Simulation Study of Electric Drive and Industrial Plants with New Smart Controller

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***Abstract*—This paper presents the simulation results of electric drives and industrial plants by using new smart controller with fixed parameters. Transient response of multiple linear and nonlinear plants with changing of control signals and disturbances are considered.**

Keywords*— stabilization, electric drive, smart controller, derivatives balance, fixed parameters, transfer function.

I. INTRODUCTION

The most essential requirement for electric drives and industrial systems of automatic control and stabilization is to ensure the specified static and dynamic properties, which is characterized by the following indicators: stable process control in the entire range of disturbance on the industrial plant; the specified quality of transient response (rise time, peak time, overshoot and oscillation); the specified control accuracy in the steady state. Another important problem is numerical control of the industrial process, which ensures the transition to new operating modes. The solution to this problem is carried out using the same automatic stabilization system, which have time varying control signal

II. LITERATURE REVIEW

The proportional-integral-derivative (PID) controller is the most common type of controllers, owing to its simple structure, satisfactory control effect and acceptable robustness [1, 2]. They are easy to implement and have a low cost. Based on [3], single-loop PID controllers models account for 64% of the controllers, while multiple loop models account for 36%. There are many modifications of PID controllers. These modifications include the following: controllers with set-point weight (two degrees off freedom - 2DoF), controllers with Pre-filter for the set-point signal, controller with two degrees of freedom, ratio controller, and controller with an internal model IMC [4, 5]. For controlling plants with a large time delay, PID controllers with Smith predictors and their modifications, predictive PI controllers, are used [2]. These modifications of the controllers do not provide the required system performance when controlling nonlinear plants, also when controlled systems have uncertainty [5]. Improving systems performance can be done by using the methods of artificial intelligent techniques such as fuzzy logic [6], neural networks [7, 8] and genetic algorithms [9, 10] ("soft-computing"). Combinations of these methods can be implemented in a single controller. The main disadvantage of fuzzy and neural network controllers is their complexity of configuration (compiling rule base and training neural network) [5]. There are large number of PID – controller tuning methods in the literature; [11].

To ensure the operability of control systems under conditions of great uncertainty, robust control systems have been developed. In the theory of robust stabilization, problems of constructing a stabilizing controller for some classes of uncertain plants are considered. Plant uncertainty in this case, acts as a disturbance of the nominal plant. The well-known methods of robust stabilization are applied to infinite families of plants of the same dynamic order and the same structure. In this case, the parameters, as a rule, change in a certain region specified by known constraints [12]. Methods specially designed to ensure operability in conditions of great uncertainty: interval control methods, methods with large gains, relay control methods with variable structure, smoothed methods with variable structure, combined control methods with uncertainty observers, adaptive control methods with parameter identification, adaptive control methods with a model, control methods using reverse dynamics [13].

Adaptive control systems include these system, where control method used by a controller which must adapt to a controlled system with parameters, structure or algorithm which vary, or are initially uncertain in control process to insure desired performance. When designing an adaptive controller, uncertainty is characterized by a set of unknown parameters and feedback is used not only to stabilize, but also to evaluate these parameters during the control process of the plant. A detailed review of adaptive control methods and systems is presented in [14, 15]. However, most of the known adaptive and robust control methods are distinguished by their complexity of synthesis procedures, as well as the complexity of the structure and high dynamic order of the resulting controller [14].

Robust stabilization problems of the systems with parametric uncertainty are similar to problems of simultaneous stabilization of a family of dynamic systems, which consist into finding a universal controller that can stabilizes a finite family of different systems with different dynamic orders [12]. The stabilization problem in this form was presented in [16] and named as simultaneous stabilization in [17]. In [18, 19] it was found that it is impossible to design an algorithm that would allow in a finite number of steps to answer the question of the simultaneous stabilization of three or more plants using only the coefficients of their transfer functions, arithmetic and logical operations, and systems of equalities or inequalities. An example of controller synthesis that simultaneously stabilizes a set of nonlinear plants with a time-varying delay and parameter uncertainties is presented in [20].

A large theoretical contribution to the development of the theory of non-stationary control systems of plants have varying parameters during control process, was published in monograph [21].

