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Slip Enhancement in Continuously Variable Transmission by Using Adaptive Fuzzy Logic and LQR Controller

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Abstract

Enhancement of fuel consumption and transmission efficiency needs a continuous improved variator performance in continuously variable transmission (CVT). This paper focuses on the improvement of aslip controller for a hydraulically actuated metal push-belt continuously variable transmission (CVT), using model for variator dynamic in the CVT. The slip control purpose is to improve the performance of variator andto increase the efficiency of CVT by determination the line pressure which generates the clamping force. The selection of slip reference-point is taken at the transition region between the micro and macro slip region to guarantee the maximum variator efficiency. The adaptive fuzzy logic control (FLC) and Linear Quadratic Regulator (LQR) controllers are applied to control the clamping force. The proposed control systems are designed to ensure the existence of a slip values within the region, which has the traction coefficient maximum value, while the load disturbances caused by suddenly changed torques in the drive lines. These approaches have potential for the CVT efficiency improvement, as compared to PID controller. The adaptive fuzzy logic control technique uses a simple group of membership functions and rules to achieve the desired control requirements of slip in CVT. Simulation results show that satisfactory slip improvement is achieved together with good robustness against suddenly changed torques. It is further revealed that all adaptive fuzzy logic control and LQR controller have a valuable effect on minimizing the slip amount and maximize the variator efficiency.

Keywords: *Push-Belt CVT, slip control, adaptive fuzzy logic control, LQR control, CVT variator efficiency*

1. Introduction

The research for improved fuel economy, reduced emission and improving the efficiency of transmission are essential challenges for the automotive industry. Continuously variable transmission (CVT) is one of the promising solutions for improved fuel economy and reduction emission issues due to its ability to achieve more efficient operating levels for combustion engine than stepper transmissions. The transmission efficiency plays a major role in the improvement of automotive power train efficiency. Due to the construction of a CVT the problem of slip is always existent but the increasing slip above certain amount has a significant unfavorable effect on the CVT performance compared to manual transmission [1, 2].

To prevent the belt slip, the high clamping force is applied that lowers the efficiency of CVT. In addition, the higher clamping force need higher hydraulic pressures, thereby leading to increase pumping losses. So the using slip control will lead to operate the CVT in its maximum efficacy points and restrain excessive belt slip amount [3]. By replacing hydraulic parts by pur electric control system, the reliability and performance of CVT vehicular can highly be improved, while the fuel consumption and cost will be further decreased. The CVT modulates velocity by the electronically controlled mechanical speed regulator mechanism cost, fuel consumption and failure rate can significantly be decreased [4-6].

In this paper, adaptive fuzzy logic control and linear Quadratic Regulator (LQR) are presented and compared to the slip control in Jatco-CK2 CVT. The aim of the slip controller is to alleviate the load disturbance which caused by suddenly torque change in drivelines. The proposed slip controller for both mentioned above are simulated in MATLAB / SIMULINK environment.

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2. Working Principle of the Push-Belt CVT

The Jatco – CK2 presented here is CVT worked with a Van Doorne's Transmission metal push belt. In a metal V-belt CVT, the torque is transferred from the driver to the driven pulley by the belt elements pushing action. Due to the existence of friction between belt elements and bands, the band, like flat rubber belts, is also participated in the transmission of torque. Therefore, the combined of push–pull action in the belt enables the torque to transmit through the metal V-belt CVT system [7].

In Van Doorne's metal push belt, the belt composed of a lot number (around 350) of V-shaped steel block elements, detained together by using a number (between 9 and 12) of thin steel tension rings. The belt is hold by two pulleys; at the engine side namely the primary pulley and at the wheel side namely the secondary pulley. The two pulleys are composed of one axially fixed sheave and the other moveable sheave, which actuated bymeans of a hydraulic cylinder. The hydraulic cylinders can be pressurized to create axial forces (thrusts or clamping forces) on the belt and they are essential for transmission the torque and change of the ratio. Shifting of the sheaves in axial directions varies the running radii of the belt and, hence, the transmission ratio [7]. Figure 1 depicts a schematic of a metal V-belt CVT working principle.

