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Implementation of a new iterative learning control algorithm on real data

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In this paper, a newly presented approach is proposed for closed-loop automatic tuning of a proportional integral derivative (PID) controller based on iterative learning control (ILC) algorithm. A modified ILC scheme iteratively changes the control signal by adjusting it. Once a satisfactory performance is achieved, a linear compensator is identified in the ILC behavior using casual relationship between the closed loop signals. This compensator is approximated by a PD controller which is used to tune the original PID controller. Results of implementing this approach presented on the experimental data of Damavand tokamak and are consistent with simulation outcome. © *2016 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4942511]

I. INTRODUCTION

Using classical controllers such as proportional integral derivative (PID) controller is common in industrial applications. This is because of simplicity in both their implementation and design methods. The design method selection has a deep effect on the performance of the controller. These methods can be classified to online and offline tuning methods. The automatic tuning methods have been commonly used for a long time,[1] where the user only needs to determine the conditions that can satisfy the performance of the control system. The concept of automatic controller tuning is different from autonomous control theory. In these methods, the controller is tuned on with no loss in production time. From economical, practical usage and application domain viewpoints, the closed-loop online approach is the more attractive one which can also be used in offline verifying methods. Autonomous control is a key technology that is used as a global definition for most of the robust and adaptive control methods, assigned mostly in online approaches. Nonetheless, both categories of methods are used for systems with high nonlinearity and complexity.

For a long time, the approach of tuning PID coefficients has been typically limited to the linear systems. However, all plants are practically nonlinear in nature. Learning-enhanced nonlinear PID controller has been developed specifically for nonlinear systems by Tan *et al.*[2] and three optimal-tuning PID controller design schemes have been presented for industrial control systems by Liu and Daley.[3] Iterative Learning Control (ILC) is a relatively new tuning approach in control applications. In this algorithm, inspired by human learning, the measurements resulted from the previous trial can be used for improving the performance of the system in the next iterations.[4] This algorithm was initially used in learning control of actuators in control systems[5] and was presented academically by Uchiyama.[6] This tool is used in many industrial applications such as automation, network systems, and robot arm manipulators. ILC tends to use system operating data to decrease target tracking in the next execution steps. This work is done without any information of system structure and the level of its nonlinearity. In other words, ILC uses of the system as a black box and tunes are based on the discrepancy between the output and the desired target. Using ILC in nonlinear systems proved that it can have good results in improving the performance of some such systems and improving the performance of the designed controller by learning in the iteration progress.

Basically, the output of ILC controller is a signal in every sample time that is added to the control signal generated by the original controller. Nevertheless, in all of these algorithms, the trajectory must be the same in all trials. In Ref. 7, an approach has been proposed that automatically tunes the PID coefficients of the closed loop system based on the relation between ILC update output and error of system. Adapting this approach, after tuning control signal by ILC algorithm, this resulted tuner signal is identified based on the error of the system in that trial to tune the parameters of the PID controller. Although the presented results show that it can improve the PID controller, it lacks the causality in identification and therefore could not be reliable. It means that the proposed algorithm tends to be involved in the equation of relation, based on error signal. But the updating signal depends on the error signal and desired trajectory.

This paper provides an overview of the new scheme of tuning the PID control parameters based on new ILC algorithm. After that, experimental results of using it on Damavand tokamak data are presented. The position of the plasma is a vital factor in producing the stable plasma and maintaining it for a long time as far as possible is indispensable.

The paper is organized as follows: In Sec. II, the frame of the proposed method is described in detail. In Sec. III, the simulation results of applying it are presented. In this section, the results of this approach are compared with those of the experimental data for the vertical position of plasma in Damavand tokamak.

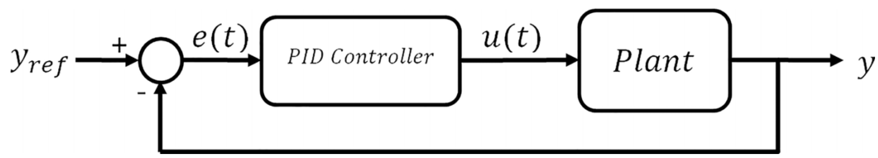

FIG. 1. Basic feedback control system.