The above review of publications allows us to state that a theoretical basis has been created for the development of automatic stabilization systems. But in order to use these achievements in practical manner, an engineer needs to study many of scientific articles and monographs, to consider the obtained results, and evaluate the possibility of their application to a specific industrial plant. In this case, the engineer will have to perform a number of experiments to identify the controlled plant in order to carry out the correct tuning of the controller.

III. Problem statement

Thus, it is relevant to develop a controller with an engineering appeal, which lies in the simplicity of its adjustment for stationary and non-stationary control plants.

It is necessary to study transient processes in stabilization systems with linear and nonlinear plants with a controller that does not change its structure and parameters during operation, provides greater flexibility in control and allows you to adapt to variations in system parameters due to changes in modes, operating conditions, interference and changes in the parameters of the control plant.

IV. Research results

The underlying theoretical approach of our new control technique is based on solving the problem of stability preservation of transfer functions of linear systems [22]. To solve such problems (partially substitution of rational function by another rational function) we using derivatives balance method. It has been developed by authors as a control system design and analysis technique. The significance and merits of derivative balance versus other design techniques, simultaneously yield the maximum precision of the system performance, robustness, full rejection of disturbances, noise elimination and huge stability margin. However, other important considerations was determined by the new method for example obtained mathematical proof of PID controller equation nature, controller parameters overlapping, structure and controller location in control loop.

The key contribution of derivatives balance method is the designing of linear feedback controllers without system parameters identification and knowledge of approximate system order. The attractive features of our method compared to Lyapunov's where unperturbed motion is compared with other possible unperturbed motions of the system to determine stability, in our case it is not necessary to determine stability of the system because the perturbed motions of the system will integrate in unperturbed motion as single system, so the obtained new system completely have the same properties as the unperturbed system. Thus, this features of our method gave us ability to design feedback and feedforward controllers to satisfy the system transient and steady state response requirements.

Generally controller can be programmed by using the standard elements of control system (proportional, integral, and derivative terms), to making smart feedback-feedforward loops for controlling both type of systems minimum and non-minimum phase. To control minimum phase systems, the main controller as shown in figure 1 using its smart loops can make full inversion of plant dynamic as control signal in feedforward path and shaping desired behavior of the system output. In case of non-minimum phase systems or systems with time delay, the main controller generate only inversion of the plant poles in the feedforward path and the sub-controller activated to predict inversion of the plant zeros in feedback path, so this procedures make full plant neutralization and main controller can shape desired output response. More advantages in this control algorithm, the obtained controller have fixed parameters during automation process regardless of plants time varying parameters or if has uncertain parameters, designed controller has ability to stabilize simultaneously infinite number of plants.

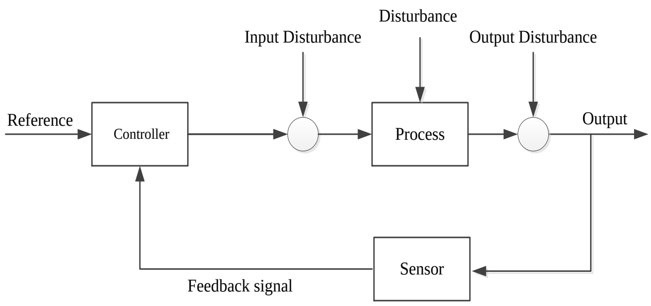

Fig. 1. Control system block diagram with proposed controller.

For testing the new control algorithm validity and veracity in practical point of view we considering some examples for different type of the dynamic systems include both linear and nonlinear systems.

Linear systems (SISO)

Consider a linear single input-single output plant described by the following general transfer function:

$$G(s)=\frac{b(s)}{a(s)}=\frac{b_0s^m+b_0s^{m-1}+\cdots+b_{m-1}s+b_m}{a_0s^n+a_0s^{n-1}+\cdots+a_{n-1}s+a_n}\ ,(1)$$

where $n \geqslant m$.

In table 1 the coefficients of the numerator (b_m) and denominator (a_n) polynomials of the plants to be controlled are presented. The first numerator corresponds to the first denominator, defining the first plant. The same relation holds for the other plants.

These plants have been randomly generated.

