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Feedback Error Learning using Laguerre-based Controller to Control the Velocity of an Electro Hydraulic Servo System

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Abstract: The objective of this article is to propose a new scheme to control the velocity of an electro hydraulic servo system (EHSS). The proposed Laguerre-based controller (LBC) is a kind of Infinite Impulse Response (IIR) structure which has the benefits of both Finite Impulse Response (FIR) and IIR structures. In addition, the proposed approach can solve their limitations in terms of stability and complexity. In the proposed method, the Feedback Error Learning (FEL) algorithm is used to control the velocity. There is no need to compute the system jacobian in FEL method which in turn makes its using more suitable for practical scenarios. The conducted experiments demonstrate that the proposed controller leads to significantly better performance in terms of settling time as well as amplitude of control signal rather than other representative intelligent controllers. The proposed controller is also robust to the given disturbance.

Key words:

INTRODUCTION

In recent years many intelligent control systems have been developed and specifically more attention has been focused on electro hydraulic servo systems. The important advantages of electro hydraulic servo systems can be categorized to following objects: 1. Their ability to handle large inertia, 2. Torque loads, 3. achieving to fast responses, 4. High degree of accuracy and performance (Merritt, H.E., 1967; Watton, J. 1989). The electro hydraulic system has different applications in industries, such as: active suspension systems and control of industrial processes. They are also used in commercial aircraft, satellites, launch vehicles, flight simulators, turbine control, and numerous military applications (Jovanovic, M. 2002).

There are many approaches for controlling the electro hydraulic servo system in the literature, most notably: Fuzzy Neural Network (FNN) (Mohseni, S.A., *et al.*, 2006), (DSMFNNC) (Mohseni, S.A., *et al.*, 2007), Multi Layer Perceptron Neural Network (MLP) (Azimian, H., *et al.*, 2007), cerebellar model articulation controller (CMAC) (Chan, L., 2001) and feedback linearization (Jovanovic, M. 2002). Although these controllers can control the system successfully, they suffer from shortcomings such as: High control signal, settling time and design complexity.

In this article we propose a novel algorithm to control the electro hydraulic servo system using an adaptive Laguerre based controller. This controller can control the process efficiently and presents desired performance in settling time, control signal. Also the proposed controller consumes less computation load than other controllers which makes it suitable for practical implementations. Moreover, the proposed controller has a good robustness against disturbances which are added to control signal.

The Feedback Error Learning method used to control the velocity of EHSS was, first proposed by Kawato (Miyamoto, H., *et al.*, 1988; Kawato, M., 1990; Tavan, M., *et al.*, 2011). The key advantage of FEL method is that in this method the Jacobin matrix is not needed to be calculated for training the weights of adaptive controller. This advantage makes this method effective in different applications.

This article is organized as follow: In section 2**.**, EHSS and its nonlinear mathematical model are described. In section 3 the design of the controller based on adaptive Laguerre structure is introduced. In section 4 the simulation results of applying proposed controller to EHSS are presented. Section 5 concludes the article.

System Description:

A schematic of relevant electro hydraulic servo velocity system is displayed in Fig. 1.

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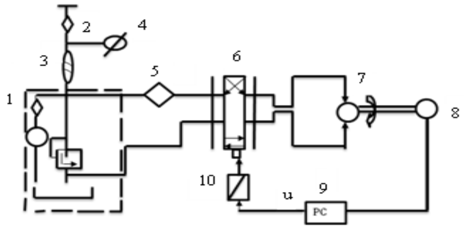

Fig. 1: A schematic of Electro Hydraulic Servo System (EHSS)

The basic parts of this system are: 1) Hydraulic power supply, 2) Accumulator, 3) Charge valve , 4) Pressure gauge device, 5) Filter, 6) Two-stage electro hydraulic servo valve, 7) Hydraulic motor, 8) Measurement device, 9) Personal computer, and 10) Voltage- to-current converter.

