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# A Novel Modified Delay- Based Control Algorithm with Experimental Application

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In the present article, a new modified delay-based control structure is proposed to improve the closed-loop performance of control systems. The controller is designed for a second-order linear time-invariant system. The controller parameters are tuned by using the integral of the absolute error criterion. Theoretical results are simulated and experimentally applied to an electromechanical system, which is identified with an interactive system identification tool. It is shown that the present controller provides better control measures and time domain specifications compared with the classical PID and PI-PD controllers in the presence of measurement noise as well as uncertainties.

**KEYWORDS:** Delay-based control, electromechanical system, system identification, experimental application, proportional integral derivative (PID), stability, optimization.

## 1. Introduction

Analysis and control of Time-Delay Systems (TDS) have received growing interest in recent years due to their prevalence in various applications across different areas such as industrial processes, communi-

cation networks, mechatronics, haptics interfaces, motion synchronization, distributed and cooperative control for the coordination of unmanned vehicles, and biological systems [16, 34, 35, 57]. A tremendous

amount of research effort has been dedicated to TDS, and numerous advances have been reported on modelling, identification, stability analysis, and control.

However, it is to be noted that well-known classical feedback control strategies and controller tuning methods cannot keep pace with the system comprising time-delay. In any control system, the time-delay causes a physical constraint, which can damage the closed-loop stability of the system. It gives rise to a quasi-polynomial characteristic equation with infinite eigenspectrum [28, 34] which makes the analysis and synthesis of TDS extremely difficult [28, 56]. The time delay often may deteriorate the closed-loop response by decreasing the phase margin of the system [57]. Most of the existing works on TDS aim at eliminating delay in control applications. A number of approximation techniques or expansion methods such as Taylor series, Padé approximations, and phase shift techniques can be employed. These methods may show satisfactory performance for some small delay values, however, they cannot deal with large delays due to the inherent restrictions. A number of studies elaborate on how to weaken the negative effects of time-delay [34, 64, 73].

An intentional time-delay, in some cases, presents an opportunity to increase the closed-loop control performance when appropriately incorporated with the control system. A number of schemes such as frequency shaping, Smith predictor, delayed-control, and delayed resonator consider the stabilizing properties of time-delays. A remarkable performance improvement can be achieved by using time delay for a nonlinear dynamical system, such as chaotic motion. In fact, the counter effect of delay on the stability and performance of dynamical systems is a critical problem that still needs to be carefully answered. Thus, recent attention has been devoted to understanding the effect of time delay on control systems. Consequently, TDS has been highly active research field with a large amount of research effort.

The present research deals with modification of delay based control scheme to achieve better control performance while consuming less energy, fewer computational burden, low design effort with respect to classical controllers. Although the general methodology introduced in [66] and [47] is used in the present research, a new Proportional Integral-Proportional Retarded (PI-PR) control scheme is proposed. In the

control scheme, a PI controller and a PR controller are combined to control a second-order system. The main idea behind the control techniques is discussed carefully including experimental applications. The contributions of the paper are:

- 1 describing favourable effects of delay with related works,
- 2 providing an overview of delay-based control schemes,
- 3 modelling and experimental identification of an electromechanical system,
- 4 describing a novel modified delay-based control strategy and providing the stability analysis,
- 5 performing an experimental implementation to highlight the validity and capability of the proposed control strategy,
- 6 comparing the proposed controller with classical low order control techniques with a number of performance measures.

The second section presents a number of favourable effects of delay with relevant literature. Some details about the experimental set-up and model development of the electromechanical system are given in the third section. The fundamental mathematical concepts, the related theoretical background, and the design procedure of the proposed control scheme are demonstrated in the fourth section. Stability analysis is presented in the fifth section. Simulations and real-time experimental results with a comparative evaluation are addressed in the sixth section. Finally, the last section presents some concluding remarks and future works.

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## 2. A Review of Favourable Effects of Delay in Control Systems

A number of studies have emphasized that the time-delay has a positive effect on the control performance if it is handled carefully. Some preliminary studies were addressed by Suh and Bien [58-59], wherein proportional minus delay controllers were highlighted. A direct estimation of unknown dynamics by using an appropriate delay value was presented in [71], wherein the main idea is to introduce an appropriate delay value in the control loop, in order to reduce the effect of additive disturbances. Abdallah

et al. emphasized that a positive delayed feedback can stabilize an oscillatory system [1]. The benefit of utilizing delay instead of derivative terms was investigated in [27, 39, 46, 47]. Introduction of delay may enhance the performance of a closed-loop system without any estimation for derivative terms [36, 46, 47, 50, 52]. The control performance of a chain of integrators is improved, when the derivative part of the controller is replaced by a delay term [36]. A number of studies address the utilization of time delays in state feedback control scheme to approximate integral and derivative terms [29, 30, 62]. In a recent research, Ulsoy [62] proved the positive effect of time delayed control on the disturbance rejection capability and tracking ability of a single input single output (SISO) system. Delay differential equation (DDE) was solved using the Lambert-W functions. The work of Jankauskiene and Rimas presents the use of the Lambert-W function in the analysis of TDS [21].