The simulation results are presented in figure 2 and figure 3, which show that with single controller and varying plant parameters and orders obtained higher precision of system performance. Figure 2 shows that the designed system meet transient response, stability and steady-state error performance specifications.

Thus, it should be highlighted that the controller has been shaped identical response for all different plants with maximum precision and the value of percentage overshoot equal to zero, in some cases of reference tracking, controller can shape response with desired percentage of overshoot value.

Furthermore, the generating control signal by controller will be always within exist limit even if controlled system have higher order.

TABLE I

COEFFICIENT'S OF NUMERATOR AND DENOMINATOR

Numerator coefficients				
No	**S^3**	**S^2**	**S^1**	**S^0**
1	0	0	0	20.402
2	0	0	9.0156	3.615
3	0	12.7033	7.4299	1.2352
4	1.7036	0.1758	0.4773	0.0429
5	0	5.5870	4.5500	1.070
6	0	0	3.5219	6.5695
7	0	0	9.3417	2.0657
8	0	0	0	3.3069
9	0	22.8714	31.0738	4.2467
10	1.7969	1.4265	0.3216	0.022
Denominator coefficients				
No	**S^3**	**S^2**	**S^1**	**S^0**
1	0.1057	- 0.3289	2.9551	9.3
2	1.7393	1.8741	- 1.2871	- 1.3723
3	1.5872	-0.1100	1.5533	2.0748
4	0.5076	- 1.5550	- 1.1336	- 0.9341
5	0	1.2985	- 1.5323	0.89
6	0	0.0805	- 0.2543	0.1536
7	0	0	1.2296	1.3654
8	0	0	0.8550	-0.1866
9	0	1.7562	- 0.5883	- 1.2747
10	0.1085	0.9204	- 0.0218	0.2248

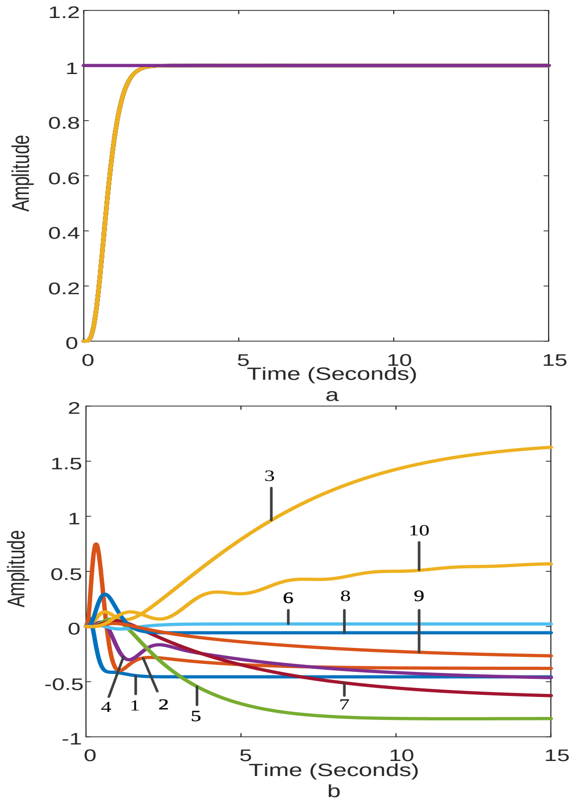

Fig. 2. Step response (a) and generated control signals (b) of the systems with identical response.

Figure 3 shows, ability of the controller to shape measured transient response of the systems with different time constant.