As it can be observed in fig. 1, controller produces a proper voltage which is applied to voltage to current converter. The output current of converter is applied to electro hydraulic servo valve and make air variations in the output of valves. By controlling this air variation it is possible to control the hydraulic motor velocity. Describing equations of system using Newton's second law for the rotational motion of the motor shaft is given by (Jovanovic, M. 2002):

$$\dot{x}_1 = \frac{1}{j_t}\{-B_m x_1 + q_m x_2 - q_m c_f\, p_s\} \tag{1}$$

$$\dot{x}_2 = \frac{2\beta_e}{V_o}\{-q_m x_1 - c_{im} x_2 - c_d w x_3 \sqrt{\frac{1}{\rho}(p_s - x_2)}\}, \tag{2}$$

$$\dot{x}_3 = \frac{1}{T_r}\{-x_3 + \frac{K_r}{K_q}u\} \tag{3}$$

$$y = x_1$$

In which (x_1, x_2, x_3) are state variables and defined as:

x_1 – Hydro motor angular velocity

x_2 – Load pressure differential

x_3 – Valve displacement

The nominal values of parameters are presented in Table I:

Table I: The parameters of EHSS and their nominal values (Jovanovic, M. 2002)

Parameter	Description	Value
j_t	Total inertia of the motor and load referred to the motor shaft	$0.03\ kgm^2$
q_m	Volumetric displacement of the motor	$7.96\times10^{-7}\ \frac{m^3}{rad}$
B_m	Viscous damping coefficient	$1.1\times10^{-3}\ Nms$
c_f	Dimensionless internal friction coefficient	0.104
V_o	Average contained volume of each motor chamber	$1.2\times10^{-4}\ m^3$
β_e	Effective bulk modulus	$1.391\times10^{9}\ p_a$
c_d	Discharge coefficient	0.61
c_{im}	Internal or cross-port leakage coefficient of the motor	$1.69\times10^{-11}\ \frac{m^3}{p_a\cdot s}$
P_s	Supply pressure	$10^{7}\ p_a$
ρ	Oil density	$850\ \frac{K_g}{m^3}$
T_r	Valve time constant	$0.01\ s$
K_r	Valve gain	$1.4\times10^{-4}\ \frac{m^3}{s\cdot v}$

K_q	Valve flow gain	$1.66\ \frac{m^2}{s}$
w	Surface gradient	$8\pi \times 10^{-3}\ m$

The control objective is stabilization of any chosen operating point of system. From equations (1), (2) and (3) it is clear that equilibrium points of system are given by:

x_{1N} - *Arbitrary constant value of our choice*[1],

$$x_{2N} = \frac{1}{q_m}\{B_m x_{1N} + q_m p_s c_f\}, \tag{4}$$

$$x_{3N} = \frac{q_m x_{1N} + c_{im} x_{2N}}{c_d w \sqrt{\frac{1}{\rho}(p_s - x_{2N})}}, \tag{5}$$

While the value of the control signal necessary to keep x_3 at the equilibrium is $u_N = \frac{K_q}{K_r} x_{3N}$.

It is assumed that the motor shaft does not change its direction of rotation, $x_1>0$. This is a practical assumption and in order to be satisfied, the servo valve displacement x_3 does not have to move in both directions to the neutral position $x_3=0$. This fact allow us to restrict the entire problem to the region where $x_3>0$.

Proposed Structure To Control The Ehss Velocity:

3.1 Feedback error learning:

The technique of feedback error learning (FEL) was proposed by Kawato, and its general structure is shown in Figure 2 (Miyamoto, H., *et al.*, 1988; Kawato, M., 1990).