II. PROBLEM DEFINITION

Consider a nonlinear system with unknown level of complexity as follows:

$$\begin{aligned} \dot{x}(t) &= A(t)x(t) + B(t)u(t), \\ y(t) &= C(t)x(t) + D(t)u(t), \end{aligned} \tag{1}$$

where $u(t)$ is the input signal to the system, according to its procedure. Fig. 1 shows the system under PID feedback control.

This controller can be assigned and implemented by either intelligent or traditional method. We consider this function as a PID controller for convenience as follows:

$$u(t) = K_p e(t) + K_D \frac{de(t)}{dt} + K_I \int_0^t e(\tau)d\tau. \tag{2}$$

This controller cannot get over all functional defects of the system, but they can be reduced by choosing appropriate controller coefficients. The method of tuning can have any level of complexity based on the system nonlinearity. One of the modification methods is called ILC-based PID parameter tuning that is classified in indirect ILC methods.[8] In this method, the control modifier signal is defined as follows:

$$u_k(t) = u_{kPID}(t) + du_{k-1}(t), \tag{3}$$

where t is the discrete time index, $u_{kPID}(t)$ is primary controller output signal and $u_k(t)$ is defined as an overall controller signal. The value of $du_k(t)$ is assigned as follows:

$$du_k(t) = du_{k-1}(t) + \lambda e_{k-1}(t+1), \tag{4}$$

where λ is the learning gain. This relation is called update law for ILC. Fig. 2 shows the configuration with the ILC augmentation. In Fig. 2, the PID controller is considered as the basic feedback controller. The ILC algorithm is used to modify the control signal.

In the configuration shown in Fig. 2, during the ith iteration, the modified $u_i(t)$ is given by Equation (3). So, the tracking error and the output of the ILC during the previous cycle are used to update the output of the ILC during the present cycle. In each execution period, the value of error is measured and is used in the next period of running to modify the performance of the controller. This process can continue until the desired mission function would be obtained. This value can be a locally desired minimum value or a globally one. In Ref. 7, Tan *et al.* suggest that a function can be defined for this signal. In that reference, identification is done based on $e(t)$ as an input and $du(t)$ as an output. This is a non-casual relationship; since based on Fig. 2, $e(t)$ is produced by y_{ref} and $du(t)$ as inputs. Therefore, $du(t)$ in the ith iteration has the effective influence on $e(t)$ in the next iteration.

III. MAIN RESULTS

In this section, the proposed tuning method of the PID controller adopting an ILC approach is elaborated. The entire

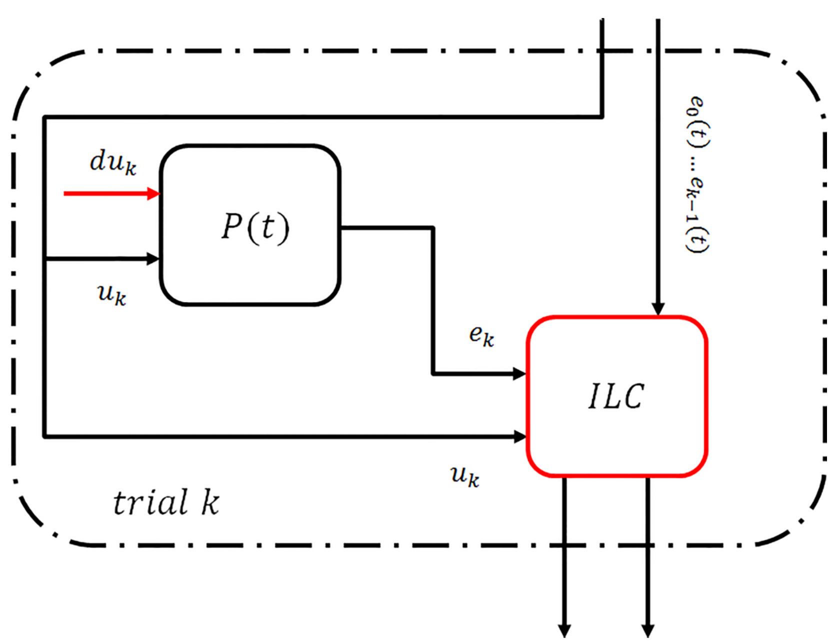

FIG. 2. Equivalent representation of the ILC-augmented control system in k-th trial.

