Real-Time Feedback Control System for ADITYA-U Tokamak Plasma Position Stabilisation

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Abstract

The ADITYA-U tokamak (R_0 = 0.75 m, a = 0.25 m) is designed to have shaped plasmas in both single and double null diverter configurations. It is quite well known that sustaining a shaped plasma in tokamak requires very good plasma column position control, both horizontal and vertical. A proportional–integral–derivative (PID) based control system has been designed and operated to achieve horizontal and vertical plasma positions control in ADITYA-U tokamak. In this control system, the transfer function model of control power supply and different position diagnostics has been incorporated such that whole system fulfils the stability criteria of the whole control system. In order to incorporate effect of change in radius of plasma column and the vessel eddy current on the position measurements, new adaptive techniques are incorporated to achieve plasma position regulation with minimum error. Detailed comparisons have been carried out between the results obtained with the conventional PID approach and adaptive method approach. Furthermore, the system has been trained to take appropriate actions during the disruption or plasma failure in the tokamak. The complete system has been rigorously tested with sample signals before implementing to the ADITYA-U plasma discharges. The control system is integrated to the composite plasma control system of ADITYA –U. The complete design, installation, operation, training of the system along with all the relevant testing will be presented in the paper.

1. INTRODUCTION

ADITYA-U tokamak [1] is upgraded to limiter-divertor configuration from ADITYA tokamak [2] with limiter configuration, which was successfully operated for 25 years. Controlled shaped plasma discharges will be performed for the plasma current of ~150 kA with newly installed divertor coils in pulsed mode operation. Real-time plasma position is required to stabilise the plasma at the vacuum vessel centre in order to control the impurity level inside the plasma and to avoid the disruption of the plasma. Real-time plasma position control for ADITYA-U tokamak is categorised into two parts: control of rapid radial movements of plasma and control of vertical position during shaped plasma discharges. Shaped plasma operation is susceptible to the vertical instabilities, which results entrance of unwanted impurities inside the plasma. These vertical instabilities are susceptible to the early disruption of the plasma. Plasma position can be automatically controlled by the passive structures surrounded by the plasma, but this is only effective for the pulsed operation. Plasma position control due to passive structures is effective only due to structures which are near to the plasma surface. As the coupling between plasma and passive structures are non-trivial and due to the space limitations inside the vacuum vessel, active system for the plasma position control is required using the poloidal field coils. Magnetic coils with very low time constants and power supply with bi-polar current is used to control the plasma position fluctuations in real time.

Various tokamak CLEO, ORMAK, HT-1 has already implemented conventional PID controller [3-5] for the real-time position control of the plasma. Traditional PID controller has been implemented to control the real-time horizontal position of the plasma for ADITYA-U tokamak. This closed loop scheme of position control will improve the duration of the plasma discharge along with better impurity control as compared to the earlier open loop control of plasma position.

Linear equations are used to determine the transfer functions of bi-polar power supply, plasma position diagnostic system and the plasma system. Stability of the integrated plasma position control system by integrating the above transfer function has been confirmed. For the initial investigation of the effectiveness of the determined transfer function, effect of eddy current, gas puffs [6] and other behaviours like heating mechanisms and effect of change in the minor radius of the plasma has been neglected.

This article is arranged in order an overview of operation and experiments in the ADITYA-U tokamak. The modelling of ADITYA-U position control system is explained in section 2, whole experimental setup has been discussed in section 3, and the experimental results are reported in section 4. Finally, the paper is concluded in section 5.

2. MODELLING OF ADITYA-U POSITION CONTROL SYSTEM

Real time position control system for ADITYA-U has been categorised into two parts: radial position control of the plasma and vertical position control of the plasma. As the elongation (k) of the simulated ADITYA-U plasma discharge is ~1.1-1.2 and triangularity ~0.45 is also very less. Hence due to the small elongation during the shaped plasma discharge, vertical displacement will be very less. In this work, currently focus is given on the radial positon control of the plasma for the circular-shaped plasma operation. It is assumed that modelling and implementation of real time vertical position control of plasma will be more or less similar to the radial position control system.