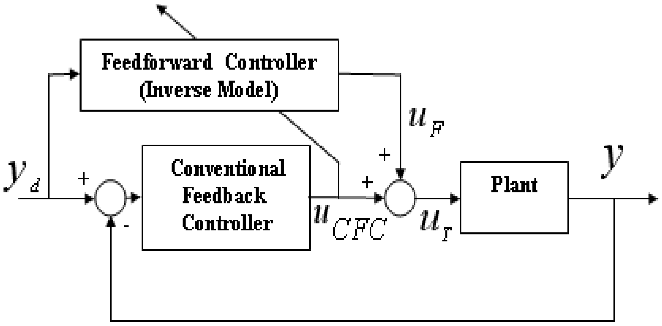

Fig. 2: The Feedback Error Learning (FEL) structure

The feedback error learning algorithms consist of two sections: In the first section, input signals are fed in a Feed forward Controller manner through the network to produce actual outputs. In the second section, the output vector of a Conventional Feedback Controller (CFC), u_{CFC} is considered as the error to propagate backward through the Feed forward Controller. The Feed forward Controller does not mimic the Conventional Feedback Controller, but acquires a fully nonlinear inverse model by trying to eliminate the feedback error. In Fig. 2, u_T is the actual input vector to the plant, u_F is the output vector from the Feed forward Controller, and u_{CFC} is the feedback control input vector. In general, the Feedback Controller was realized by a predetermined constant gain Feedback Controller (PID or PD) for FEL scheme in many applications (Vojislav, D. *et al.*, 2000). The only criterion which is important to select the gain is stability of the system (Vojislav, D. *et al*., 2000). In this article other FEL method (Regulation) is used to control the EHSS. Figure 3 shows this controller structure for velocity control of EHSS.

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[1] $x_{1N} = 200\frac{rad}{s}$

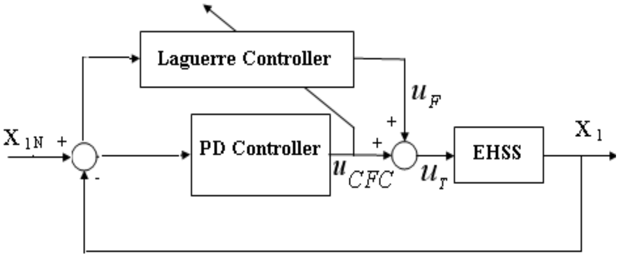

Fig. 3: The EHSS velocity control with FEL method

3.2. Conventional Feedback Controller (CFC):

A PD controller was used in conventional feedback controller section and can be represented by:

$$u_{PD} = K_p(x_{1N} - x_1) + K_d(\dot{x}_{1N} - \dot{x}_1) \tag{6}$$

Where K_p and K_d are proportional and derivational feedback gain.

Choosing proper values for K_p and K_d results in an appropriate PD controller for controlling the velocity of EHSS.

3.3. Laguerre Based Controllers:

A Laguerre function with length M is constructed of a single pole Low-Pass term at the input and M cascaded All-Pass term after that. The all-pass terms are also single pole and the positions of all poles in Laguerre structure are the same (Tom´as Oliveira e Silva, 1995). A block diagram of a continues Laguerre structure is shown in Fig. 4.

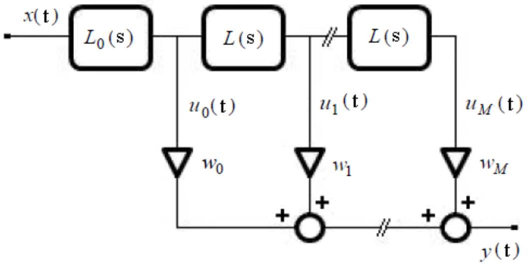

Fig. 4: Basic diagram of Laguerre structure

Where $L_0(s)$ and $L(s)$ are described as follows:

$$L_0(s) = \frac{\sqrt{2a}}{s+a} \tag{7}$$

$$L(s) = \frac{s-a}{s+a}\ , \ a > 0 \tag{8}$$

The output of Laguerre filter is the linear combination of its sections outputs and its weights.

$$y(k) = \sum_{m=0}^{M} w_m\, u_m(k) \tag{9}$$

With Laguerre structure, the approximation of systems with long or infinite impulse response with smaller number of parameters than transversal structure is possible. By choosing proper position of the pole of Laguerre structure the appropriate performance and stability of controller is guaranteed.

Laguerre functions can be defined in the Laplace domain as follows:

$$L_K(s,a) = \sqrt{2a}\,\frac{(s-a)^K}{(s+a)^{K+1}} \qquad a > 0 \tag{10}$$

Where k=0, 1, 2 … and a is a positive real number. These functions constitute an orthogonal complete set in the Hilbert space. Rational transfer function of each term of Laguerre structure makes it suitable for practical implementations.