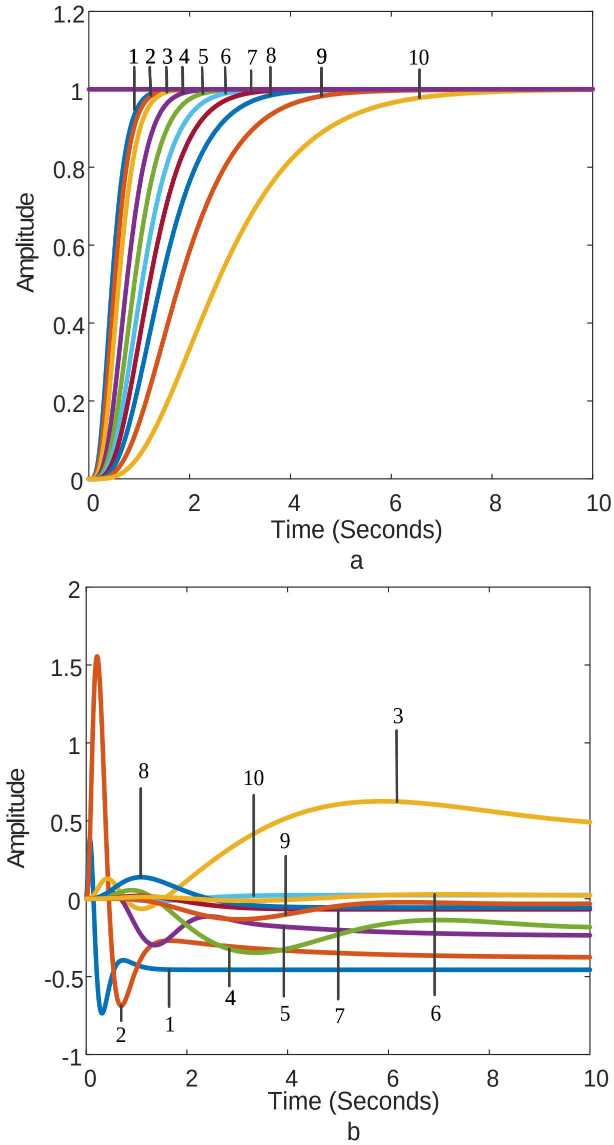

Fig. 3. Step response (a) and generated control signals (b) of the systems with different constant time response.

Higher order linear systems

In this example we shall consider a higher-order systems in closed loop with input multiplicative disturbance and output additive disturbance, used controller designed by the same technique.

Let the higher-order model with open-loop transfer function G(s) be as shown in equation (1). Consider a system a ninth - order with open-loop transfer function.

$$G(s) = K\frac{s^3 + 4s^2 + 10s + 5}{s^9 + 7s^8 + 5s^7 - 11s^6 + s^5 + 5s^4 + 3s^3 + 2s^2 + 10s + 9}. \quad (2)$$

Where input disturbance is step function of coefficient K and output disturbance is sinewave function with frequency 20 Hz.

Simulation results show the ability of controller to shape high accuracy response without approximation to low order and make full rejection of all disturbances. Simulation result shown in figure 4.

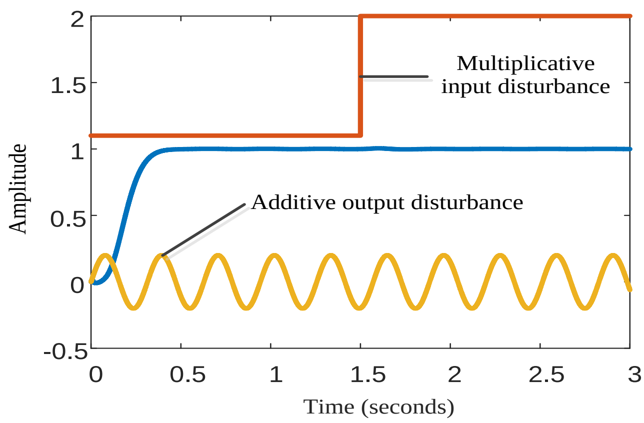

Fig. 4. Step response of ninth order system with input multiplicative disturbance and output additive disturbance.

Nonlinear systems

In this example, we will study nonlinear systems subject to internal uncertain disturbance that may change dynamic behavior of controlled system. Consider nonlinear systems described by the following second order differential equations [23]:

$$\begin{cases} x_1(t) = f_1(x_1(t)) + k_1 x_2(t), \\ x_2(t) = f_2(x_1(t), x_2(t)) + k_2 x_3(t), \\ \cdots \\ x_n(t) = f_n(x_1(t), x_2(t), \dots, x_n(t)) + k_n u(t), \end{cases} \quad (3)$$

where $x_1(t), x_2(t), \dots, x_n(t)$ are state variables;
$f_1, f_2, \dots, f_n$ are some known functions;
$k_1, k_2, \dots, k_n$ are some coefficients?
u(t) is the control signal.

