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Design Controller for a Class of Nonlinear Pendulum Dynamical System

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ABSTRACT

Designing proportional integral derivative (PID), Linear Quadratic Regulator (LQR), Fuzzy Logic Controller (FLC) and Self-Tuning Fuzzy PID (STFP) controller is used for nonlinear pendulum dynamic system in this paper.The promising performance of the proposed controllersinvestigates in simulation. The effectiveness, robustness against noise and the comparison of the controller methods for Nonlinear Pendulum Dynamical System are delivered in this paper.

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1. INTRODUCTION

Historically Pendulums were used as gravimeters to measure the acceleration of gravity in geophysical surveys, and even as a standard of length. Generally, they used to regulate pendulum clocks, in scientific instruments such as accelerometers, seismometers and widely in aerospace technology, robotics and etc [1]. Many researches on modern control theory and intelligent control theory it as study object and many new control theories and methods are developed, because it consists of some physical subjects such as the simple harmonic motion, the period of oscillation, the acceleration of gravity, the center of mass, the moment of the inertia, momentum, etc [1]. The Nonlinear Driven Pendulum Dynamical system poses a challenging control problem. However, the comparatively complex system is hard for low cost microcontrollers to process in many control systems.Intelligent computational techniques such as Artificial Neural Network (ANN), Fuzzy Logic theory (FL), Genetic Algorithm (GA) and etc, which have given novel solutions to the control nonlinear system problems [7], [8], [9], [10], [11].

The term "*fuzzy logic*" was introduced with the 1965 proposal of fuzzy set theory by Lotfi A. Zadeh [21]. The pioneering research of mamdani and his colleagues on Fuzzy Control [14], [15], [16] was motivated by zadeh's seminal papers on the linguistic approach and system based on the theory of fuzzy sets [17], [18], [19], [20]. Fuzzy logic used in many fields, for sample control theory to artificial intelligence. FLC is an intelligent control method based on language rules. The core of fuzzy control algorithm is fuzzy inference that is an algorithm with the ability of human thinking. FLC is the representative one among many intelligent control methods, which has already achieved many successful applications in industry field, including in the Nonlinear Pendulum System control and it is convenient to implement in the complex process, [12], [13].

A PID controller is a generic control loop feedback mechanism and regarded as the standard control structures of the classical control theory. PID control has prominent advantages and it is widely used as an effective control scheme such as simple controller structure and easier parameter adjusting. PID is the most commonly used feedback controller, literally everywhere in industrial applications. The Although conventional PID control works well on linear system only near the design point but When object system goes far away from the design point and or system is nonlinear, this method can hardly hold the dynamic performance. The Composition both advantages of fuzzy control and PID control so that the dynamic performance far away from the design point can be improved [6]. STFP controller is base on the conventional PID controller that has both advantages fuzzy control and PID control.

Optimal control theory plays a very important role in progress Control Science with the problem of finding a control law for a given system such that a certain optimality criterion is achieved. There are many optimization and optimal control techniques which are present. The intelligent optimal control has emerged as viable recent approach by the application of these intelligent computational techniques. LQR, an optimal control method, and PID control, which are generally used for control of the linear dynamical systems, but they applied to control the Nonlinear Driven Pendulum dynamical system.

The paper aims to studying Positioncontrol the nonlinear Driven Pendulum dynamical system under the step input. To solve this problem, theories of PID control, PID control based on LQR control, fuzzy control and self-tuning fuzzy PID are analyzed to demonstrate the effectiveness of the control schemes, the comparative assessment on the system performance for each of controllers are presented then they are designed. Finally, Simulation is developed within Simulink and Matlab for evaluation of the control strategies.

2. MATHEMATICAL MODELLING

It is obvious that in order to analysis and control of a physical system, it is necessary to construct the mathematical modeling. The schematic picture of the suspended pendulum control system is given in figure 1.

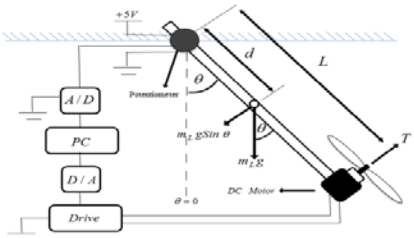

Figure 1. The Driven Pendulum system

In the above picture, there is a DC motor with a propeller on the lead of a suspended stick. After applied voltage, the propeller spins and generates torque T to pull up the pendulum. It is the most benefits of driven pendulum that enables us controlling its behavior with regulating the applied voltage. Therefore, the control variable for this system is the angle of the pendulum settled and the manipulated variable is the voltage fed to the motorized-propeller.