In nonlinear systems area, it is stated that a remarkable performance improvement can be achieved by using time delay for controlling chaotic motion. A positive effect of time delay is reported on the delayed resonator, which is utilized with a delayed position feedback to enhance vibration absorber performance [20]. In [69], a bifurcation control problem is investigated for an Internet congestion control problem. A non-collocated vibration control example is addressed by Yang and Mote [70]. Udwadia et al. presented a number of favourable effects of time delay in control of flexible structures [61]. A robust time-delayed control scheme was proposed by Roy and Kar for a class of nonlinear uncertain systems [54]. A delayed sliding mode controller was addressed in [9], wherein the sign function was approximated by a time delay. It was shown that this realization still provides robustness of sliding mode control, while the chattering is reduced. The reported studies show that the delayed controllers have shown satisfactorily better performance in the presence of uncertainties and model mismatches.

A number of positive effects of time delay were demonstrated on tracking performance of type-I control systems [26]. Pyragas proposed a novel time-delayed feedback control algorithm, which raised a new research avenue in physics [44]. Moreover, the chattering phenomenon for a high-speed milling system was reduced by using time-delay in [63]. An inverted

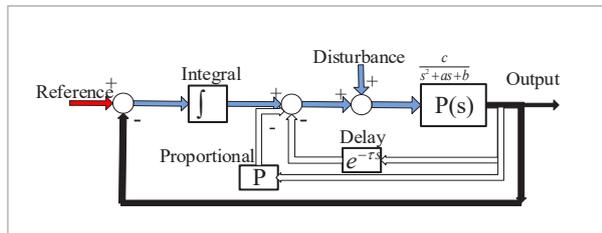
pendulum stabilization problem was elaborated with Pyragas-type controller [6]. The research studies, known as delayed control, contain the active utilization and intentional introduction of the time-delay as a design parameter. However, it is to be noted that the parameter tuning and stability analysis issues are still challenging [39, 47].

An intentional delay in the controller may help to design effective and simple control strategy, which is known as a delay-based control. This strategy can be considered as an alternative control to conventional PID type low-order control algorithm. The main advantage of the control scheme is that the designer does not consider any additional filter through the implementation, which preserves simplicity, reduces the energy consumption of the controller. Furthermore, satisfactory performance can be achieved if the noise levels are low [31, 36, 72]. Suh and Bien addressed a controller that attenuates high-frequency noise by performing an averaged derivative action over a finite period [59]. An improved PI-type controller with a filtered integral action was proposed in [31]. A delay type PID controller comprising delayed integral and derivative terms were highlighted in [73]. Villafuerte et al. addressed the stability analysis and tuning strategy of a PR control scheme [66], wherein simple tuning rules for assigning the dominant poles of second-order system were addressed via a PR controller. The PR controller outperforms the classical proportional-derivative (PD) controller in terms of tracking performance and control signal quality. Another benefit of the PR control strategy is that its numerical realization is computationally more efficient than other classical control techniques such as a PID controller. PR control application to a mechatronic system was presented in [37,38], wherein the authors present a pendulum control performance without tweaking differentiators. Yet another study elaborated the closed-loop stability analysis of voltage buck using proportional-delayed controller [17] that the is also based on the geometric approach, which allows partitioning the parameters space into regions with a constant number of unstable roots. In the work of Diez et al., a transparent bilateral control scheme for a local teleoperation system was realized by using a proportional-delayed controller [19]. Fragility analysis, which is based on computing of the maximum controller parameters deviation without losing the closed-loop stability, was carefully elaborated. A different PID type

dead-time controller was highlighted in [55], in which a delay was added to the integral loop of the PID controller. Ramirez et al. addressed a proportional integral retarded (PIR) control scheme and the stability analysis is derived in the sense of the algebraic geometric analysis [47]. Moreover, Ramirez and Sipahi demonstrated the design of delay-based controller for stabilization of network systems [48, 49, 50]. The control structure of PIR is depicted in Figure 1.