procedure is essentially carried out through three phases. In the first phase, the initial controller is implemented on desired trajectory of practically vertical position of plasma at Damavand tokamak. After that, a modified ILC procedure is carried out to yield the input and output signals of the overall ILC-augmented control system. This procedure is executed iteratively offline on simulator model of vertical position of plasma designed at Ref. 11. The advantage of the simulator model is the capability of executing in unlimited time to reach a satisfactory result. The second phase uses these signals to casually identify the best-fitting general transfer function with an extended least-squares (ELS) algorithm. In the third phase, based on the Bode diagram of identified function for ILC system, an approximation is obtained as a PD controller. The resulted controller can be added to the initial controller to improve its performance. This augmented controller is implemented on practical Damavand tokamak to be validated by an alternative trajectory.

When the ILC convergence is obtained, the actual error $e_k = y_{ref} - y$ approaches to a satisfied value and the ILC stops updating. Then, $du_{i+1}(t)$ is maintained at the same value as $du_i(t)$.

Achieving a satisfactory level of the control performance, the ideal input $e(t)$ and output $du(t)$ for a cycle of the reference signal would be available for the next phase.

In the next phase, transfer function between $e(t)$ and $du(t)$ resulted from ILC algorithm is derived. As mentioned before, $e(t)$ is produced by y_{ref} and $du(t)$ as inputs. This relation can be written in a linear regression form

$$e(t) = \varphi^T(t)\theta, \tag{5}$$

where the regressors are made by dynamics of $du(t)$ and y_{ref}. The trajectory signal must be used for this identification to distinguish its effect on $e(t)$ from that of $du(t)$. So, we can have a casual and approximately accurate relation between $e(t)$ and $du(t)$. Based on this assumption, we have

$$e(t) = g(t) \cdot du(t) + T(t) \cdot y_{ref}(t). \tag{6}$$

The ELS are used to estimate the parameters of these functions. The effect of ILC signal $du(t)$ on the error signal $e(t)$ could be written as

$$g(t) = \frac{e(t)}{du(t)}. \tag{7}$$

By reversing the above transfer function, we can obtain the desired function

$$g^{-1}(t) = \frac{du(t)}{e(t)}. \tag{8}$$

This controller can be used as a compensator together with the initial PID controller to improve the performance of it. This compensator is computed using a specific reference signal y_{ref}. However, if a persistent excitation reference signal is introduced to the control system when the ILC is computed, then this compensation can be used for any reference signal. This is superior to ILC, in which the compensation control signal is set point dependent.

In the third phase, $G^{-1}(z^{-1})$ is approximated by a PD controller using its Bode diagram, as follows:

$$G(z^{-1}) = \frac{1 + \bar{a}_2 z^{-1}}{\bar{b}_1 z^{-1} + \bar{b}_2 z^{-2}}. \tag{9}$$

Since $G(z^{-1})$ is actually a strictly proper transfer function, its inverse is improper; therefore, it can be approximated by a PD transfer function which has a relative degree of -1.

Once the PD controller is obtained, its parameter is added to the parameters of the original controller which ends with a new tuned PID controller. If the initial controller is considered as follows:

$$G_{PID\text{-}ctrl}(z^{-1}) = \frac{b_1 + b_2 z^{-1} + b_3 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}. \tag{10}$$

So

$$\begin{aligned} G_{PID\text{-}ctrl\text{-}new}(z^{-1}) &= G_{PID-ctrl}(z^{-1}) + G^{-1}(z^{-1}) \\ &= \frac{c_1 + c_2 z^{-1} + c_3 z^{-2}}{1 + d_1 z^{-1} + d_2 z^{-2}}, \\ K_{P\text{-}new} &= K_P + K_{P\text{-}comp}, \\ K_{D-new} &= K_D + K_{D\text{-}comp} \end{aligned} \tag{11}$$

that $G_{PID\text{-}ctrl\text{-}new}(z^{-1})$ is the modified controller by the estimated function, and $K_{P\text{-}new}$ and $K_{D\text{-}new}$ are the newly modified controller coefficients.