2.1. Nonlinear System Equations of Driven Pendulum

The rational equation between V voltage which applied to DC motor and thrust T , can be written as follows:

$$T(s) = Km.V(s) \tag{1}$$

According to Newton’s laws and angular momentum, the motion equation of driven pendulum is derived as:

$$J.\ddot{\theta} + c.\dot{\theta} + m_L.g.d.\sin\theta = T \tag{2}$$

The generated trust T in above equations is not manipulated variable for control system since the pendulum is adjusted by applied voltage.

$$\ddot{\theta} = \frac{K_m V - c.\dot{\theta} - m_L.g.d.\sin\theta}{J} \tag{3}$$

Where, m = weight of the pendulum, L = Length of pendulum, J = inertia moment, g = acceleration of gravity, V = voltage DC motor, T = the thrust which is provided by DC motor, θ = angular position, c = viscous damping coefficient, d = the distance from suspending point tocenter of mass.For numerical simulation of the nonlinear model for the driven pendulum system, it is required to represent the nonlinear equations (4) into standard state space form:

$$\frac{d}{dt}X = f(x,u,t) \tag{4}$$

Now these equations may be represented into state space form by considering the state variables as following;

$$X_1 = \theta \quad , \quad X_2 = \dot{\theta} = \dot{X}_1 \quad , \quad \dot{X}_2 = \ddot{\theta} \tag{5}$$

Then, the final state space equation for the driven Pendulum system may be written as:

$$\frac{d}{dt}X = \frac{d}{dt}\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} \tag{6}$$

Where,

$$f_1 = X_2$$
$$f_2 = \frac{K_m V - c.\dot{\theta} - m.g.d.\sin\theta}{J} \tag{7}$$

The pendulum angle θ is the variable of interest, and then the output equation may be written

$$Y = [\theta] = CX = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} \tag{8}$$

2.2. Linearization of Nonlinear Dynamical System

There are literatures present which have taken linearization model of nonlinear Driven Pendulum dynamical System for implementing the various control schemes [2], [3], [4], [5]. To linearize the system around equilibrium point, we can consider $Sin\theta \approx \theta$. The state space equations of the driven pendulum are given by:

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{m_L.g.d}{J} & -\frac{C}{J} \end{bmatrix} . \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_m}{J} \end{bmatrix} .u \quad , \quad Y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \tag{9}$$

3. METHODOLOGY

In this section, to control the nonlinear Driven pendul-um dynamical system the following control methods are presented in this paper.

3.1. Classicalcontrol using PID Controller

To stabilize the suspended pendulum control using PID control, the equations of PID control are given as following:

$$u(t) = K_P e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad or \quad u(t) = K_P \left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d \frac{de(t)}{dt} \right) \tag{10}$$

Where, u(t) = controller output, e(t) = error angle, Kp = proportional gain, Ki = integral gain, Kd = derivative gain, Ti = integral time and Td = derivative time.

3.2. Optimal Control using LQR

LQR is an optimal control approach which is based on closed loop optimal control with the linear state feedback or output feedback [1]. The block diagrams of state feedback controller displayed in figure 2

R U Y

\+

− X

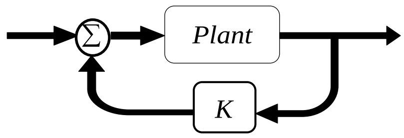

Figure 2. Block diagram of LQR controller

The proposed cost function in LQR method is as:

$$J = \int_0^\infty (x^T Qx + u^T Ru)dt = \int_0^\infty x^T Qxdt + \int_0^\infty u^T Rudt \tag{11}$$

The selection weight matrices Q and R are very importance in LQR that should be symmetric and nonnegative matrices. The weight matrices affect the control performance. These matrices are determined by experience of engineers who are familiar with the controlled system. Determination the matrix K of the optimal control, $u = -KX$, is written as:

$$K = R^{-1} B^T P \tag{12}$$

And P is defined by solving the algebraic Riccati equation (ARE)

$$A^T P + PA - PBR^{-1} B^T P + Q = 0 \tag{13}$$

In the optimal control of nonlinear driven pendulum dynamical system using PID controller and LQR approach, all the instantaneous states of the nonlinear system, pendulum angle θ, and angular velocity $\dot{\theta}$ have been considered available for measurement which are directly fed to the LQR. The LQR is designed using the linear state-space model of the driven pendulum system.The optimal control value of LQR is added negatively with PID control value to have a resultant optimal control.