**Figure 1**

PIR controller [9]



Analytical tuning approaches are discussed for this new class of delay-based control scheme [47,51,52]. The aforementioned studies presented an explicit analytical tuning strategy containing a dominant triple root assignment with the aim of producing the maximum exponential decay rate of the closed-loop system. Zalluhoglu et al. proposed different types of delayed feedback control schemes for Rijke tube thermoacoustic instability problem [72]. Cluster treatment of characteristic roots (CTCR) is utilized to meet the objectives. In [32-33], a position control problem of servo drives was elaborated by using a cascade proportional integral retarded control. An integral absolute error (IAE) optimization of a PID controller with delay was addressed by Zitek et al. [75]. A geometric approach for the stability analysis of a proportional delayed controller was highlighted in [18]. A further discussion on delay-based control design techniques was represented in [42]. That work presents an experimental comparison of PID and PIR controllers. Further, some preliminary results of the present study were addressed in [43]. A direct integration technique for time-delayed control was addressed in [68]. Ramirez and Sipahi proved that the using of multiple intentional delays improve the consensus control performance by facilitating fast consensus and reducing the noise in a multi-agent system [48, 49, 50, 51, 52].

### 3. Preliminaries and Experimental Setup

Modelling and control of electromechanical systems have been greatly attracted in control community since they are encountered in a wide range of application areas. Direct Current (DC) motors have been used in various industrial control applications [11].

DC motors have various advantages like easy position/speed regulation, simple structure, and low maintenance. Therefore, numerous studies are dedicated to position and velocity control of DC motors achieving set point regulation, tracking accuracy, robustness, and energy efficiency.

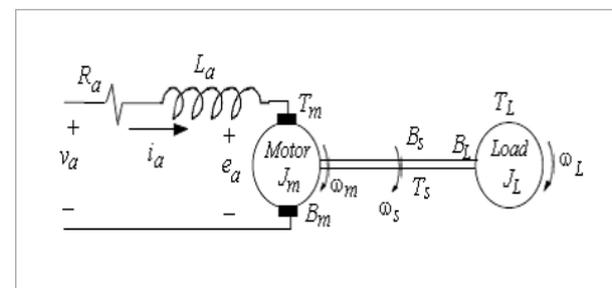
#### 3.1. Modelling of the Process

Angular position and velocity are the main control variables in DC motor control applications. Thus, the control designer needs velocity measurement, which may contain a considerable amount of high-frequency noise. Designer quite often adapts an appropriate low pass filter into the feedback system in order to attenuate high-frequency noise. However, employing such a filter structure may increase the complexity of the control scheme, computational burden, and energy consumption.

Inserting a time delay in a motion control algorithm may offer several opportunities. Such as, a time-delayed controller avoiding unnecessary velocity measurements. In other cases, if velocity measurements are not available, a derivative filter is used to estimate the velocity from position data. The dynamical equations of the electromechanical system are given as in [10, 11, 13] and the schematic diagram of the system is depicted in Figure 2.

**Figure 2**

The schematic diagram of the electromechanical system



The electrical and mechanical equations are described as (1)-(4):

$$v_a(t) = L_a \frac{d}{dt} i_a(t) + R_a i_a(t) + K_m \omega_m(t), \tag{1}$$

$$J_m \left( \frac{d}{dt} \omega_m(t) \right) = T_m(t) - T_s(t) = R_m \omega_m(t) - T_f(\omega_m), \tag{2}$$

$$T_s(t) = k_s (\theta_m(t) - \theta_L(t)) - B_s (\omega_m(t) - \omega_L(t)), \tag{3}$$

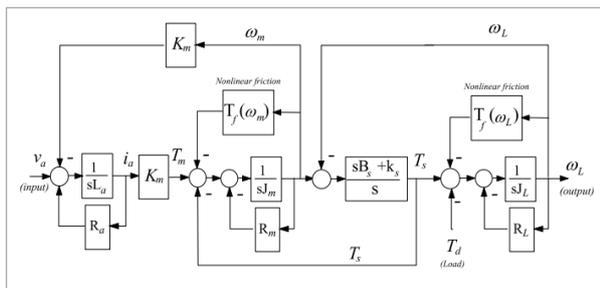
$$\frac{d}{dt} \theta_m(t) = \omega_m(t), \frac{d}{dt} \theta_L(t) = \omega_L(t), \tag{4}$$

where, the DC motor parameters in (1-4) are given in Table 1, and the block diagram of the system is presented in Figure 3. The motor shaft consists of several disks, which operate different kinds of transducers. Among them, the slotted-opto transducer is employed to obtain shaft speed. The tachogenerator, which produces

**Table 1**  
DC motor model parameters

DC Motor Parameters			
$v_a$	Armature voltage	$R_M$ $R_L$	Viscous friction,
$L_a$	Armature inductance,	$K_M$	Torque coefficient,
$R_a$	Armature resistance,	$T_M$	Generated motor torque,
$i_a$	Armature current,	$T_d$	External load disturbance,
$T_s$	Nonlinear friction,	$T_f$	Transmitted shaft torque,
$J_m$ , $J_L$	Moments of inertia,	$\omega_m$ , $\omega_L$	Rotational speeds