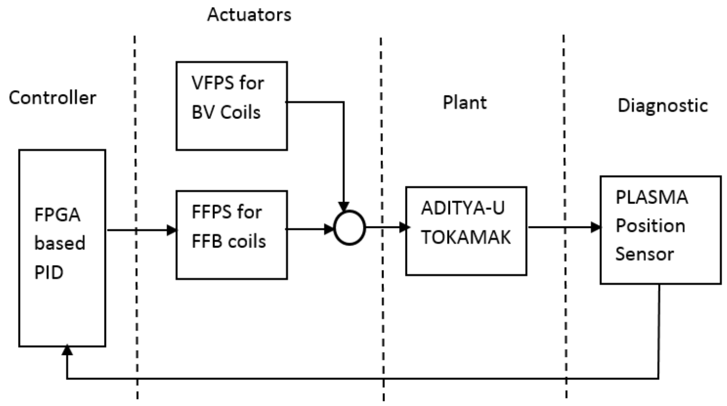

FIG. 1. Schematic of ADITYA-U Horizontal Plasma Position Control

Different systems of tokamak can be modelled into the electrical components so that transfer function of these components can be obtained for the implementation of the closed-loop feedback system. Power supply system and plasma position diagnostic can be modelled as low pass filter [7], such that their transfer function will be of the form $A(s) = \frac{1}{1+s.\tau_{act}}$ and $D(s) = \frac{1}{1+s.\tau_{diag}}$, where τ_{act} and τ_{diag} are the response time of power supply for the radial plasma position control and the plasma position diagnostic system. Two different power supplies are under the application for the stabilisation of the plasma column. High Voltage, high current (2.4 kV, 12.5 kA) thyristor based vertical field power supply (VFPS) and low voltage, high current (220V, ±2 kA) IGBT based fast feedback power supply (FFPS). Similarly, magnetic diagnostics such as flux loops, Mirnov coils and cosine coils are used for the radial position determination of the plasma. Values of τ_{act} and τ_{diag} are determined experimentally, τ_{act} = 1 ms and τ_{diag} = 1 ms.

Radially outward force on the plasma is given by

$$F_w = 2\pi R_0.I.B_v = \frac{\mu_0 R_0 I^2 r}{{a_0}^2}\left(1 + \frac{2a_0}{2\pi R_0}\right) \quad (1)$$

where R_o, a_0 and r are the major, minor radius of the plasma and r horizontal displacement of the plasma. B_v is the required vertical field for the stabilization [7] of the plasma against different inherent forces experienced by plasma due to its geometric configuration, current profile and plasma pressure profile. In ADITYA-U tokamak, this field is provided by poloidal field (B.V) coils. So, the desired force, F_{wd} required to maintain the plasma in equilibrium at the machine centre is as given by eq (2).

$$F_{wd} = -\frac{\mu_0 R_0 I^2 r}{{a_0}^2}\left(1 + \frac{2a_0}{2\pi R_0}\right) = = 2\pi R_0.I.\Delta B_v = \mu_0.I.\Delta I_{vf} \quad (2)$$

where ΔB_v and ΔI_{vf} are the variation in the vertical field and current for the vertical field coil.

Assuming plasma current to be constant and allowing for the finite conductivity of vacuum vessel wall.

$$\frac{R_0.\ I\ .\ r}{{a_0}^2}\left(1 + \frac{2a_0}{2\pi R_0}\right) = (\Delta I_{vf} - \frac{d\Delta I_{vf}}{dx}\ .\ \tau_w) \quad (3)$$

where τ_w= penetration time of the magnetic field into the vacuum vessel, τ_w = 2.8 ms.
And taking into account of P.F circuit

$$L_{vf}\ \frac{d\Delta I_{vf}}{dx} + R_{vf}\ \Delta I_{vf} = \Delta U_{vf} \quad (4)$$

where L_{VF} and R_{VF} are the inductance and resistance of the vertical field circuit. Vertical coil system of ADITYA-U tokamak composed of two sets of coil for the fine and coarse control of the radial plasma position. Existing B.V coils are used for the fine control and Fast feedback (FFB) coils are used for the coarse control of the radial position of the plasma. Similarly plasma can also be modelled with some approximation, whose transfer function will be of the form:

$$P(s) = \frac{I(s)*r(s)}{\Delta U_{vf}} = \frac{(s\tau_w - 1)}{K(L_{vf}.s + R_{vf})} \quad (5)$$

$$\text{where } K = \frac{-R_o}{{a_0}^2}\left(1 + \frac{a_0}{\pi R_0}\right) \quad (6)$$

For ADITYA-U, R_o = 0.75 m and a_0 = 0.25 m and value of K is -13.27.