3.2. Intelligent Control using Fuzzy Logic

Fuzzy Logic Controller (FLC) is a fast developed technology over the last decade. FLC is conceived as a better method for sorting and handling data. Also it has proven to can be an excellent choice for many control system applications because of non-linearity, complex mathematical computation and real-time computation needing. Generally, a fuzzy control system consists of four basic segments: fuzzy processing, fuzzy rule base, fuzzy inference and de-fuzzy processing, which displayed in figure 3.

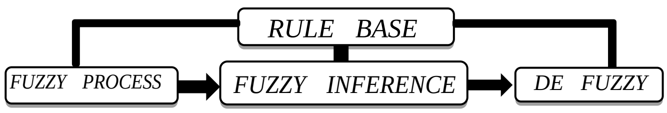

Figure 3. Block Diagram of Fuzzy Control System

4. SIMULATION AND RESULTS

In this section, four control schemes are proposed and describe in detail that are PID controller, PID controller based on LQR controller, FLC, and STFP. The considerations have to be met which are rising time less than 2 second, settling time less than 5 second, percentage of overshot less than 5% and steady state error less than 2% .The reference angle has been set to 40 Degree (0.698 rad). The Matlab-Simulink models for the simulation of Modeling, analysis, and control of nonlinear driven Pendulum dynamical system have been developed. If the value of d = 0.03 m, $m_l = 0.36\ kg$, g = 9.8 m/sn^2, J = 0.0106 Kgm^2, c = 0.0076 Nms/rad, Km = 0.0296. The basic concepts of controllers and the mathematical model of system are presented in past sections. The response curve of open loop Nonlinear Driven Pendulum Dynamical System displayed in figure 4.

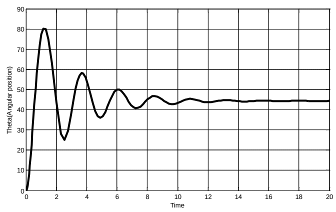

Figure 4. Open Loop responses of System

4.1. PID controller

According to equations (10), the tuned PID controller parameters of these control schemes are given as in table 1.

Table 1. Comparison

Controllers	Parameters		
	Kp	Ki	Kd
PIDcontroller	5	0.01	2
PID controller based on LQR controller	1	0	2
Self tuning fuzzy PID	2	0.01	2

The proposed PID with the nonlinear driven Pendulum dynamical system plant in Simulink and response curve are shown in figure. 5.

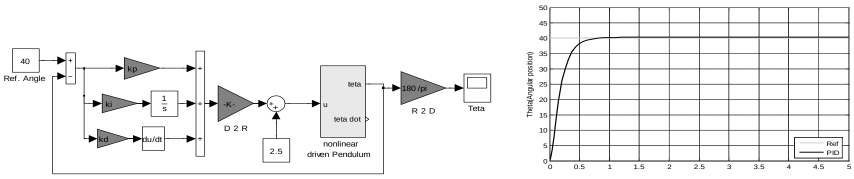

Figure 5. Block Diagram and Responses of Nonlinear System with PID

The result demonstrates that PID controller achieved steady-state response with the settling time of 0.653 s and rising time of 0.633 s. Furthermore the PID controller tends to produce high steady-state error (Ess) that is 0.777% and 0.01% of overshoot.

4.2. PID Controller Based on LQR Controller

After linearization the system matrices used to design LQR are computed as below:

$$A = \begin{bmatrix} 0 & 1 \\ -9.9849 & -0.7170 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 2.7925 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 \end{bmatrix}, D = 0 \qquad (15)$$

With the choice of,

$$Q = \begin{bmatrix} 28.77 & 0 \\ 0 & 0 \end{bmatrix} \;,\; R = 1 \tag{16}$$

We obtain LQR gain vector as following:

$$K = [2.87 \;\; 1.19] \tag{17}$$

The proposed PID based on LQRwith the Nonlinear Driven Pendulum Dynamical System plant in Simulink and response curve are displayed in figure 6.