3.4. Training the Weights of Laguerre Structure:

In identification applications, it is necessary that the parameters of identifier change over the time to approximate the related system. In Laguerre structure there is two important parameters which can be trained over the time: 1) Laguerre poles and 2) Laguerre weights. There are some adaptive methods to adapt the position of the Laguerre pole in the literature (Asadi, M., F. Razzazi, 2009). In this article we place the Laguerre pole in the appropriate position empirically and train the weights of Laguerre structure adaptively. Fig. 5 shows a Laguerre structure which its weights change to minimize the error signal. As we can see the Laguerre output is subtracted from desired signal and the error signal is formed. The Least Mean Square (LMS) algorithm uses this error signal to adjust the weight adaptively. The LMS algorithm is given by:

$$W(k+1) = W(k) + \mu U(k)\, e(k) \tag{11}$$

which μ is the learning step size of algorithm.

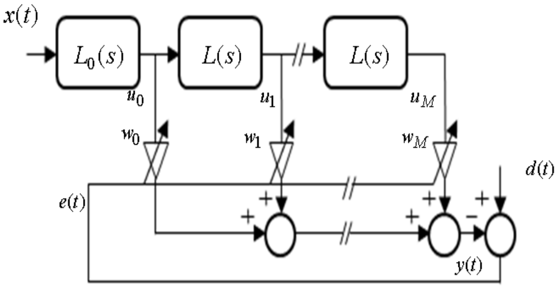

Fig. 5: Training the weights of Laguerre structure

With designing a proper Laguerre structure with appropriate length and pole position and training the weights of it adaptively, identifying of unknown systems is possible (Malboubi, M., *et al*., 2010).

Performance Evaluation:

4.1 Experiments Setup:

In this article, an adaptive Laguerre structure is used to control the EHSS in FEL. Initial conventional feedback controller parameters are:

$$K_p = .025, K_d = .0001 \tag{12}$$

The adaptive Laguerre structure which is used to control the velocity of EHSS has 40 all-pass sections. The pole position of the low-pass section is set to 55 on real axis. The poles of Laguerre all-pass sections are placed on different positions on real axis empirically. This results in better performance than choosing same pole for Laguerre sections. The value of a_i in Laguerre all-pass sections are as follow:

a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}
10	20	30	40	50	60	70	80	90	100

The learning step size for adaptive learning of Laguerre structure weights is chosen as:

$$\mu = 1 \times 10^{-8} \tag{14}$$

Arbitrary constant value and the initial condition of EHSS which described previously are set as follow:

$$x_{1N} = 200 \frac{rad}{s} \quad , x(0) = 0$$

Stability of the controller and small settling time are the most important parameters in velocity control of EHSS.

4.2 Evaluation Of The Proposed Controller:

Experiment 1:

In this experiment the proposed controller was used to show its efficiency in control process. As it can be observed in Fig. 6, the proposed controller is stable and it can control the velocity of EHSS efficiently with settling time 1.7 s.

