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Optimization and performance of a high-speed plasma position digital control system

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Abstract. This paper addresses optimization of a high-speed digital feedback controller for a plasma position in Damavand tokamak. Damavand tokamak discharges have plasma currents up to 40 kA with discharge duration greater than 15 ms and toroidal magnetic fields up to 1.2 T. The plasma position is measured using saddle-loops and Rogowski coil and is controlled by electromagnetic forces generated by passing currents through control coils placed around the plasma. A desired control objective is maintaining the plasma in the center of vacuum vessel and to stabilize the plasma in the presence of disturbances in a time domain of the order of few milliseconds. In order to achieve maximum performance it is essential to optimize the control system. In this paper plasma position measurement and the details of implementing high-speed PID controllers based on a TMS320c25 digital signal processor along with the system optimization are presented.

Keywords. Tokamak plasma position control; digital proportional-integral-derivative; radial perturbations.

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1. Introduction

The limited supply of fossil fuels and the environmental risks associated with fission reactors are driving research into alternative methods of electrical power production. One of the most interesting is the possibility of power generation using thermonuclear fusion. The easiest achievable fusion reaction uses the hydrogen isotopes deuterium and tritium; plenty of deuterium is present in sea water and tritium may be extracted from lithium. The reaction occurs at temperatures of the order of 100 million K and releases more energy per gram than any other realistic fuel. The difficulties associated while handling the extremely hot fuel (which is in the state of plasma) are compensated for by the facts that there are no greenhouse gases and there is no possibility of uncontrolled runaway reactions.

A tokamak is a plasma confinement device, which uses magnetic fields to generate and control the plasma; plasma is an ionized gas and therefore consists of charged

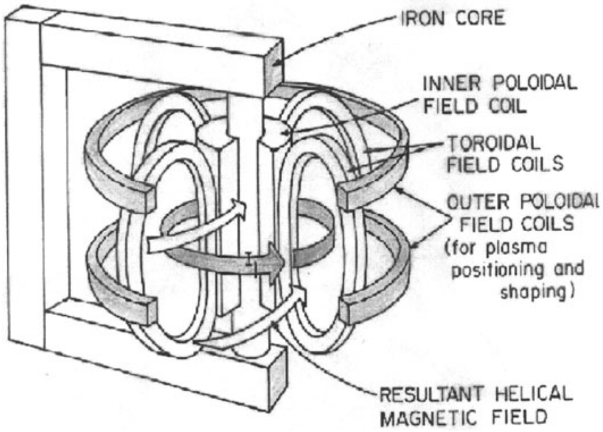

Figure 1. Schematic of a tokamak showing magnetic field structure.

particles [1]. The basic principles of this device are illustrated in figure 1. Essentially, a closed magnetic field is created from two separate magnetic field sources, a field, which passes the long way around the torus (toroidal), and a field which passes the short way around the torus (poloidal). The toroidal field is generated by external field coils, while the poloidal field is generated by inductively-driven plasma current. As is shown in this figure there is a set of toroidally wound coils, which are used to position the plasma and prevent it from interacting with vacuum vessel. Damavand tokamak has an elongated plasma cross-section [2]. This tokamak allows one to realize the physical plasma research in the ITER (International Thermonuclear Experimental Reactor) magnetic configuration [3]. The tokamak cross-section is shown in figure 2 and its main plasma parameters are given in table 1.

A great deal of work has been done on the control of plasma position in tokamaks [4–6] and the plasmas have been controlled using the generalized proportional-integral-derivative (PID) structure [7,8]. This paper describes optimization of a

Table 1. Damavand tokamak parameters.

Parameters	Max. values	Typical values
Major radius of the tours	$R_0 = 36$ cm	
Transversal cross-section	$2a/2b = 20/56$ cm	
Toroidal field	$B_t = 1.2$ T	1.0 T
Discharge duration	50 ms	>15 ms
Plasma density	$n(0) = 3 \times 10^{19}$ m^{-3}	2×10^{19} m^{-3}
Electron temperature	$T_e(0) = 300$ eV	280 eV
Ion temperature	$T_i(0) = 150$ eV	110 eV
Plasma current	$I_p = 40$ kA	25 kA

Under ohmic heating.