IV. PLANT DESCRIPTION

The need for new energy sources is expected to become a critical problem within the next few decades. The International Energy Agency predicts that energy consumption will increase 60% by 2030. Nuclear fusion is a renewable and nature friendly candidate source of energy with sufficient energy density to supply the world with its steadily increasing demands. The tokamak concept invented in the late 1950s is now the major and most promising magnetic confinement approach being pursued around the world to realize the fusion principle dreams. The fundamental task of experimental tokamaks is to discover methods for confining and heating the plasma so that the sustained fusion reactions can occur. The plasma needs to be sustained under high temperature and high pressure to increase the frequency on collision between atoms, thereby producing fusion.[9] This will be done by several magnetic fields imposed from different directions on the plasma. These magnetic fields cause to some instabilities that necessity of the active control will be clarified. Additional control problems include improving performance, for example, in terms of sustained plasma pressure, temperature, and length of time that energy is confined within the plasma. The position and shape of the plasma are two essential parameters that must be controlled. Damavand tokamak is one of the research assets categorized with these features. Fig. 3 shows a view of this plant. The D cross section of this tokamak makes it an important experimental plant to experience different physical and control methods. The technical specifications of this tokamak are shown on Table I.

The newly implemented control system in Damavand tokamak includes of 3 subsystems equipped with series 5000

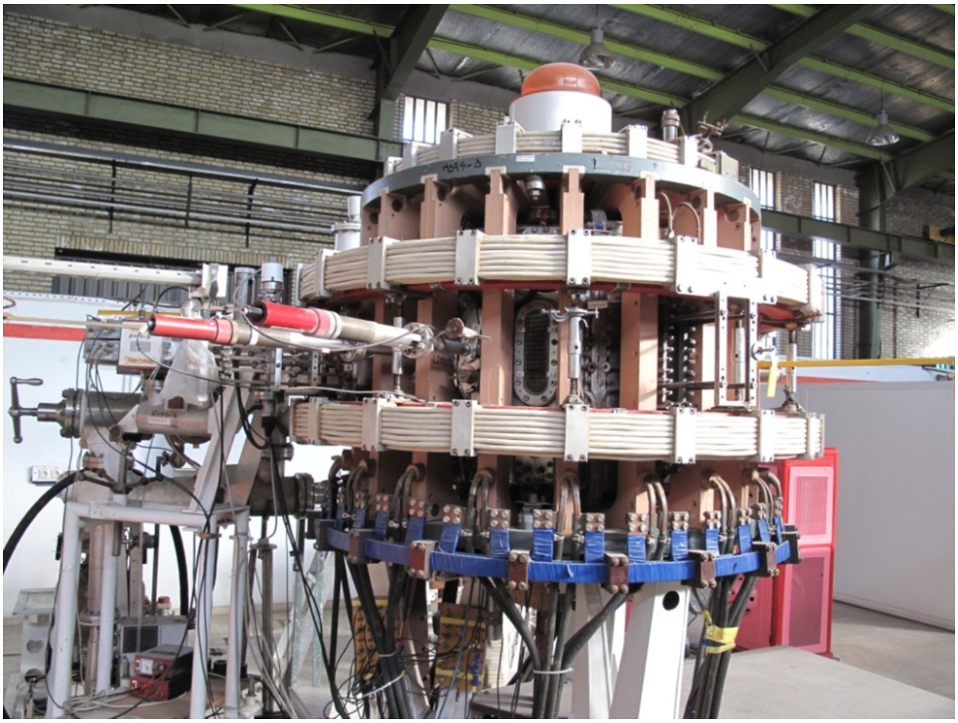

FIG. 3. A view of Damvand tokamak.[10]

DSP processor.[12] Each subsystem is responsible for controlling one of the vertical and horizontal positions of plasma and plasma shaping. Each unit is designed with capability of implementation of various classic and intelligent controllers. The resulted output of these controllers can be transformed to the related coils by using a newly designed power actuator system, so as to obtain the desired control command. The actuator system is designed so that it can provide the possibility of commands transmission in maximum bandwidth of 100 kHz. The block diagram in Fig. 4 shows the total structure of the newly implemented processing system. According to the figure, this system can be categorized in two main parts: data collection and processing unit. In data collection part, the operation of pre-processing includes integrating, initial filtering of data, appropriate amplifying, buffer, and analog to digital converter, which are scheduled. The resulted data are fed into the processing block and after that, the appropriate commands are transmitted to turn on/off insulated-gate bipolar transistor (IGBT) switches. In this system, the control structure and the processing unit are designed so that different classic control structures, including PD, PID, fractional PID,[13] and intelligent frameworks, such as neural and neuro-fuzzy networks, can be implemented.