**Figure 3**  
Block diagram of the electromechanical system



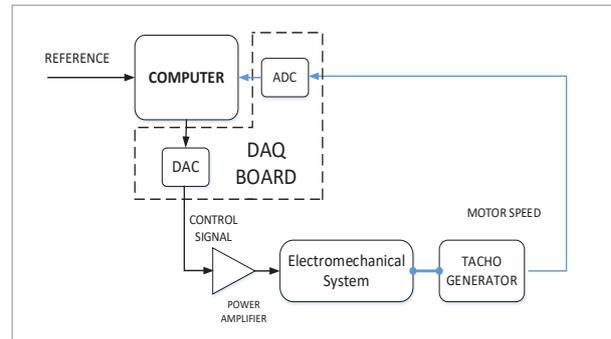
the voltage proportional to the shaft speed is utilized as a speed transducer for control applications [14].

### 3.2. Real-Time Identification of the Electromechanical System

It is evident that the exact numerical values of model parameters are difficult to obtain. Therefore, a number of system identification methods, wherein the mathematical models of dynamical systems are built from observed input-output data, are used to assign the model parameters easily.

The experimental setup is linked to the computer by an Advantech data acquisition (DAQ) board in order to carry out real-time applications. The DAQ card has 16 analogue input- 4 analogue output, 48 Digital I/O, 250Ks/s-16 bit maximum sampling rate and resolution. Further, a personal computer having Intel®core TM(2) Quad CPU Q850 @2.7GHz processor, 8GB RAM, 1024 MB VGA card is used. The experiment is conducted by Real-time Windows target option of Matlab/Simulink®, which is used as a software realization platform to generate the machine code. The schematic diagram of the experimental setup is depicted in Figure 4 [15, 40, 41].

**Figure 4**  
The schematic diagram of the experiment

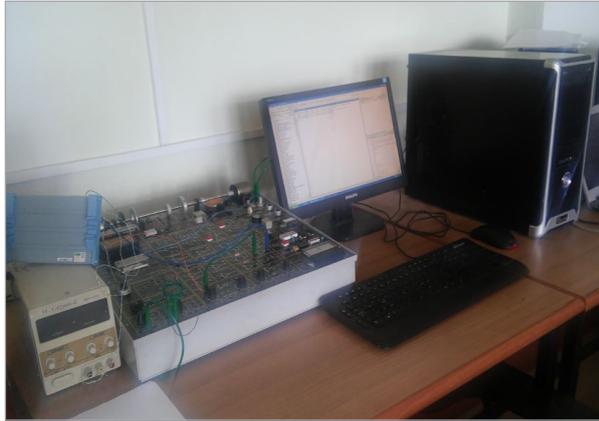


Control designer always needs a proper model in order to achieve satisfactory closed-loop control performance. However, the highly complicated nature of the most physical systems makes the development of exact models a tedious task. Thus, a proper model should be obtained by system identification techniques. In the present study, the identification problem has been treated as linear time-invariant (LTI) one in order to obtain an appropriate model. The actual system output is compared with predicted model

output to validate the model [11, 23]. A scene from the laboratory is given in Figure 5.

**Figure 5**

A scene from the experimental set-up



The process reaction curve is a well-accepted tool to determine the characteristic properties of a system under different operating conditions. A number of dynamical properties of the system such as rise time, settling time, and time constant can be obtained directly from the output data [7, 11]. In order to obtain the plant model, the armature of the DC motor is excited by a step input, of magnitude 5.20 Volts, and shaft speed is measured in revolution per minute (rpm). The output voltage produced by the tachogenerator is measured to be 4.48 Volts that corresponds approximately to 1200 rpm shaft speed. Then, a second-order system model is approximated as [10, 12, 13]:

$$G(s) \cong \frac{K}{(1+T_d s)(1+T_p s)} = \frac{c}{s^2 + as + b}, \quad (5)$$

where plant coefficients are calculated from the system output to be  $K=0.823$ ,  $T_d=0.0087$ ,  $T_p=0.1418$ . The second-order model is given as:

$$\ddot{y}_m(t) = -a\dot{y}_m(t) - by_m(t) + cu(t) + d(t), \quad (6)$$

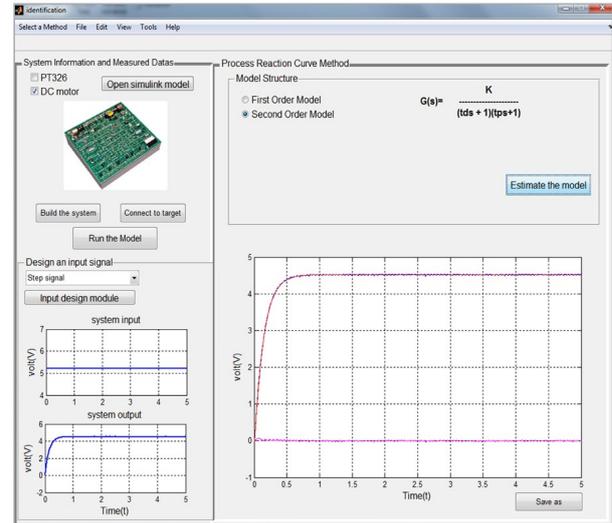
where  $a = a_n$ ,  $b = b_n$ ,  $c = c_n$ , and  $d(t)$  are the nominal system parameters and disturbance, respectively. The nominal model parameters are obtained as  $a_n=118.1763$ ,  $b_n=783.5862$ ,  $c_n=663.4968$  [11, 12, 39, 40, 41].