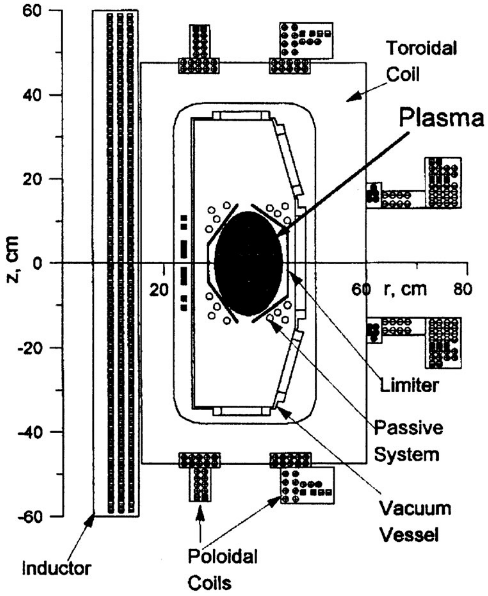

Figure 2. Damavand tokamak cross-section.

high-speed digital PID controller using self-oscillating relay systems as a current driver.

2. Plasma position control system

The automatic horizontal and vertical control over plasma position was realized with two orthogonal feedback control systems. Both feedback systems are identical in structure and only differ in the control coils and in the plasma position measurement. The plasma position digital control system is shown in figure 3. This system consists of an object of control (plasma column), plasma position processor (Rogowski coil for plasma current measurement, magnetic loops, integrators, divider and an adder), digital controller (Digital Signal Processor DSP, A/D and D/A), a control current driver (capacitor storage bank and a voltage inverter) and a control coil. DSP board is based on a TMS320c25 Texas Instrument digital signal processor. This processor efficiently implements many common digital signal-processing algorithms. Its architecture supports features that solve numerically intensive problems usually characterized by multiplication or accumulation [9,10]. In both vertical and horizontal feedback control systems one capacitive storage, $C = 0.09$ F with a 400 V operating voltage is used as a power supply source to the voltage inverters. Both inverters operate in a free running mode at $f \sim 1$ kHz, providing the accuracy of the plasma column position sustainment with respect to r and z in the order of 2 mm.

Damavand is a tokamak with non-circular cross-section plasma and a rectangular vacuum vessel. Therefore, a particular design is used for measuring the horizontal

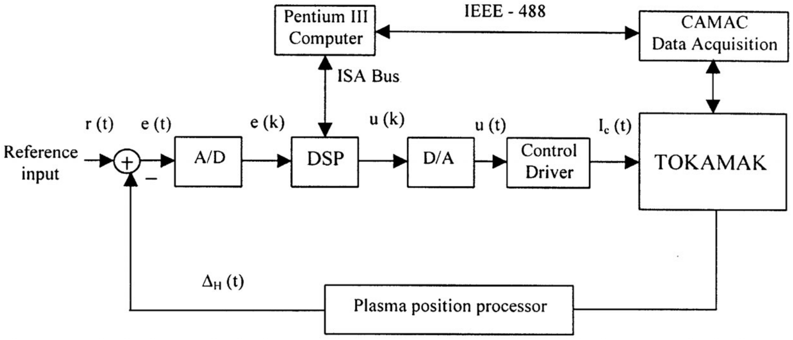

Figure 3. Plasma position digital control system.

and vertical positions (figure 4). For each position two sensors have been used: (1) Rogowski coil for plasma current measurement I_p and (2) saddle-like loops that are intended for measuring the poloidal magnetic field fluxes with their outputs (in linear approximation) proportional to,

$$\frac{\mathrm{d}}{\mathrm{d}t}(I_p \cdot \Delta)$$

where Δ is the plasma horizontal or vertical displacement. After electronically integrating the above equation and dividing by the plasma current, plasma column displacement Δ is singled out. This signal enters the summator, where it is compared with the reference input, $r(t)$, and error signal $e(t)$ is generated and it is used as controller input. The controller forms the control signal, $u(t)$, which operates the voltage inverter.