TABLE I. Technical specification of Damavand tokamak.[11]

Parameter	Value
Main radius	36 cm
Vertical radius of plasma	12 cm
Ratio of chamber magnetic field	1.2 T
Plasma current	40 kA
Plasma density	3×10^{19} m^{-3}
Ion temp	150 eV
Electron temp	300 eV
The number of chamber windings	20
RF frequency	15 GHz
Plasma confinement time	21 ms

According to Fig. 4, the new processing system, based on initial pre-processed data, calculates the value of distortion of the desired position and delivers it to the controller, as error. As mentioned before, the selected optimum classic controller for plasma position control is a PD controller. It is obvious that the conversion of a continuous function to discrete one is feasible in various ways.[14] One of the solutions to implement a controller in a digital processor is discretizing that function. By sampling of error signal in period time, it can be approximated as follows:

$$u(nT_s) = K_p e(nT_s) + \frac{K_d(e((n+1)T_s) - e(nT_s))}{T_s}. \quad (12)$$

In this equation, the controller coefficients are configurable in the wide range of [0 70]. In designed user interface software, the parameters of K_p, K_d, and sample time of T_s are assigned by an operator and while using controller in shot procedure, the above relation is used. Fig. 5 shows the processing unit board of this new system.

To control the position and shape of the plasma, different commands are produced by the processor, converting the commands from 0 to 5 V in digital form to signals with amplitude of −5 to 15 V. IGBT switches of the actuator can be turned on with 15 V voltage and turned off with −5 V on their gate. The IGBT converter block, similar to the previous Trystor converter system, is structured as a bridge and it can drive the coil of position control and shaping of plasma in one direction. In the other words, the produced commands of the central control system are able to drive the current in

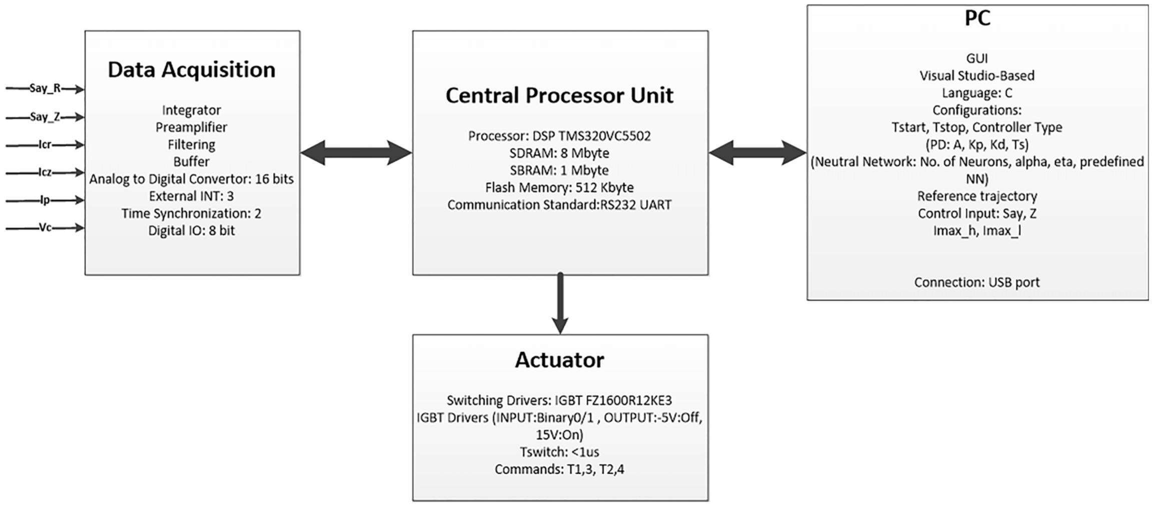

FIG. 4. Total block diagram for implemented control system.

the control coils. Providing the current charge in the coils causes magnetic field force in such a direction that the constituted plasma in the vessel can be moved in Z or R direction. The plasma when required to reach the control goal necessitates energy in the voltage range of 1000 V, the current of 1500 A, and switching frequency 6 kHz. Furthermore, considering investigations in Ref. 10 for Damavand tokamak system, FZ1600R12KF4 IGBT switch (Infineon Co.), was the best choice. This modified application presents the required hardware to pull down the obstacles of switching in control system and improve its capability to locate the output position at proximity of the defined trajectory as well, despite the physical limitations.[9]