An interactive software tool, which is highlighted in [14-15], is used in the present work. The proposed

graphical user interface (GUI), which is presented in Figure 6, provides some facilities to the users.

**Figure 6**

An exemplar scene from the system identification GUI



The experimental steps (model structure, parameter estimation and validation) of the proposed methods can be observed and manipulated in the same screen. The model structure, model and measured outputs, and the modelling error are demonstrated on the right panel. The modelling error, defined as the difference between the measured output and the model output  $y_m(t) - \hat{y}(t)$ , is presented in Figure 6 such that the red line presents approximated model response, the blue line demonstrates the real system measured output, and the pink line shows the modelling error between the measured output and the model output. The comparison of the measured output and predicted output responses shows that the model gives a satisfactory result as far as the modelling error about 2% including transient and steady-states [15].

## 4. Application of the Controller

Until recently, various feedback control strategies such as adaptive controllers with intelligent methods, non-linear control algorithms, and robust control strategies have been investigated to achieve better control performance. Among these strategies, those of PID controllers are the most commonly used control algorithm in the industry due to its simplicity, functionality, and

applicability. However, it has a number of drawbacks. The controller gains  $K_p$ ,  $K_i$ , and  $K_d$  are determined by classical controller design approaches based on a nominal system model obtained around a desired operating point. Thus, PID controller may show unsatisfactorily control performance for the systems subject to uncertainties, modelling mismatches, and disturbances. In addition, some situations such as noisy measurements may lead to unexpected performance degradation, in particular during the experimental application. The tuning of the derivative term, which may amplify the high-frequency measurement noise, is another challenging task. In fact, as indicated in [53], the arguments given advise approximating the derivative term in most applications.

Several modifications of the PID control scheme have been addressed in order to overcome the drawbacks [2, 22, 53]. A PI-PD control [4], which is one of the modified forms with four parameters controller, can provide better performance especially for controlling integrating, unstable, and resonant processes [3, 4, 60]. In PI-PD control, the transfer function of the PI controller affects both its poles and zeros; however, the PD controller affects only the poles. [5, 24, 60].

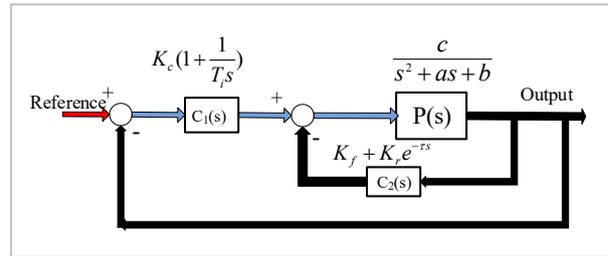
#### 4.1. Modified Control Structure

In the present control scheme, a proportional gain and a delay term are located in the inner loop for stabilizing the system and proportional integral controller is located in a forward path to reduce the steady-state error. The block diagram is presented in Figure 7. In fact, this control structure is different from the controllers presented in [33, 47, 65] because of the delayed feedback part instead of a delay output feedback.

In spite of the alternatives available in the literature, the structure of the control system and the role of time delay make the proposed control scheme an efficient and suitable for real-time experimental applications. The present study considers a novel design to obtain better tracking ability, improved noise rejection capabilities, and more applicable control signal than those utilizing classical PID and PI-PD control techniques. To the best of the author's knowledge, until now, no work has been reported in the literature to design of the PI-PR control for an electromechanical system.