3. EXPERIMENTAL SETUP

Model of the horizontal position control after integrating different model of is mentioned in eq(7).

$$G(s) = A(s)*P(s)*D(s) \quad (7)$$

Hence it is represented in open loop representation as mentioned in eq (8),

$$G(s) = \frac{1}{1+s.\tau_{act}}\frac{1}{1+s.\tau_{diag}}\frac{(s.\tau_w - 1)}{K(s.L_{vf} + R_{vf})} \quad (8)$$

For the system designed in closed loop feedback system, closed loop transfer function will be of the form as mentioned by eq (9).

$$H(s) = \frac{G(s)}{1 + G(s)} \quad (9)$$

Now closed loop transfer function can be represented by eq (10) and whole transfer function modelling of the ADITYA-U horizontal position control is shown in fig 2.

$$H(s) = \frac{(s.\tau w - 1)}{((s.\tau w - 1) + (1 + s.\tau act)(1 + s.\tau diag).K.(s.Lvf + Rvf))} \quad (10)$$

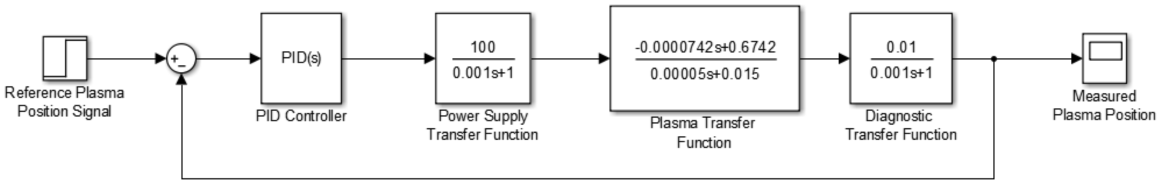

FIG.2. Transfer Function Model of ADITYA-U Horizontal Plasma Position Control

Routh-Hurwitz criteria is implemented for checking the stability of the given system and the above transfer model can be used for the real-time ADITYA-U horizontal position control.

Closed loop transfer function for ADITYA-U horizontal plasma position control system is given below in eq (11).

$$H(s) = \frac{(7.5*10^{-2} - 2.11*10^{-4}s)}{18*10^{-8}s^3 + 198.4*10^{-6}s^2 + 18.2*10^{-3}s + 11.2*10^{-2}} \quad (11)$$

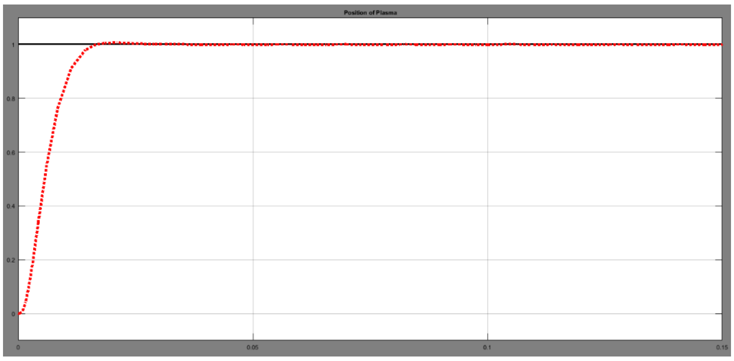

FIG. 3. Response of Horizontal Plasma Position Control Model for P = 0.4, I = 10 and D=0 for 150 ms of Plasma Operation.

Simulation for the parameters P=0.5, I=10 and D=0 has been performed for the above mentioned transfer function using the optimal control tool in MATLAB is shown in fig.3.

4. RESULTS

Typical ADITYA-U discharges for plasma current of ~80-100 kA along with the horizontal position of the plasma column is shown in fig 4. FFPS power supply is used to supply the Fast Feedback Coils (FFB) for the open loop position control of plasma. Observation from the consecutive ADITYA-U plasma discharges clearly confirms the dependence of the plasma discharge duration on the application of the current in the FFB coil.