V. EXPERIMENTAL IMPLEMENTATION

In this investigation, the vertical position of the plasma is measured with respect to its difference in the center of the chamber. The block diagram of closed loop control system of plasma vertical position for Damavand tokamak is shown in Fig. 6 where $\dot{\psi}_z$ is the output of the sensor (saddle loop). It is entered into a circuit with the transfer function of $H(s)$, and it simulates the vertical position,[11]

$$H(s) = \mathrm{k}\frac{1010}{s + 1.377}. \tag{13}$$

In Fig. 7, $G_c(s)$ is the controller with the following transfer function:

$$G_c(s) = K_p + K_d\frac{s}{s + 10^4}. \tag{14}$$

Using the control signal (u) and the rectifier power circuit (actuator), the control current (I_{cz}) flows into the external poloidal coils. $F_p(s)$ represents dynamic of the plasma vertical position. Initial values of controller coefficients have been chosen as $K_p = 5.2, K_d = 1.2$. In this paper, the signal of producing plant Z_{ref} is constructed and it is used in the closed loop control system to vertically adjust the position of the plasma column inside the vacuum chamber, ranging from -12 cm to $+12$ cm.[10] Investigations show that error norm will get to its minimum value, based on ILC coefficient of $\lambda = 0.01$ and 350 iterations. By means of ILC algorithm, a modification is done in the controller system. Fig. 7 shows the trend of changes in norm of error for different iterations of modifying the controller by new ILC algorithm.

According to Ref. 14, an identification is made based on $e(t)$ and $du(t)$, as follows:

$$G(z^{-1}) = \frac{0.249 - 0.1582z^{-1}}{1 - 1.601z^{-1} + 0.6093z^{-2}}. \tag{15}$$

By reversing this function, we have

$$G^{-1}(z^{-1}) = \frac{1 - 1.601z^{-1} + 0.6093z^{-2}}{0.249 - 0.1582z^{-1}} = G_{ilc\text{-model}}(z^{-1}). \tag{16}$$

If we insert this model in place of the ILC modifier system and evaluate its results, we shall be aware of the ability of this algorithm to improve the performance of the system.

Now, we try to approximate a PD model for this function. This will be done by finding a function that presents a Bode diagram similar to the identified model. Selecting Bode diagram is because of its capability to present more specifications of function. This function also must have the characteristics of

FIG. 5. A view of processing board and data collection module.

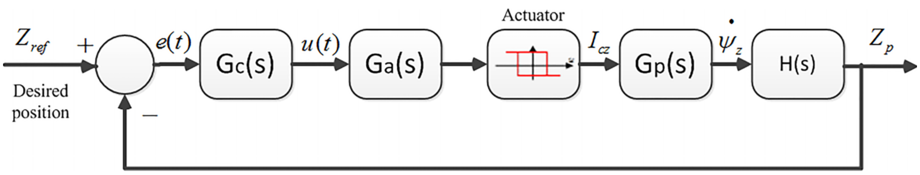

FIG. 6. Block diagram of closed loop system to control plasma in the vertical position in Damavand tokamak.

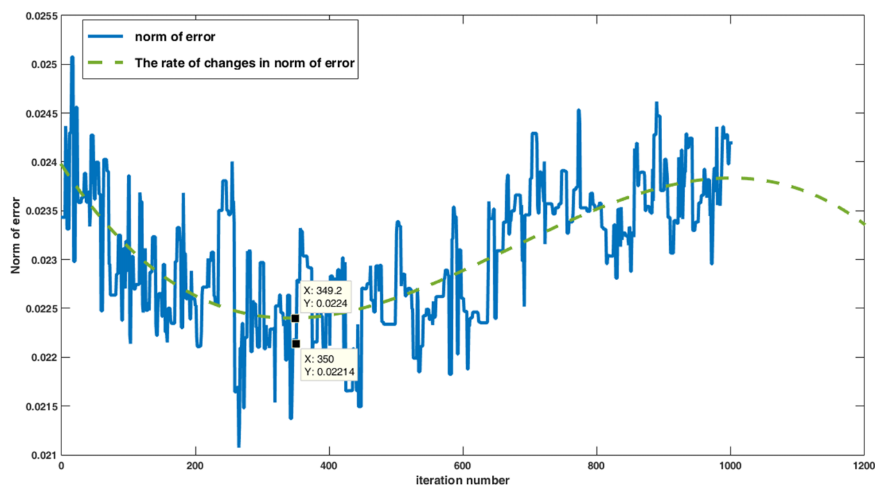

FIG. 7. The variations of the norm of error in different iterations of modifying the controller by new ILC algorithm.