**Figure 7**

Block diagram of the modified control structure



The present control technique has some advantages. First, it provides better transient response and fast convergence of tracking error. Further, the control signal is smoother than control signal of PI-PD and PID control. The chattering is attenuated in the presence of noisy measurements because there is no derivative term in the control structure. Moreover, this controller requires only memory registers that make it easier to implement. The designer does not need to use any estimation of the derivatives, which is a tedious task for the systems subject to measurement noise and uncertainties. Hence, the computational complexity and the cost of the controller design will significantly be reduced. The controller, which is given in Figure 7, can be presented as:

$$C_{PI}(s) = K_p + \frac{K_i}{s}, \quad (7)$$

$$C_{PR}(s) = K_f + K_R e^{-sh}, \quad (8)$$

where  $h > 0$  is the delay and  $K_p$ ,  $K_i$ ,  $K_f$  and  $K_R$  represent controller parameters. Thus,  $C_1(s)$  and  $C_2(s)$  present the conventional PI and proportional retarded (PR) controllers, respectively. The closed-loop system can be presented as:

$$\frac{Y(s)}{R(s)} = \frac{G(s)C_{PI}(s)}{1 + G(s)(C_{PR}(s) + C_{PI}(s))}. \quad (9)$$

Accordingly, the following transfer function is obtained:

$$\frac{Y(s)}{R(s)} = \frac{\frac{K_p s + K_i}{s} \frac{c}{(s^2 + as + b)}}{1 + \left( \frac{c(K_f s + K_R s e^{-sh} + K_p s + K_i)}{s^2 + as + b} \right)}. \quad (10)$$

Then the characteristic equation can be written as

$$\Delta(s) = s^3 + as^2 + bs + cK_p s + cK_f s + cK_i + K_R c s e^{-sh} \quad (11)$$

As stated previously, the proposed control strategy is a different version of the one addressed in [47], however, a modified delayed output feedback controller is integrated. The characteristic equation of the system is a quasi-polynomial with the model parameters  $a$ ,  $b$ ,  $c$  are defined in Section 2. The closed-loop stability of the control system strictly depends on the location of the roots of the characteristic equation. It should be noted that the delay-free ( $h=0$ ) system is stable under the conditions are satisfied:

$$\left\{ \begin{array}{l} b + K_f c + K_p c + K_R c > 0, \\ a > 0, K_i c > 0. \end{array} \right\}. \quad (12)$$

Even though it is assumed that the plant does not have any delay, the synthesis of the controller and stability analysis of the closed-loop system entails coping with infinite dimensional characteristics, thus, some algorithms are used for the computation of the roots [67, 74]. However, in the present work, the sketch of the stability analysis is addressed by using the technique presented in [46]. The stability regions are investigated with respect to delay ( $h$ ) and the proportional gain of delay ( $K_R$ ). A useful outline can be found in [8]. Accordingly, the computation of the roots of characteristic quasi-polynomial containing an infinite number of roots is a tedious task. However, a number of algorithms have been developed for the computation of the roots [8, 49, 74]. It should be pointed out that the analytical tuning of the proposed controller is more difficult than the controller presented in [47]. An alternative and easy parameter tuning method are addressed to eliminate the aforementioned challenges.

## 5. Stability Analysis and Parameter Tuning

A number of tuning methods have been addressed for PI-PD control. Atherton and Boz analyse a step response with standard forms [5]. Tan highlights the stability locus boundaries for obtaining all stability regions and controller parameter [60]. The inner

control loop is designed based on the proportional delayed (proportional retarded) control technique [66], while the outer PI control can be tuned by minimization of predetermined performance indexes such as IAE, integral of the squared error (ISE), integral of the squared control input (ISCI), and the Total Variance (TV). The performance measures are given as:

$$IAE = \int |e(t)| dt, \quad (13)$$

$$ISE = \int e^2(t) dt, \quad (14)$$

$$ISCI = \int u^2(t) dt. \quad (15)$$

The central notion is to place a triple real dominant root for the closed-loop system [66]. It is achieved by using a spectral analysis, which provides the designer more specific information about the dominant poles. For every given desired exponential lower bound on the decay  $\sigma > 0$ , satisfying  $\sigma > \delta v$ , where  $v$  is the non-damped frequency and  $\delta$  is the damping factor which can be obtained from Equation (6) [66], the controller parameters are obtained as [66]:

$$K_f = \frac{[(\sigma - \delta v)^2 - v^2(1 - \delta^2)]}{b}, \quad (16)$$

$$h = \frac{1}{[\sigma - \delta v]}, \quad (17)$$

$$K_R = \frac{[2(\sigma - \delta v)^2]}{b e^{\sigma h}}. \quad (18)$$

Now, the outer loop is tuned by the integral absolute error (IAE), which is a well-known minimization technique for controller parameter tuning [25]:

$$J = \int |r(t) - y(t)| dt = \int |e(t)| dt. \quad (19)$$

The controller's gains are chosen as given in Table 2. The output-voltage and rpm values for each optimized controller are presented in Table 2.