To illustrate the effectiveness of the new algorithm obtained by derivative balance method, consider the system of second order nonlinear differential equation

$$\begin{cases} x_1(t) = f_1(x_1(t)) + k_1 x_2(t), \\ x_2(t) = f_2(x_1(t), x_2(t), \varepsilon(t)) + k_2 x_3(t), \end{cases} \quad (4)$$

where ε(t) is uncertain internal disturbance.

The responses of the closed-loop systems with the new controller shown in figure 5, a and 5, b results show the effectiveness of proposed control algorithm for manipulating nonlinear process. Furthermore, controller completely rejected unknown disturbance using its smart loops. We would like to note that, for all tests (figure 3, 4 and 5) the same controller is used with same parameters.

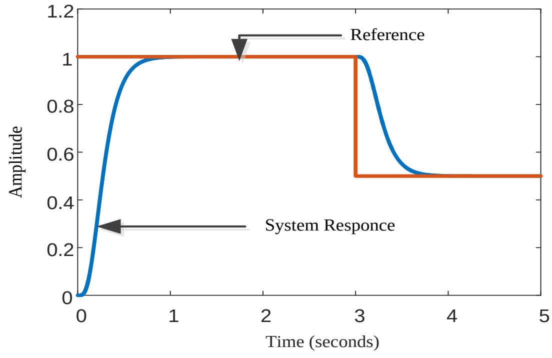

Fig. 5, a. Step response of nonlinear systems with disturbance.

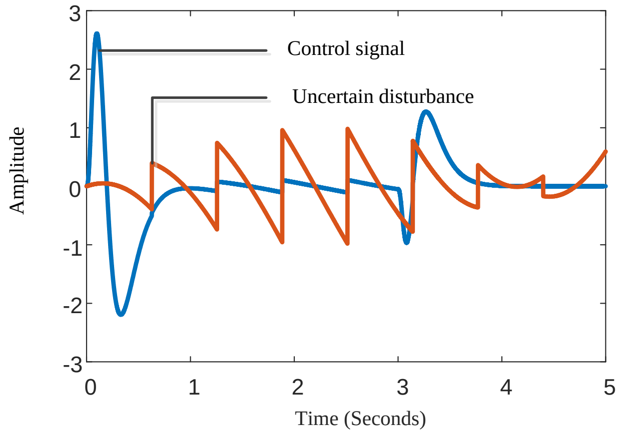

Fig. 5, b. Generated control signals of nonlinear systems with disturbance.

Uncertain disturbances and noises rejection

Another example illustrate the rejection of additive disturbances, using the same controller as in previous examples with same parameters to reject unknown disturbances effectively.

Transfer function of the plant.

$$G(s) = K\frac{s+13}{s^2+7s-3}. \quad (5)$$

In this example we will consider additive noises in controller output and additive disturbance in process output as shown in figure 1. In case of additive noise and additive disturbance controller generate output signal as follow: controller output equal to control signal ± noise ± disturbance. Where control signal directly equal to inverse function of process and identificated function of noise and disturbance has different sign compared to original signal, function of noise and disturbance are generated randomly. In process control identificated functions of noise and disturbance subtracted with original noise and disturbance functions, in results we have full elimination of noise and disturbance as shown in figure 6.

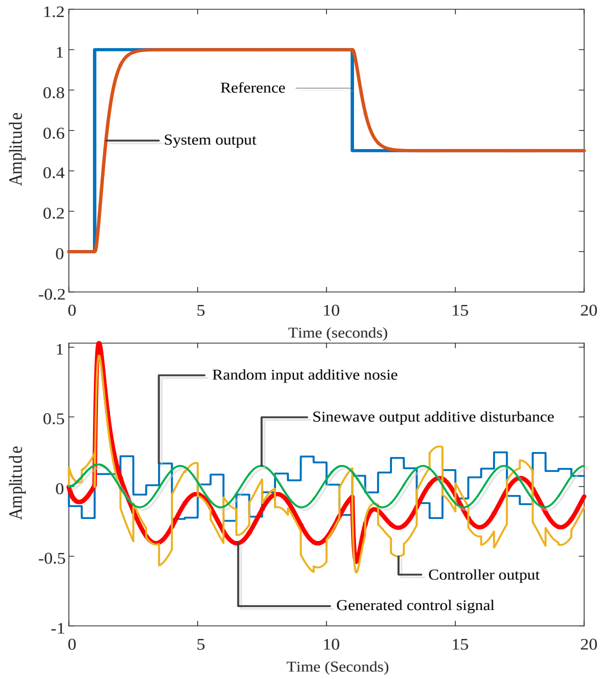

Fig. 6. Step response and generated control signals of the system with proposed controller.