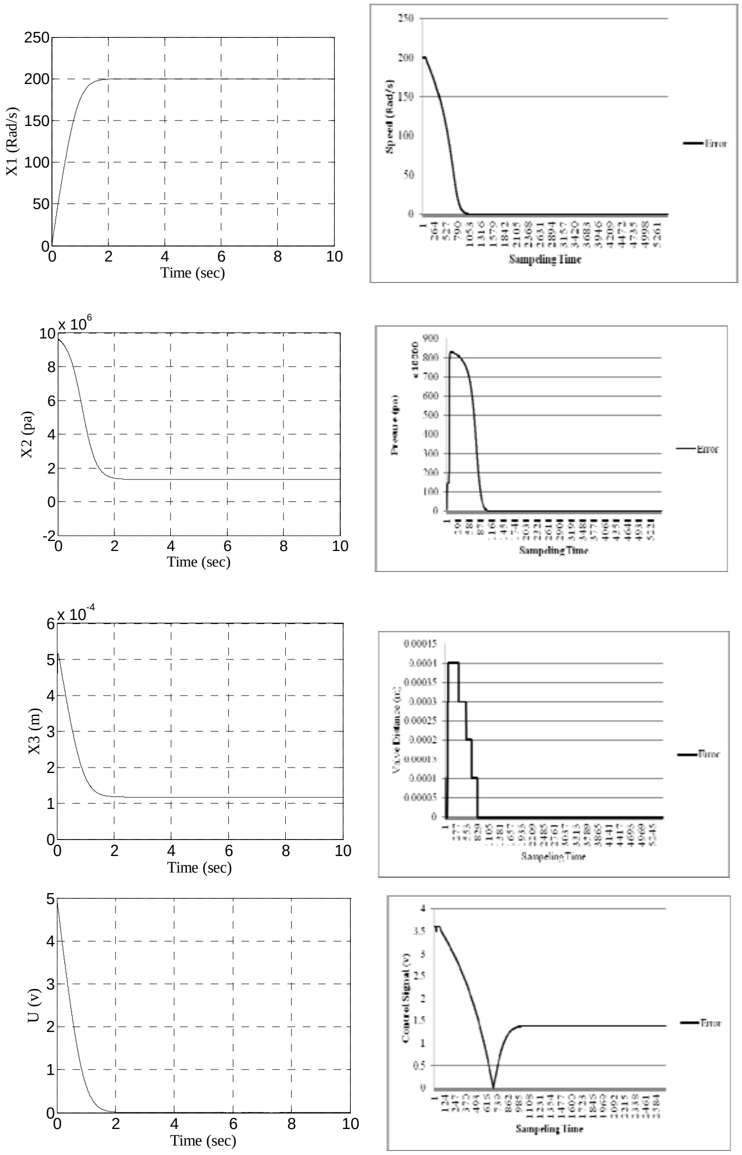

Fig. 6: States of system, control signal and error of them in velocity control of EHSS using Laguerre based controller

Another advantage of Laguerre controller is controlling the velocity successfully with low amplitude control signal. Also by using Laguerre controller, the response has not any steady state error.

Experiment 2:

In this experiment a disturbance signal is added to the control signal to evaluate the robustness of controller against disturbance, as it is shown in fig 7. The disturbance signal is a voltage pulse added to U_T after setteling time in which steady state error is zero (I. e., time interval between 6s and 7s). It is supposed that the amplitude of disturbance pulse is 1v and the pulse duration is 1s. Figure 7 depicts the structure of the proposed controller.

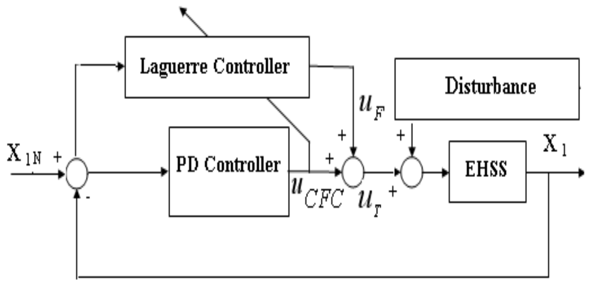

Fig. 7: Structure of controller in presence of Disturbance

The simulation result of the proposed controller in presence of disturbance is shown in fig 8.

