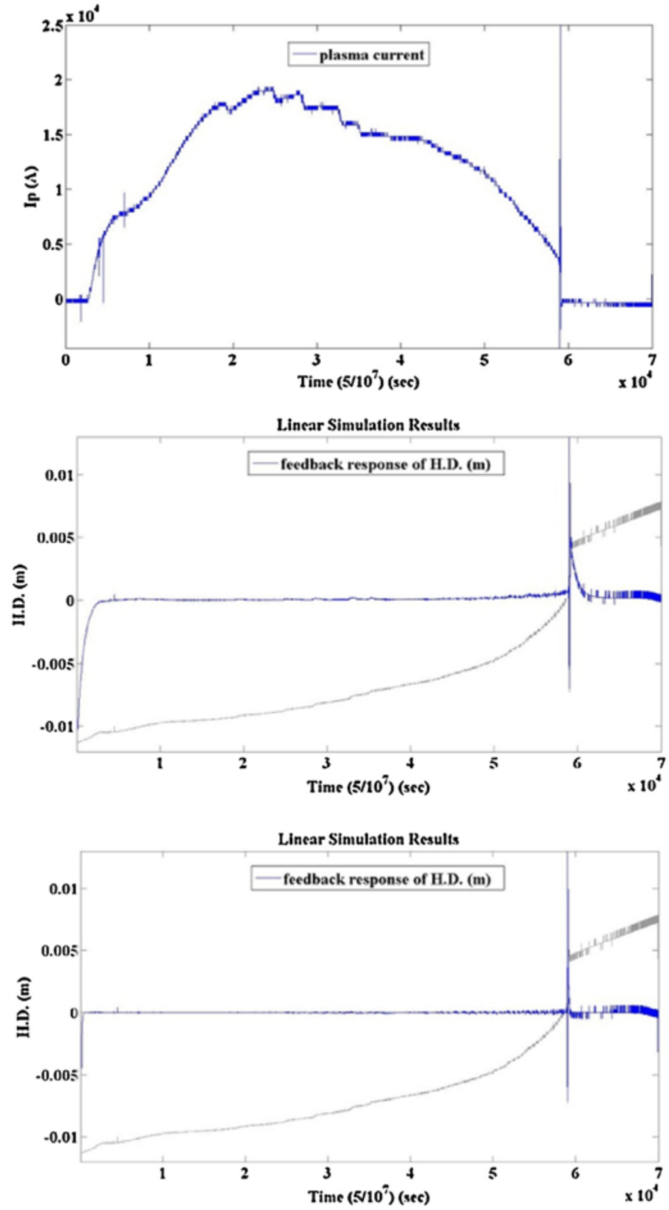

Fig. 8. From top to bottom respectively: Plasma current, Horizontal displacement (H.D.) and its feedback response for V = 3 kV with pole = 1, and pole = 10. The whole time interval is 35 ms.

mum value of that. About optimizing the pole of the PS model, we should imply that our main purpose is investigation of PS dynamic performance in the overall system dynamic. To guarantee the stabilization of model, in Fig. 3 we show Bode diagrams of the response (open loop and closed loop response). From Figs. 2 and 3, we can see that $a = 2$ has approximately better performance in view of control and stability than other responses and in which gain and phase margins are sufficiently high. This value gives us an estimate and actually the optimum value of a must be experimentally validated.

In second case we consider these effects (the plasma resistance and the eddy currents distribution). First we consider the plasma and eddy currents circuit equations:

$$\begin{pmatrix} L_e^* & L_{ep}^* \\ L_{pe}^* & L_p^* \end{pmatrix} \begin{pmatrix} \delta \dot{x}_e \\ \delta \dot{I}_p \end{pmatrix} + \begin{pmatrix} L_{ea}^* \\ L_{pa}^* \end{pmatrix} \delta \dot{x}_a + \begin{pmatrix} R_e & 0 \\ 0 & R_p \end{pmatrix} \begin{pmatrix} \delta x_e \\ \delta I_p \end{pmatrix} = 0. \tag{7}$$

Now we define two new parameters as:

$$\begin{pmatrix} \delta\psi_e \\ \delta\psi_p \end{pmatrix} = \begin{pmatrix} L_e^* & L_{ep}^* \\ L_{pe}^* & L_p^* \end{pmatrix} \begin{pmatrix} \delta x_e \\ \delta I_p \end{pmatrix} + \begin{pmatrix} L_{ea}^* \\ L_{pa}^* \end{pmatrix} \delta x_a \tag{8}$$