3. Digital control system

3.1 *Introduction*

One of the most widely used controllers in the design of single-input single-output (SISO) control systems is the proportional-integral-derivative (PID) controller. The digital PID control algorithm implemented for this work is used in rectangular approximation $(T/(z-1))$ for the integral operation $(1/s)$ and backward difference approximation $((z-1)/Tz)$ for the derivative operation (s) [11] where $z = \mathrm{e}^{sT}$ and T is the sampling period. It should be realized that as long as the sampling frequency is much bigger than the system bandwidth the approximation holds. A digital PID controller algorithm using the above approximation can be written in the form of a recursive difference equation as

$$u(k) = u(k-1) + k_0 e(k) + k_1 e(k-1) + k_2 e(k-2), \tag{1}$$

where $e(k)$ and $u(k)$ are the controller input, output and k_0, k_1, k_2 are given by

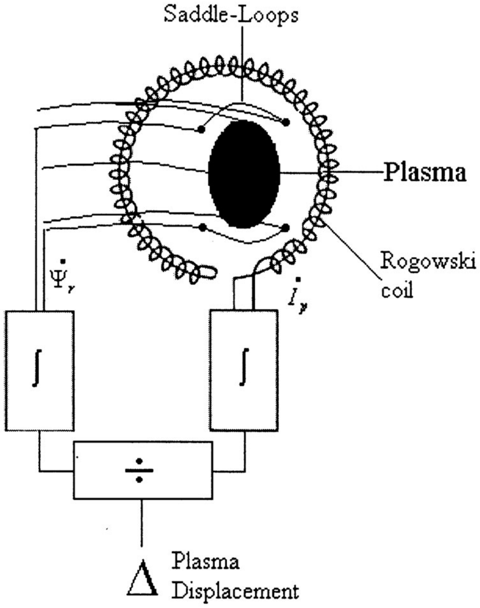

Figure 4. Plasma position measurement.

$$k_0 = \left(k_p + \frac{k_d}{T}\right), \tag{2}$$

$$k_1 = \left(-k_p + k_i T - \frac{2k_d}{T}\right), \tag{3}$$

$$k_2 = \frac{k_d}{T}, \tag{4}$$

where k_p, k_i and k_d are the coefficients of the equivalent analog PID controller. The DSP can execute (1) within 1.3 μs at a 40-MHz clock rate [9,10].

3.2 *Digital controller performance*

Let us consider the control process with P and PD controllers at a change in the differentiator gain, k_d, from 0.05 to 5. As shown in figure 5, the application of the proportional control law (small k_d) results in setting of self-oscillation at a low frequency with high amplitude, which makes the system unstable. In the case of $k_d = 0.05$, the voltage inverter operates at the low frequency, $f = 0.5$ kHz and the amplitude of self-oscillations is rather great (figure 5a). Using PD controller and increasing the coefficient k_d, one manages to increase the frequency of the self-oscillations and, as a result, to reduce their amplitude. At $k_d = 0.5$, the frequency $f = 1.25$ kHz (figure 5b) and at $k_d = 5, f = 1.5$ kHz (figure 5c).