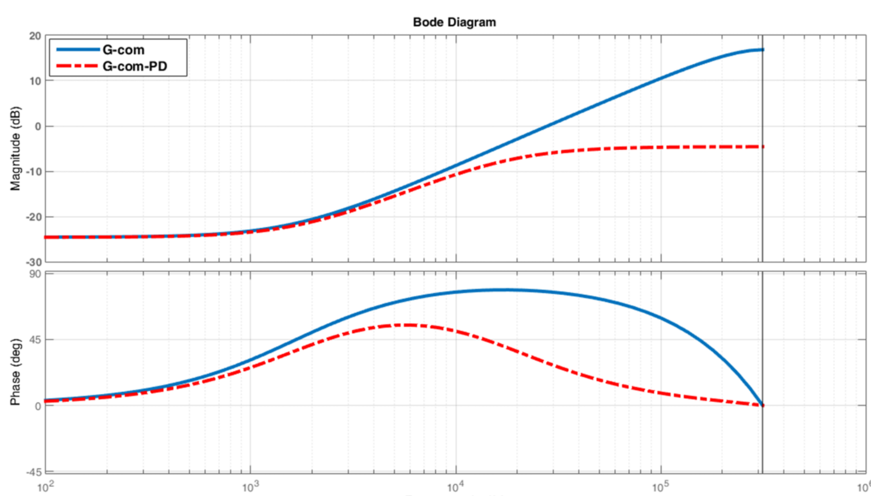

FIG. 8. Approximating a PD model for ILC identified function in Bode diagram; G-com (ordinary line) as the identified function for compensator controller, G-com-PD (dashed line) as the PD approximated compensator controller function.

a PD controller. This choice is obtained based on steady state gain and −3 dB frequency of originally compensator function. Fig. 8 shows the behavior of the Bode diagram for transfer function of compensator and its approximated function as a PD controller.

Based on this approximation, we have

$$G_{PD\_com}(z^{-1}) = \frac{7.731 - 7.55z^{-1}}{9.475 - 7.475z^{-1}}. \tag{17}$$

According to this model, we have

$$G_{com\_PD}(s) = \frac{0.8159s + 2138}{s + 2.371 \times 10^4} \tag{18}$$

which presents updates for controller coefficients, as follows:

$$K_{p\_com} = 0.0902, \quad K_{D\_com} = 0.7257. \tag{19}$$

These values show that initial values, chosen for controlling system have been selected appropriately. Fig. 9 shows a comparison between different stages of updating controller system by ILC new approach.

The criterion of performance in the proposed algorithm is the value of root mean square error (RMSE). This parameter