Sensor with bad dynamic behavior

The performance of an industrial process is strongly dependent on available sensor measurements. Since the sensor dynamic is taken into account, so we will consider in our control loop sensor with slow response and with osculating output behavior. For high precision performance we need to identifications such sensor transfer function.

To illustrate this example we selected transfer function of the system from table 1.

The plant transfer function

$$G(s) = \frac{9.0156s + 3.615}{1.7393s^3 + 1.8741s^2 - 1.2871s - 1.3723}. \quad (6)$$

Sensor transfer function with slow response

$$H_1(s) = \frac{1}{2s + 1}. \quad (7)$$

Sensor transfer function with osculation behavior

$$H_2(s) = \frac{1}{s^2 + 0.2s + 1}. \quad (8)$$

Referring to simulation results, the proposed derivatives balance method has enough power to design controller that, make system output signal does not affected by sensor dynamic behavior (figure 7).

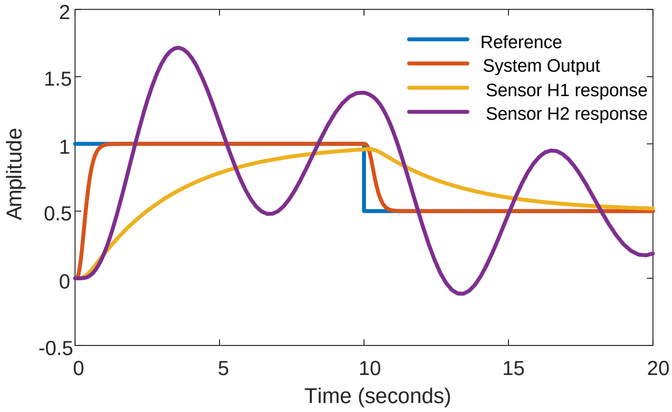

Fig. 7. Step response of the system with sensors output.

Reference tracking

Here we present example of tracking control systems with using the same approach (derivatives balance) to design controller for motion control in electromechanical system with two electric drives. The motion control system of 3-axis CNC milling machine with simultaneous coordinated movements in XY plane.

In circular interpolation, the simultaneous motion of two axes generates arc at constant tangential velocity, or feedrate V_0. The axial velocities satisfy the following equation:

$$\begin{cases} V_X(t) = V_0 \sin\ \theta(t), \\ V_Y(t) = V_0 \cos\theta(t), \end{cases} \quad (9)$$

where

$\theta(t) = \left(\frac{V_0}{R}\right)t,$

and R is radius of the circular arc.

In order to employ derivatives balance method, this example does not required system parameters identification. Smart controller can obtain the characteristics of the system and the mathematical models automatically as inverse function.

Machine tool feed electric drive servo control systems are designed to accomplish a task that is to control the positions and velocities of machine tool axes.

Based on brushless DC motor feed electric drive with transistor converter has inner current loop with current relay controller. Speed and position loops are designed with PI controller and proposed controller to illustrate the effectiveness of derivatives balance method when changing load torque and noisy sensor measurement (figure 8).