**Table 2**  
Control parameters

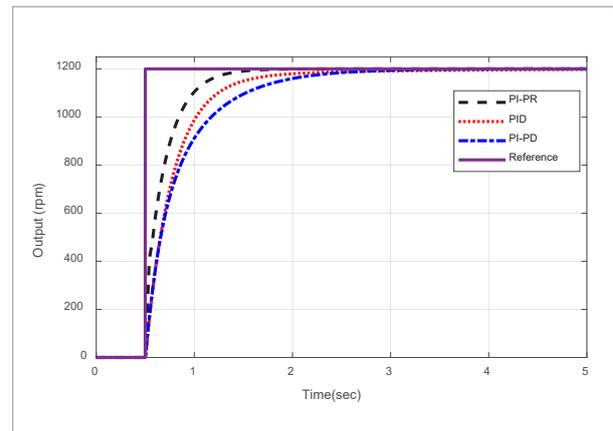
	PI-PR	PI-PD	PID
$K_p$	2.84	$K_p$ 7.86	$K_p$ 6.26
$K_i$	82.32	$K_i$ 25.56	$K_i$ 3.569
$K_R$	0.00518	$K_d$ 1.826	$K_d$ 1.572
$K_f$	16.32	$K_{p2}$ 8.234	
h	1.9231		
$\sigma$	59.376		
rpm	1203	1208	1227
Output-Voltage	4.4912	4.509	4.5808

## 6. Simulation and Experimental Results

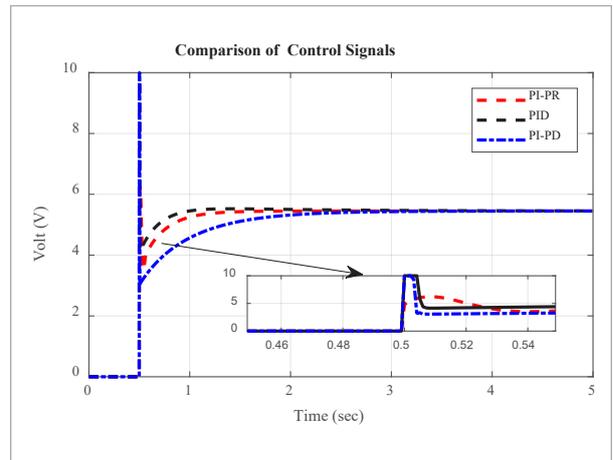
The closed-loop performance of the elaborated control scheme is simulated and experimentally investigated. A comparison with conventional feedback controllers is performed to highlight the advantages of the elaborated control method. The controller gains  $K_p$ ,  $K_i$  and  $K_d$  are determined by classical controller design approaches based on a nominal system model obtained around a desired operating point. Thus, PID controller may show unsatisfactorily control performance on the systems that are subject to uncertainty, model mismatches as well as noise. However, the present control method outperforms classical PID and PI-PD methods in terms of some performance measures. The selected criteria to evaluate the performance of the strategy are the IAE, ISE, error variance (EV), and ISCI. In order to visualize a better comparison, some of the performance measures are normalized. According to the simulation results, the set point response is illustrated in Figure 8 and the control signals are shown in Figure 9.

The experimental application is performed to demonstrate the effectiveness of the proposed controller. The performance metrics of elaborated controllers are presented in Table 3 such that the numerical results of the present control system provide better performance measures. PI-PR controller shows better results in terms of IAE, EV, and ISE measures. Moreover, PI-PR control scheme performs

**Figure 8**  
Tracking performance of the control schemes



**Figure 9**  
Control signals

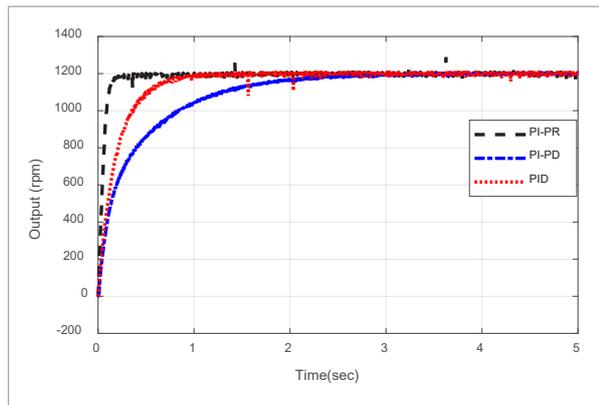


**Table 3**  
Performance comparison in terms of IAE, EV, ISE, TV, and ISCI indices

	PI-PR	PI-PD	PID
IAE	1.0335	1.8563	1.9856
EV	0.2354	0.5313	0.36183
ISE	1.1232	2.0225	1.5756
TV	0.17943	4.3594	0.3407
ISCI	81.1253	135.4823	94.6736

**Figure 10**

Real-time tracking performance of controllers



better in terms of transient response and tracking ability. It also produces a smooth control signal in the presence of noise.

Real-time experimental results are presented in Figure 10 and control signals are given in Figure 11.

The simulation results and experimental tests with tabulated performance measures show that the closed-loop system enables more efficient control behaviour, while reducing energy consumption by producing a smooth control signal in comparison with conventional PI-PD and PID control techniques.