With considering of Eqs. (7) and (8), we have:

$$\begin{pmatrix} \delta\dot{\psi}_e \\ \delta\dot{\psi}_p \end{pmatrix} = -\begin{pmatrix} R_e & 0 \\ 0 & R_p \end{pmatrix} \begin{pmatrix} L_e^* & L_{ep}^* \\ L_{pe}^* & L_p^* \end{pmatrix}^{-1} \begin{pmatrix} \delta\psi_e \\ \delta\psi_p \end{pmatrix} + \begin{pmatrix} R_e & 0 \\ 0 & R_p \end{pmatrix} \begin{pmatrix} L_e^* & L_{ep}^* \\ L_{pe}^* & L_p^* \end{pmatrix}^{-1} \begin{pmatrix} L_{ea}^* \\ L_{pa}^* \end{pmatrix} \delta x_a, \ \delta y = \begin{pmatrix} C_e & 0 \\ 0 & C_p \end{pmatrix} \begin{pmatrix} L_e^* & L_{ep}^* \\ L_{pe}^* & L_p^* \end{pmatrix}^{-1} \begin{pmatrix} \delta\psi_e \\ \delta\psi_p \end{pmatrix} + \left(\begin{pmatrix} C_a \\ 0 \end{pmatrix} - \begin{pmatrix} L_e^* & L_{ep}^* \\ L_{pe}^* & L_p^* \end{pmatrix}^{-1} \begin{pmatrix} L_{ea}^* \\ L_{pa}^* \end{pmatrix} \right) \delta x_a. \tag{9}$$

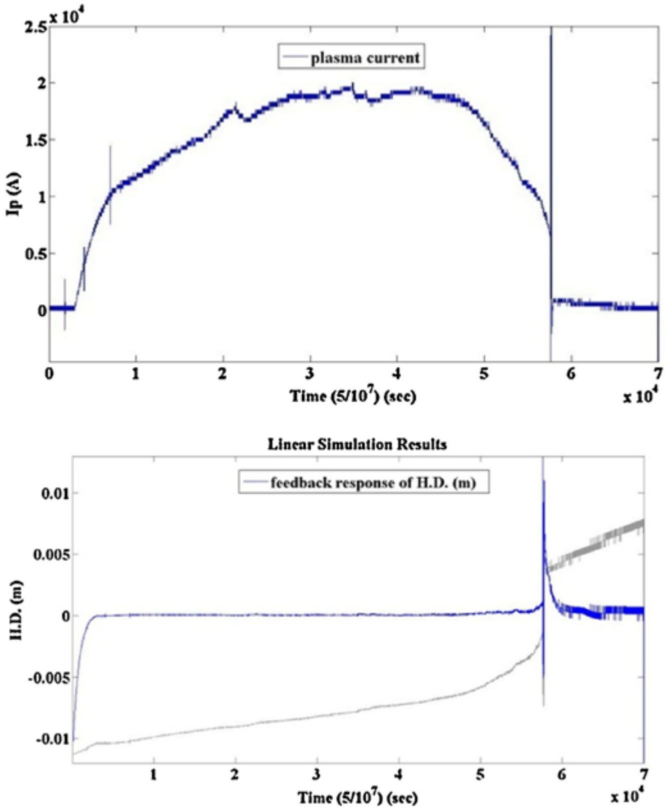

Fig. 9. From top to bottom respectively: Plasma current, Horizontal displacement (H.D.) and its feedback response for V = 3.25 kV with pole = 1, and pole = 10. The whole time interval is 35 ms.

For this case, we have linearized deviation of vertical coil current from equilibrium value as input (δI_v) and two new parameters ($\delta\psi_e$ and $\delta\psi_p$) as state vector. We called this model as current driven model [18,21]. Again Comparison of Eq. (9) with Eq. (1), give us unknown values A, B,C and D for current driven model (as we cited in Section 4). The time constant of eddy current responses which are generally considered to be the skin time of the vacuum chamber is very short compared to time constant of variation of vertical field coil current and the eddy currents become almost stationary after the skin time. The uniform eddy current is sustained during the time constant of variation of vertical field coil current. In the case of control with eddy currents effect, the sampling time of the plasma position controller should be shorter than the time constant of the eddy current. Same procedures are done for second case in Figs. 4 and 5. From these figures, we can see that there is no significant difference between the values of *a*. This means that the dynamic of our passive structure is dominating. Again this issue must be experimentally validated.

6. Magnetic probes method

In general the magnetic sensors (magnetic probe or diamagnetic loop) work by Faraday's law and measures component(s) of the local magnetic fields or magnetic fluxes for use in plasma control, equilibrium reconstruction and detection of plasma energy, poloidal beta and MHD instabilities. Magnetic probe consists of a coil in solenoidal form, which whose dimensions are small compared to the gradient scale length of the magnetic field. A total magnetic flux passed through such a coil is $\Phi_B = nAB$, where n is the number of turns of coil, A is the average area of cross section of coil, and B is the local magnetic field parallel to the coil axis. Design parameters of the magnetic probe are presented in Table 2

Table 2
Design parameters of the magnetic probe.

Parameters	Value	Parameters	Value
Resistivity (Ω)	33	Turns	500
Inductance (mH)	1.5	Sensitivity (mV/G)	0.7
Wire diameter (mm)	0.1	Frequency response (kHz)	22
Coil average radius (mm)	3	Effective nA (m^2)	0.022

[22]. Therefore in order to measurement of the magnetic field distribution we must be integrating the output signals of the magnetic probe.