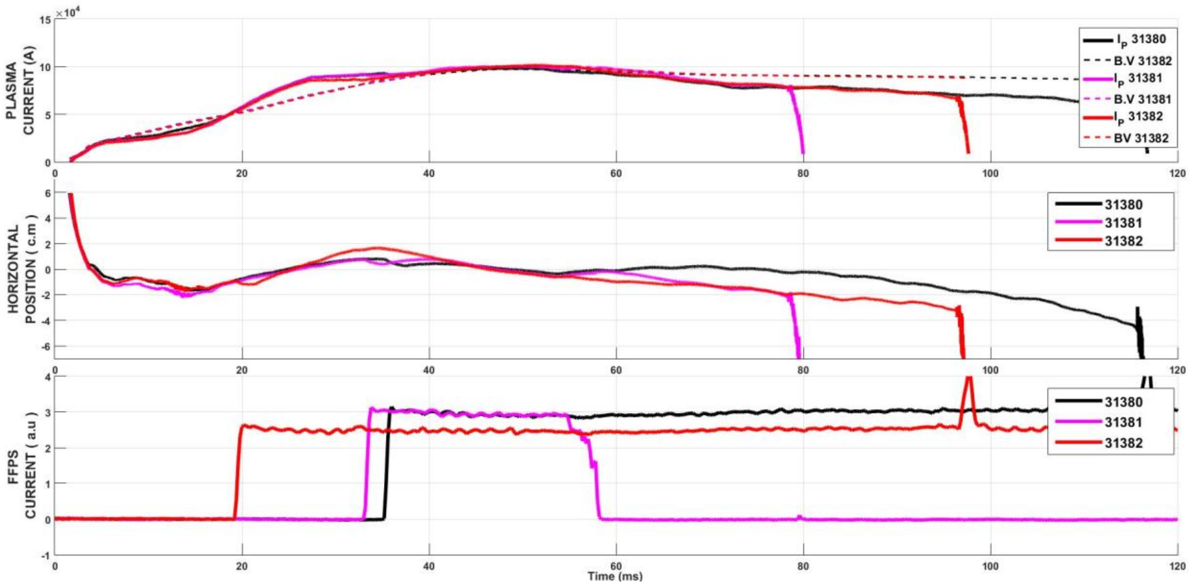

FIG.4. Typical ADITYA-U plasma discharge with open loop plasma position control.

Application of PID controller is required for the real-time position control of the plasma column. FPGA based PID controller is used for the application of closed loop plasma position control. Real-time plasma position is implemented for the control of horizontal plasma position. Desired results are obtained for the typical discharges of ADITYA-U tokamak in closed loop configuration. Operation of real-time is started from 30 ms after the peak loop voltage. Current in B.V coil for the stability of the plasma shows mismatch with the plasma current as it was in open loop configuration. It can be seen that FFPS current has changed a lot due to fluctuations in the plasma position for the PID parameters P=3,I=1. Oscillation in the plasma output can be observed for which FFPS current has resulted in the oscillation in the current output. Plasma position control for ADITYA-U plasma discharge with real-time horizontal position control is shown in fig.5.