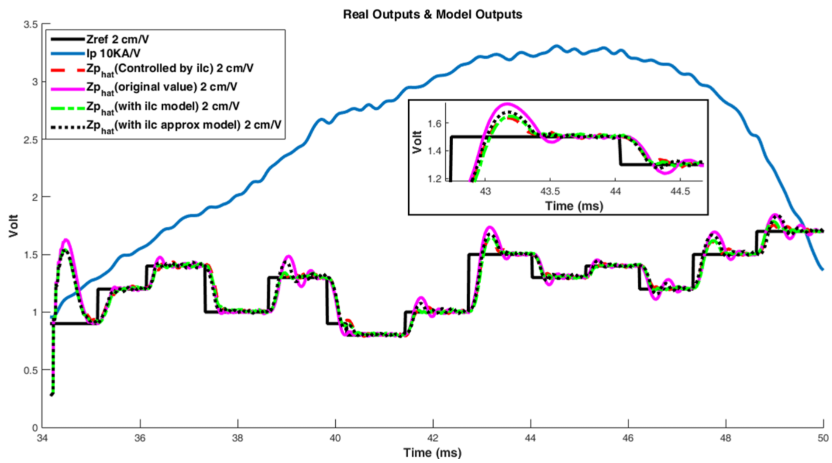

FIG. 9. Comparison of responses of the system based on different steps of modifying with new ILC approach; Zref 2 cm/V (black ordinary line) the desired vertical position of plasma, Ip 10 kA/V (blue ordinary line) the plasma current, Zp-hat(controlled with ilc) 2 cm/V (red dashed line) the position of plasma modified by ILC, Zp-hat(original value) 2 cm/V (pink ordinary line) the vertical position of plasma with initial controller, Zp-hat(with ilc model) 2 cm/V (green dashed line) the vertical position of plasma modified by ilc identified model, Zp-hat(with ilc approx model) 2 cm/V (black dotted line) the vertical position of plasma modified by PD approximated compensator controller.

TABLE II. Comparing RMSE function on different steps of improving vertical position of plasma by newly upgraded ILC algorithm in some common positions.

	Type of controller			
Operation point	Initial controller	Compensator signal assigned by ILC + initial controller	Identified model for compensator signal + initial controller	PD approximated model + initial controller
1	0.0112	0.01	0.0098	0.0114
1.2	0.0075	0.0085	0.0095	0.0068
1.4	0.0078	0.0079	0.0085	0.0073
1.7	0.0059	0.0025	0.0028	0.0035
Average	0.0324	0.0289	0.0306	0.029

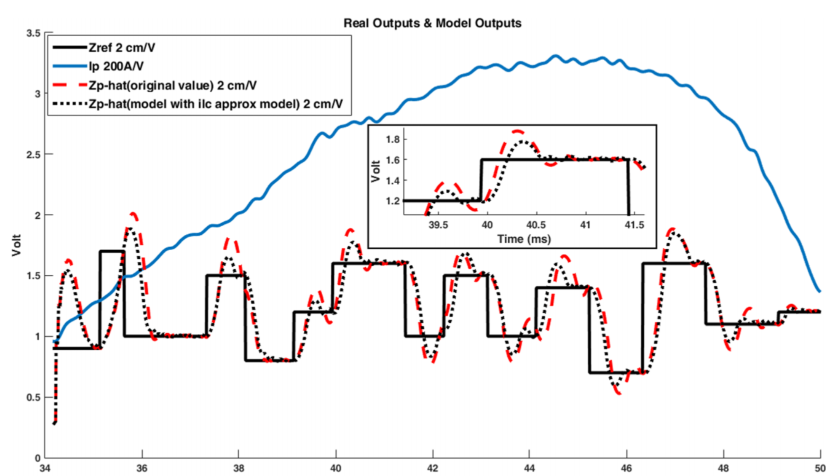

FIG. 10. Implementation of new modified PD controller on an alternative trajectory; Zref (black ordinary line) the desired vertical position of plasma, Ip (blue ordinary line) the plasma current, Zp-hat(original value) (red dashed line) the vertical position of plasma with initial controller, Zp-hat(with ilc approx model) (black dotted line) the vertical position of plasma modified by PD approximated compensator controller.

is affected by the range of the inertia of response in compared with the desired trajectory. The inertia factors in control concepts are as follows.[14]

- Settling time: the elapsed time to get within 2% of final value.
- The overshoot percentage: the percent of exceeding response from final value at the first peak.
- Rise time: the elapsed time for response to reach to 63% of final value.

Table II shows a comparison between RMSE on different stages of target position in different steps of the proposed algorithm.

Now, by using this modified ILC controller, the controller can be utilized for any alternative trajectory, defined by the user. Fig. 10 shows the results of implementing the very controller on a newly defined trajectory. It displays the effect of the modified new controller on unknown trajectory, very well.

VI. SUMMARY

In this article, we illustrated the proposed approach on new ILC algorithm[10] on the experimental data of Damavand tokamak. This approach presents a tuning rule that can be used not only for the specific trajectory used in ILC but also on any other trajectory. Thanks to this approach, we implemented a new power actuator on control system to improve the constraints of the switching system. After that, by using the ILC algorithm to obtain a tuning signal for the control signal, this compensator signal can be casually identified. The obtained transfer function is approximated by a PD controller to satisfy the proper conditions. The results show that the previous controller on the system can be modified better by using this new algorithm and it is possible to improve the performance of controlling the vertical position of plasma in the system to have better judgment on plasma behavior in our studies.

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