Because of dependence of the plasma position and plasma current distribution to magnetic field distributions around the plasma, therefore magnetic pickup coils give us information about the plasma position or Shafranov shift, Δ_s. Poloidal and normal magnetic fields distributions around the plasma are [23]:

$$B_\theta = \frac{\mu_0 I_p}{2\pi b} - \frac{\mu_0 I_p}{4\pi R_0}\left\{\ln\frac{a}{b} + 1 - \left(\Lambda + \frac{1}{2}\right)\left(\frac{a^2}{b^2} + 1\right) - \frac{2R_0\Delta R}{b^2}\right\}\cos\theta, \quad (10)$$

$$B_r = -\frac{\mu_0 I_p}{4\pi R_0}\left\{\ln\frac{a}{b} + \left(\Lambda + \frac{1}{2}\right)\left(\frac{a^2}{b^2} - 1\right) + \frac{2R_0\Delta R}{b^2}\right\}\sin\theta, \quad (11)$$

where the Asymmetry factor defined as:

$$\Lambda = \beta_p + \frac{l_i}{2} - 1, \quad (12)$$

and where $I_p, R_0, a, b, \beta_p, l_i$ are the plasma current, major and minor plasma radiuses, chamber minor radius, poloidal beta and internal inductance of the plasma, respectively, and where we use the quasi-cylindrical coordinates $\left(r, \theta, \phi\right)$. Therefore, by rearranging the above equations, relation for the Shafranov shift, ΔR, obtained:

$$\Delta R = \frac{a^2}{4R_0}\left\{\left(\frac{b^2}{a^2} - 1\right) - 2\ln\frac{a}{b}\right\} + \frac{\pi b^2}{2\mu_0 I_p}\left\{\langle B_\theta\rangle\left(1 - \frac{a^2}{b^2}\right) - \left(\frac{a^2}{b^2} + 1\right)\langle B_r\rangle\right\}. \quad (13)$$

Eqs. 10 and 11 accurate for the low beta, large aspect ratio and circular cross section tokamaks as IR-T1, and where:

$$\langle B_\theta\rangle = B_\theta\left(\theta = 0\right) - B_\theta\left(\theta = \pi\right), \langle B_r\rangle = B_r\left(\theta = \frac{\pi}{2}\right) - B_r\left(\theta = \frac{3\pi}{2}\right). \quad (14)$$

Based on this method, in the IR-T1 tokamak four magnetic probes were designed, constructed, and installed, two magnetic probes were located on the circular contour Γ of the radius b = 16.5 cm in angles of $\theta = 0$ and $\theta = \pi$ to detect the tangential component of the magnetic field B_θ and two magnetic probes are also located above, $\theta = \frac{\pi}{2}$, and below, $\theta = \frac{3\pi}{2}$, to detect the normal component of the magnetic field B_r. This configuration is shown in Fig. 6. After integration of magnetic probes output, and by substituting the poloidal and normal components of the magnetic fields in Eq. 13, displacement of the plasma column center was determined. Also, plasma current obtained from the Rogowski coil [22].

7. Results of feedback response of the plasma horizontal displacement

With considering that operational value of vertical field coil system voltage of IR-T1 tokamak is approximately 3 kV, we change it to values 3.25 and 2.80 kV and then evaluate corresponding plasma horizontal displacements (by the method described above) that are inputs of the feedback controller. Time behavior of plasma current, plasma horizontal displacements and corresponding feedback responses of the plasma horizontal displacements for these three values of vertical field voltage and two values for the PS pole a = 1 and 10 are calculated and depicted in Figs. 7–9 that shows good performance of the feedback controller except at the later times and due to disruptions.

These figures show that horizontal displacement and also its feedback response are not very sensitive to small changes in vertical field coil voltage of IR-T1 tokamak. However we have better performance of the controller for pole = 10. By considering approximations in the method for determination of horizontal displacement and also in the controller design, we must indicate that final validation of these achievements depends on construction, installation and implementation of the controller which is the purpose of our future works.

8. Discussion

First step for control of plasma horizontal position is the controller design. In this paper we have worked with the plasma-circuits linearized model as a base for controller design. Also we proposed PID controller and PS of vertical coil system for IR-T1 tokamak. Step closed-loop response of the overall system of IR-T1 tokamak and corresponding Bode diagrams for two cases with and without the plasma resistance and the eddy currents distribution are presented. Also with changing of vertical field coil system voltage of IR-T1 tokamak, plasma horizontal displacement determined by magnetic probes of IR-T1 tokamak and then used as input to the controller and performance of that is investigated. Results show good performance of this controller. Due to approximations in the controller design, construction, installation and implementation of the controller is necessary and this is the purpose of our future works. With considering that target time constant of feedback control system for our work must be approximately in microsecond range then we need to upgrade the hardware to implement the our model.

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