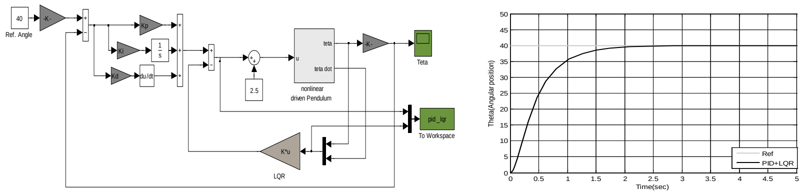

Figure 6. Block diagram and responses of System with PID+LQR Control

The PID controller based on LQR controller is able to give a response without produce any overshoot. The response is comparatively slow that give the settling time about 1.777 s and rise time about 1.065 s.This controller reduces steady-state error up to 0.006%.

4.3. Fuzzy Logic Control

In the FLC method, there exist two inputs and an output. The inputs are the error, E(t), and the error gradient, Ec=dE(t)/dt. The input signals, the error and derivation of error are converted to fuzzy parameters. The most frequent approach of fuzzy inference system, Mamdani model, is applied for inferring. A conceptual presentation of the FLC in a closed loop system and fuzzy inference block are shown in figure 7.

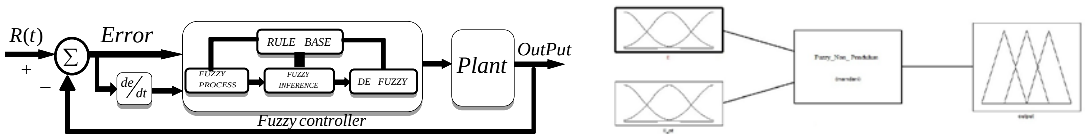

Figure 7. The FLC forNonlinear Systemand Fuzzy Inference Block

The input variables need to be converted from exact quantities into fuzzy quantities at first, which should be the infrastructure for fuzzy inference. This process may be considered as a mapping from accurate quantities to fuzzy subsets by the membership functions. For achieve a practical range, the controller is simulated with the model with different parameter quantities. The changes of membership functions are defined based on the influence on the control performance. All of the fuzzy subsets of the outputs and the inputs of the fuzzy controller are represented by triangular membership functions. The fuzzy sets for input variables and output consisting of five linguistic variables such as, Positive Big, Positive Small, Zero, Negative Small, and Negative Big or {NB, NS, Z, PS, PB}.For sample membership functions of inputs E and Ec are shown in figure 8.

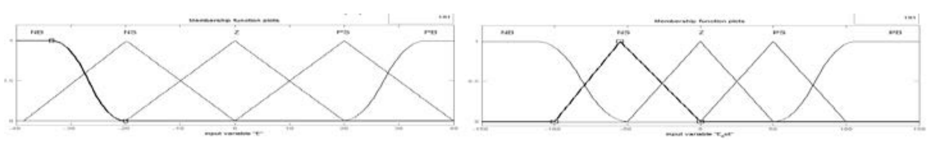

Figure 8. Membership functions of the linguistic variables for E, Ec

The inputs are the classical error, E(t) and the rate of the change of error (dE(t)/dt). The fuzzy rules based on empirical knowledge of expert are shown in Table 2.

Table 2. Fuzzy Controller Rule Based

	E				
Ec	**NB**	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NS	z	Z
NS	NB	NB	∞	Z	PS
Z	NB	NS	Z	PS	PB
PS	Z	Z	PS	PB	PB
PB	Z	Z	PS	PB	PB

The proposed FLC with the nonlinear driven Pendulum dynamical system plant in Simulink and response curve are displayed in figure 9.