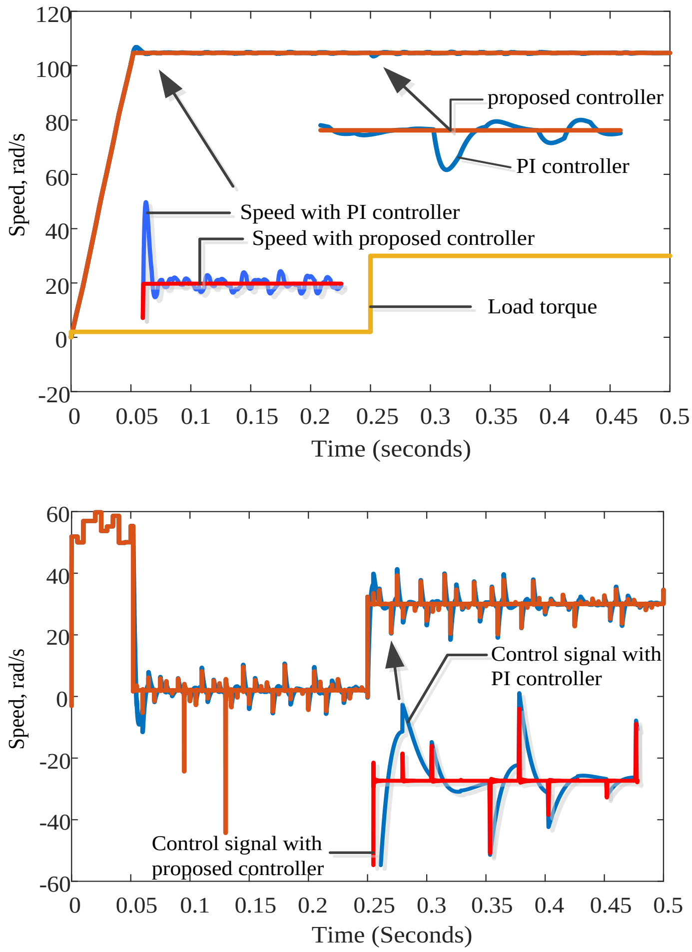

Fig. 8. Simulation result of motor speed loop comparison between proposed controller and PI controller.

Simulation results of speed loop control of feed rate DC brushless motor show the effectiveness of proposed controller compared to PI controller. It can clearly be seen that the proposed and PI controllers achieve less than 1% and 3% overshoot respectively.

Basically attached noise and disturbance was full rejected by proposed controller as shown on figure 8.

The response of circular motion of machine tools according XY plane shown on figure 9, the result show the deviations of positioning with PI controller when acting with noise. Repeatability of position with proposed controller represent a high accuracy in reaching the same position from which the movement starts. All tests have been done with same condition for both controllers PI and proposed controller.

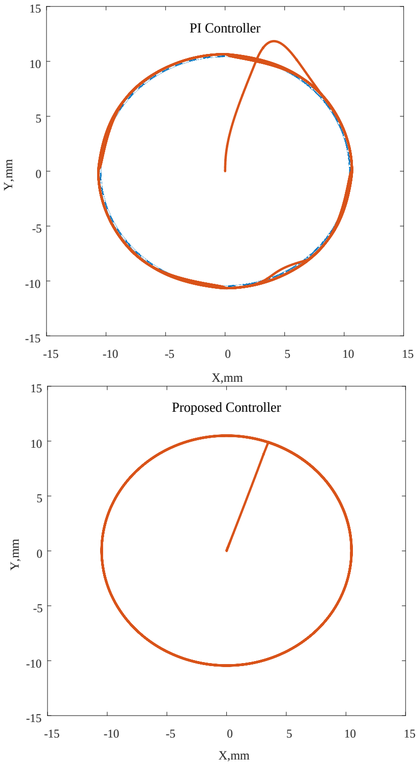

Fig. 9. Simulation result of circular motion test comparison between proposed controller and PI controller, input signal frequency 60 Hz.

V. Conclustions

The design methodology based on derivative balance method allow to design controller for linear and nonlinear systems. Based on obtained transient response results with proposed smart controller, we can make the following conclusions.

1. Controller with constant parameters provides non-overshoot response with desired constant time (within exist limits) for linear and nonlinear systems when the transfer function order of the linear part of the system is changed.

2. When varying the additive and multiplicative disturbances on the controlled system, the controller ensures the stability of the closed loop system with the desired performance of transient and steady state response and without a significant deviation of the system output from the reference value in the steady state.

3. In the case of system output sensor has bad dynamic behavior or big time constant, control system designer should make accurate identification of senor dynamics when configuring controller. So bad sensor dynamic and noise in our smart controller loop cannot effect output of the system.

The direction of our further research will include the improvement of non-minimum phase and delayed systems control techniques using derivatives balance method.

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