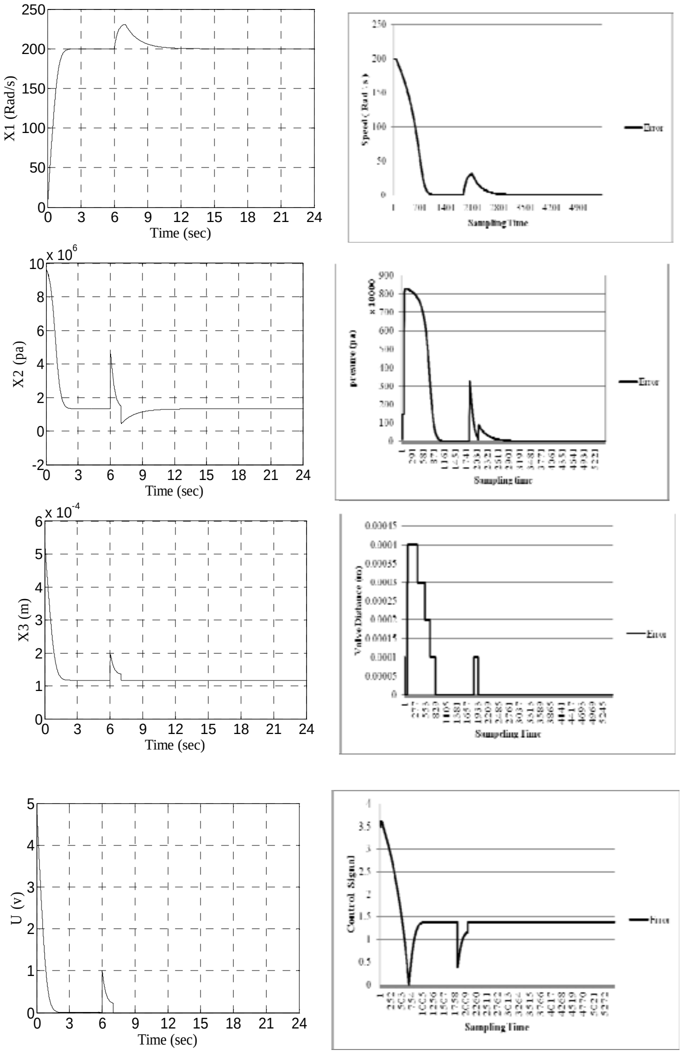

Fig. 8: Results of simulation in presence of disturbance

The results in fig. 7 and fig. 8 show that the controller can control the EHSS velocity successfully in presence of disturbance and it has an acceptable robustness against disturbance.

4.4. Comparing of Proposed controller with Other Controllers:

The results of EHSS velocity control using different controller are used to obtain the efficiency of the described method five well-known controllers were considered: Neural Network controller, Classic Nonlinear

Controller with Feedback Linearization, Decoupling sliding mode with Fuzzy neural network controller (DSMFNNC), Fuzzy Neural Network Controller (FNN) and Parallel Distribution Compensation (PDC) Controller (Tavan, M., *et al*., 2011).

The settling time in EHSS velocity control for these controllers are compared in table II.

Table II: Settling time and control signal changes using different controllers

Type of Controller	Settling Time	Control Signal Amplitude
Neural Network controller	6 s	3.8 v
Classic Nonlinear Controller with Feedback Linearization	5 s	2.3 v
Decoupling sliding mode with Fuzzy neural network controller (DSMFNNC)	2 s	28 v
Fuzzy Neural Network Controller	4 s	1.6 v
Laguerre Based Controller	1.7 s	4.5 v

With comparing the results of different controller it is clear that the Laguerre based controller introduces better settling time than other controllers. Although for the DSMFNN controller settling time reach to 2s, it needs large number of fuzzy rules which increases the complexity of controller. Also the value of control signal is increased to 28v which is inappropriate. The Laguerre based controller introduces 1.7s settling time with less computational load than other controllers. The amplitude of control signal which is used to control the velocity is in appropriate interval (0-5v) for Laguerre filter. This, prevent saturation during control process and causes better performance of EHSS during its work.

4.5 Effect of Laguerre Controller Pole Position on Its Performance:

In this experiment different values of step size μ in Laguerre controller were considered to study the effect of these changes on settling time which is the most important factor in velocity control of EHSS. Table III has summarized the results:

Table III: Effect of different values of step size on settling time

Values of Step Size μ	Settling Time	Overshoot
1e-8	1.7 s	0
1e-7	1.4 s	0.3
1e-6	0.9 s	43.5
1e-5	Unstable	Unstable

As it can be understood from Table III, although increasing the value of step size causes smaller settling time, also increase the overshoot. Large values of step size cause instability in system while small values of step size increase the settling time. Best value for step size without introducing any overshoot is 1e-8.

Table IV demonstrates that the controller can also control the EHSS in presence of many different values of disturbance. Also, the steady state of error in presence of disturbance is zero.

Table IV: Effect of different values of disturbance on settling time, over shoot and signal control

The amplitude of disturbance pulse	Settling time after adding disturbance	Signal control after disturbance	Overshoot after disturbance
2 v	11.4 sec	2 v	30%
3 v	12.22 sec	3 v	44%
4 v	13.01 sec	4 v	57%

Conclusion:

The control of electro hydraulic system is an important feature in many industrial applications. To properly control the system, many intelligent controllers are presented in recent years. In this article an adaptive Laguerre based controller is proposed for controlling the velocity of EHSS. The experiments and results showed that proposed method can control the process efficiently with better performance than other methods. Most important advantages of the described controller is its simplicity and better settling time in comparison with other methods. This controller introduces better settling time by using small control signal and also it hasn’t any steady state error. These advantages and other benefits such as: simple structure, low computational load of Laguerre based controller and robustness against disturbance make this controller more efficient and practical in velocity control of EHSS. This controller can also control the EHSS in presence of different values of disturbance in which the steady state of error in presence of disturbance gets to zero.

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