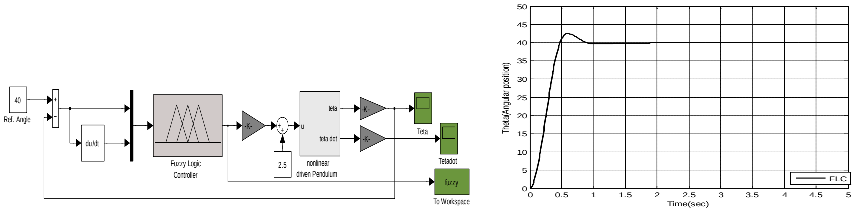

Figure 9. Block Diagram and Responses of Nonlinear Inverted Pendulum System with FLC

FLC provides acceptable performance in term, have nearly fast response regarding to the settling time 1.4078 s and rise time 0.411s. Percent Overshoot is 6.177%. The result also demonstrated that fuzzy logic controller is without steady-state error. This can be indicating that FLC controller can handle the effect of disturbances in the system.

4.4. Self Tuning Fuzzy PID

The new PID control strategies based on some intelligent algorithms can improve dynamic performance far away from the design point. In this work, STFP controller has been applied for stabilization of the driven pendulum system. The STFP controller is base on the conventional PID controller that employs the Fuzzy Inference System (FIS) to tune the PID parameters, which has both advantages fuzzy control and PID control. In the STFP, there exist three outputs and two inputs. The outputs are PID coefficients, Kp, Ki and Kd. The inputs are the error, E(t), and the error gradient, Ec=dE(t)/dt. In the STFP of the input signals, the error and derivation of error are converted to fuzzy parameters. Then, fuzzy inference provides a nonlinear mapping from the inputs to the PID coefficients.A conceptual presentation of the STFP in a closed-loop system and the configuration of the implemented Self-tuning fuzzy PID are presented in figure 10.

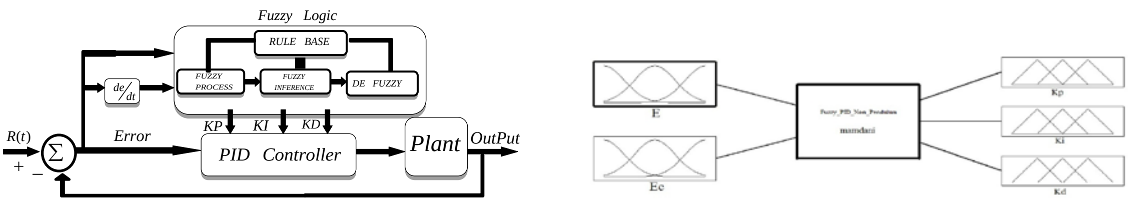

Figure 10. The STFP for Nonlinear Driven Pendulum System and Fuzzy Inference Block

The membership functions of inputs (E, Ec) and outputs (Kp, Ki and Kd) are shown in figure 11 and figure 12 respectively. The linguistic variables of these outputs are assigned as: {NB, NS, Z, PS, PB}.

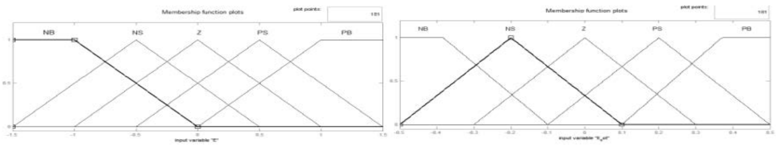

Figure 11. Membership functions of the linguistic variables for e, ec

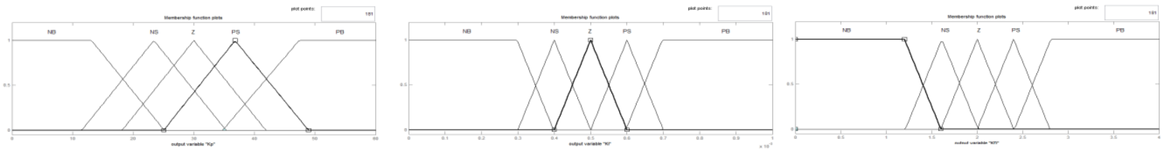

Figure 12. Membership functions of the linguistic variables for Kp, Ki and Kd

Generally, fuzzy rules are depended on the plant to be controlled and the summary of designer's knowledge and experience. Therefore, the fuzzy rules are formulated as they are presented in Table 3.