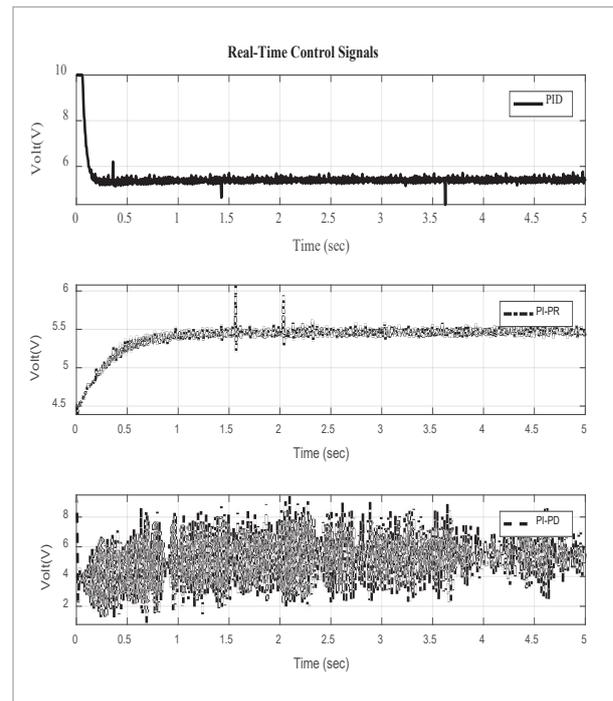
From the results, the delay-based controller provides more advantageous than conventional PID and PI-PD controllers since it requires only memory registers, which make it easier to implement [27, 46, 47].

Since the controller does not contain any derivative term it would not be noise amplification problem. Thus, it is not necessary to consider any additional filter during the experimental realization [50, 51, 65, 66].

It is widely known that the control signal should be in an applicable range considering the upper and lower limits of the actuator. This constraint is considered during the real-time application, in order to avoid actuator saturation and integral wind-up problem. According to the control signals, the proposed scheme necessitates a lower value of voltage in comparison with traditional control schemes. Thus, the energy consumption of the control input has been reduced. It can be concluded that the rapid changes and oscillations for the PI-PR control are less than that with conventional PI-PD and PID control approaches. The

**Figure 11**

Real-time control signals



rapid changes in control signal may reduce the lifetime of the actuators by damaging its components. Because of failing to produce a smooth control input, the poorest results are obtained with the classical PI-PD controller in terms of the error variance.

## 7. Conclusion and Future Works

The real-time control of the electromechanical system, represented by second-order LTI model, is addressed by using a novel modified delayed type controller. The proposed controller is compared with the conventional PI-PD and PID controllers. The algorithms are tested experimentally on a real benchmark electromechanical system.

The proposed control scheme provides satisfactory performance in terms of performance metrics. The controller can be easily implemented for practical applications. The main advantage of inserting a delay in the controller is that the closed-loop control system does not need any additional filter to attenuate noisy measurements.

**Table 4**

Advantages and drawbacks of the controllers

Control Scheme	Advantages	Drawbacks	Improvements
PID	<ul style="list-style-type: none"> <li>_ Simple structure</li> <li>_ Easy parameter tuning</li> <li>_ Fast response</li> </ul>	<ul style="list-style-type: none"> <li>_ Poor performance with wide operation range</li> <li>_ Lack of robustness</li> <li>_ Cannot cope with model uncertainties</li> </ul>	<ul style="list-style-type: none"> <li>_ Parameter optimisation and automatic tuning can be adapted</li> </ul>
PI-PD	<ul style="list-style-type: none"> <li>_ Wide operation range</li> <li>_ Suitable for unstable integrated processes</li> </ul>	<ul style="list-style-type: none"> <li>_ Larger error variance</li> <li>_ Needs an exact model</li> <li>_ High control input variations in the presence of noisy measurements</li> </ul>	<ul style="list-style-type: none"> <li>_ Strong robustness can be provided</li> <li>_ Fractional controller can be designed</li> </ul>
PI-PR (Proposed)	<ul style="list-style-type: none"> <li>_ Reduce control effort</li> <li>_ Smooth control signal</li> <li>_ Less energy consumption</li> <li>_ Low computation cost</li> <li>_ Needs no additional filter</li> </ul>	<ul style="list-style-type: none"> <li>_ To obtain analytical stability is a tedious task</li> <li>_ Controller parameter tuning is a challenge</li> </ul>	<ul style="list-style-type: none"> <li>_ Optimal parameters can be selected</li> </ul>

The proposed controller may provide several advantages by reducing the cost, providing a simplicity, as well as improving the closed-loop performance. Table 4 presents summary of the control structures.

Future works will mainly focus on analytical controller parameter tuning. Stability regions will be investigated according to delay and controller parameters changes, then robustness of the control scheme will be addressed.

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