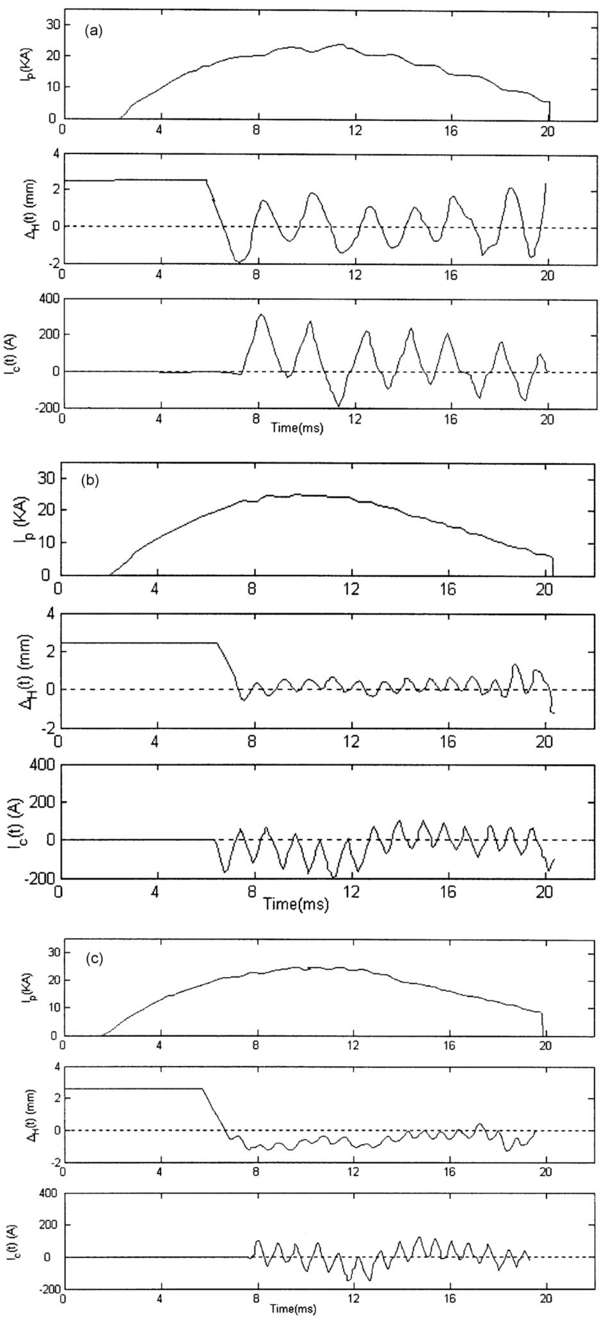

Figure 5. Time evolution of the plasma currents (I_p), plasma displacement (Δ_H), and feedback control current $I_c(t)$ when (**a**) $k_d = 0.05$, (**b**) $k_d = 0.5$, and (**c**) $k_d = 5$.

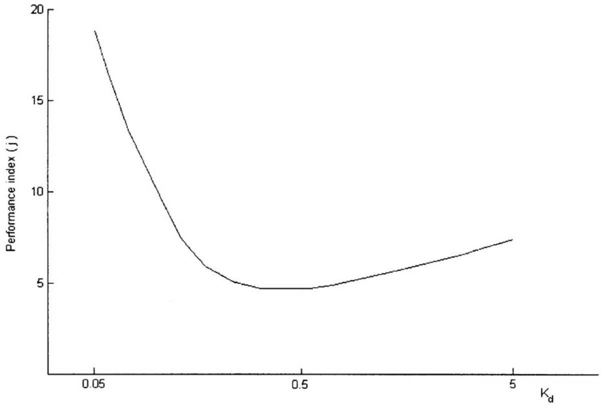

Figure 6. Dependency of the performance index in differentiator coefficient k_d.

The closed control system operation can be evaluated by two principal criteria: stability and accuracy. In the self-oscillating relay system one should provide a stable periodic process of control, first of all, and then, improve its quality. Here it is desired to minimize the following performance index in terms of k_d.

$$J = \int_0^{\infty} \Delta_H^2(t)\mathrm{d}t. \tag{5}$$

The dependency of the performance index in differentiator gain k_d is given in figure 6. Hence one can see that the range for optimal k_d is around 0.5, when the PD controller is used in the plasma column position digital control system. The results of PD and PID controller utilization are given in figure 7. In our case the stabilization system with PID controller does not reduce a steady-state error but changes its nature, converting it from a non-periodic to an oscillating one. At high coefficient constants in the integrating circuit, k_i, the system becomes unstable (figure 7c).

4. Conclusion

The study of the high-speed plasma position control system with digital PID controllers have given the following results:

A digital control system based on TMS320c25 signal processor has been designed and built. The results show that digital signal processor performance is satisfactory as long as the sampling frequency is much bigger than the system bandwidth.

The dependency of the performance index in terms of the controller derivative coefficient, k_d, when the PD controller is used, has been obtained. The dependency has shown the presence of an optimal value for k_d.

Introduction of an integrating circuit in the PD controller within the control system (utilization of the PID controller) did not result in the expected reduction in the steady-state error but produce a low-frequency component in plasma position. The results with the PID controller require further study in order to find out the

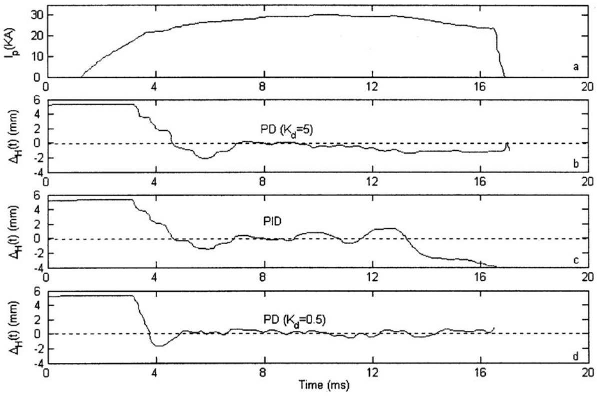

Figure 7. Time evolution of the plasma current (**a**) and comparison of the plasma displacement controlled by the non-optimal PD (**b**) and PID (**c**) controllers and by the optimal PD (**d**) one.

reasons for the reduction in stabilization accuracy in the presence of an integral component in the control law.

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