Rule 1: If E(t) is NB and Ec (t) is NB then Kp = PB and Ki = NB and Kd = PB

Table 3. Fuzzy rules of Kp, Ki and Kd

Ec	E Kp, Ki, Kd	NB	NS	Z	PS	PB
	NB	PB, NB, PB	PB, NB, PB	PB, NB, PB	PS, NS, PS	Z, Z, Z
	NS	PM, NB, PB	PB, NB, PB	PS, NS, PS	Z, Z, Z	NS, PS, NS
	Z	PB, NB, PB	PS, NS, PS	Z, Z, Z	NS, PS, Z	NB, PB, Z
	PS	PS, NS, PS	Z, Z, Z	NS, PS, NS	NB, PB, NB	NB, PB, NB
	PB	Z, Z, Z	NS, PS, NS	NB, PB, NS	NB, PB, NB	NB, PB, NB

The proposed STFP controller with the nonlinear driven Pendulum dynamical system plant in Simulink and response curve are displayed in figure 13.

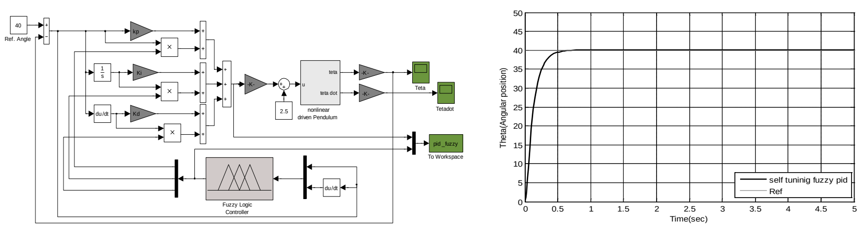

Figure 13. Block Diagram and Responses of Nonlinear Driven Pendulum System with STFP

In the Self-Tuning Fuzzy PID controller, the parameter's value of Kp, Ki and Kd are tuned by using signals from fuzzy logic block based on the change of error between reference signals and output signals. This controller has the fastest response with the settling time of 0.473 s and rising time of 0.458s. For the percent of overshoot, LQR has 0.02% which is met the desired requirement of controller design and produce steady state error (Ess) is 0.2%.

5. DISCUSSION

The simulation results for the closed loop system response under conventional PID, PID +LQR, FLC, and STFP controller are shown in figure.14.

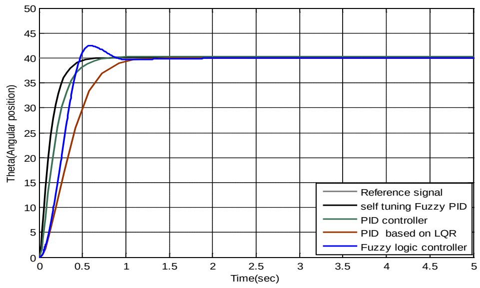

Figure 14. Responses of NonlinearDriven Pendulum System with all controllers

The dynamic parameter of the response such as rise time, settling time, steady-state error and overshoot are shown for different scenarios in figure 15.

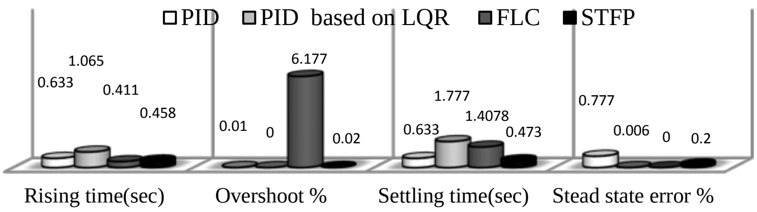

Figure 15. Performance comparison controllers

By referring to the figure 14, it can be seen that STFP controller has the best performance and has achieved better response in compare other controllers. It indicates faster settling time and faster rising time. At the same time, four control designs produce the output response low steady-state error and little overshoot. Therefore, from the obtained results in figure 15, it can be concluded that performance of Nonlinear Driven Pendulum Dynamical System using STFP controller has been improved.

6. CONCLUSION

In this work, the nonlinear dynamical equations of a Pendulum System are derived. In order to improve the response parameters such as oscillation, rise time, overshoot, settling time and steady state error less, a conventional PID controller, LQR, self-tuning Fuzzy PID has been applied for the Driven Pendulum System. Based on the Simulation results, the system responses indicate the performance a Nonlinear Driven Pendulum Dynamical Control System has improved significantly using self-tuning fuzzy PID.

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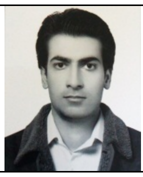
BIOGRAPHIES OF AUTHORS



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