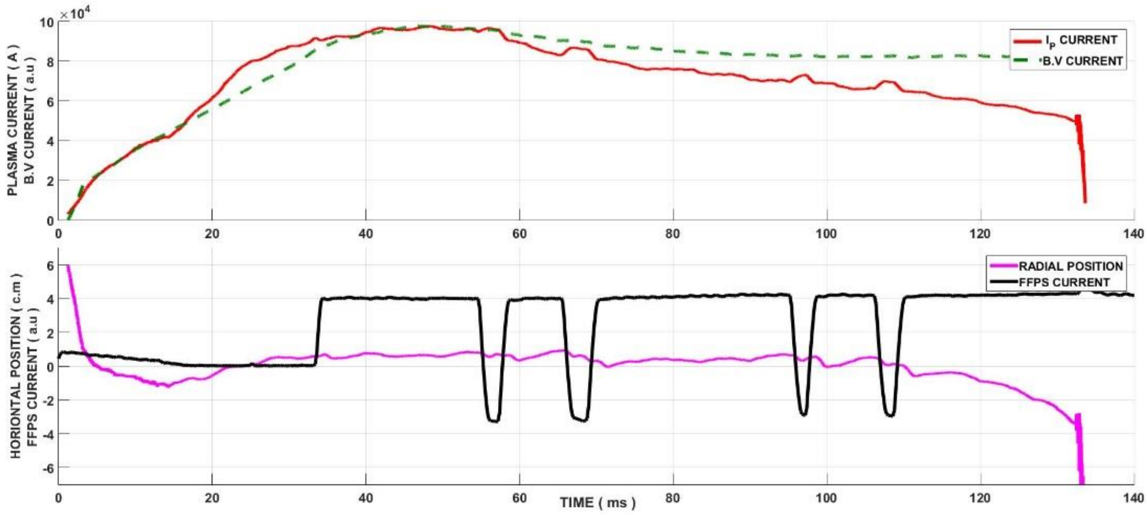

FIG.5. Real-time horizontal position control plasma discharge for ADITYA-U with P=3, I=1.

In order to reduce the fluctuations and output in the error signal integral part is increased and proportional parameter has been reduced for the plasma discharge for P=1 and I=5 is shown in fig.6.

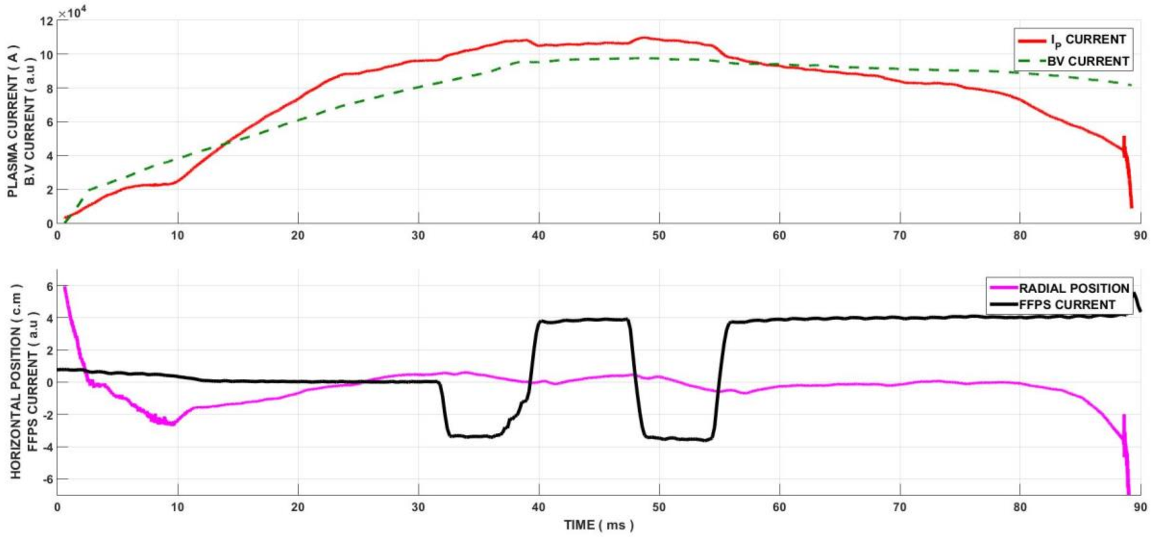

FIG.6. Real-time horizontal position control plasma discharge for ADITYA-U with P=1, I=5.

5. CONCLUSIONS

Modelling of the transfer function of the ADITYA-U power supply for position control coils, diagnostic system for position control and ADITYA-U tokamak system has been performed. Stability of the closed loop feedback system has been confirmed in order to obtain the desired output with minimum oscillation, steady state error and fast response. In FPGA based PID controller system, the output parameters can be adjusted accurately and precisely as per the experimental requirement by selecting the proper values of P,I and D. Here, experimental observation matches quite well for the designed transfer function model for the real time horizontal position control system designed in MATLAB. Same position control scheme can be easily used for the real time vertical position control for the plasma. Adaptive control scheme will be used in future ADITYA-U plasma discharges to control the position more accurately after implementing the plasma uncertainties in the existing transfer function model.

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