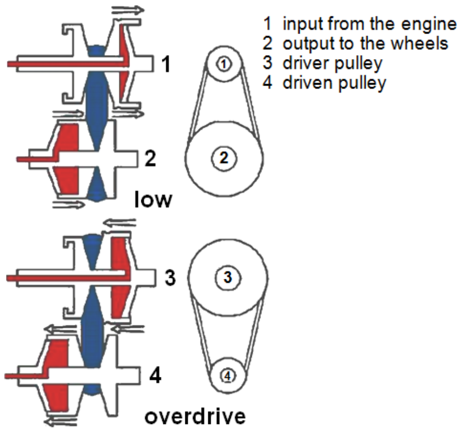

Figure 1. The Continuously Variable Transmission Metal Push-belt Working Principle

3. Slip Control Strategy

In Figure 2, the relation between traction coefficient μ_{eff}, and variator efficiency against the slip v are shown. The significance of slip control is evident because an increasing of slip amount will drive to an increasing in traction coefficient in the micro-slip region; therefore the torque will transmit efficiently. In the contrary, in the macro-slip region, the slip increase leads to destructive effects in the case of no action taken to maintain the amount of slip at the maximum traction coefficient.

The maximum effective traction coefficient occurs at the turning point between the two regions. The improvement of variator efficiency can be achieved near to this turning point, as shown in Figure 2.

The most of clamping force strategies are maintained the slip amounts where the traction coefficient is maximum that leads to maximize the efficiency of the variator. Any increase in the torque will cause excessive slip but by modifying the clamping force the slip will back to acceptable level so the damage can be avoided [8, 9].

The slip dynamic model is required to design the slip controller which based on the dynamic modling by Bonsen et al. [3]. Figure 3 represents the dynamic model of CVT. The relative slip v between the belt and pulley is described as:

$$v = 1 - \frac{r_s}{r_g}. \quad (1)$$

Where r_s denote the speed ratio and r_g is geometric ratio.

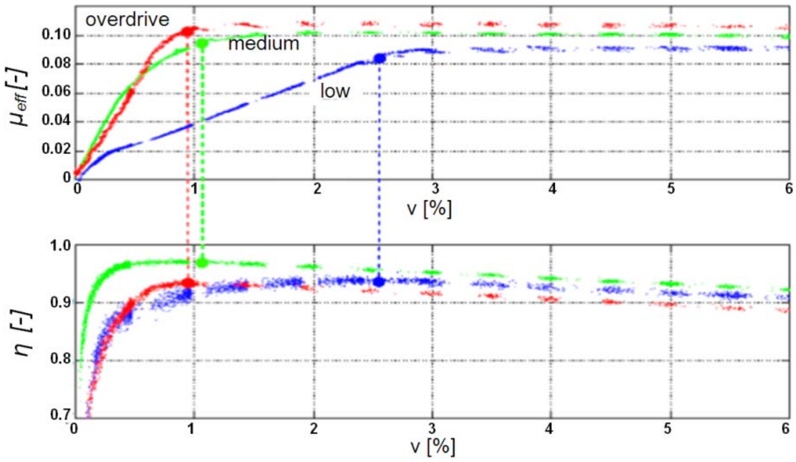

Figure 2. Effective Friction Coefficient and Efficiency versus the Slip in Variator

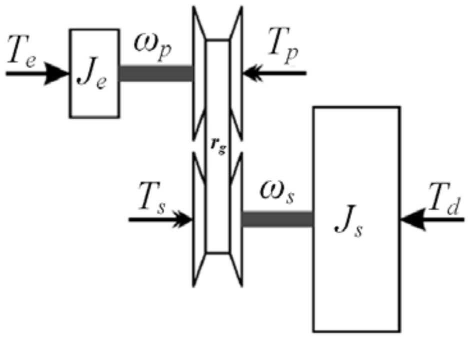

Figure 3. Model of CVT on Drive Train

The speed ratio r_s is described as:

$$r_s = \frac{\omega_s}{\omega_p} \tag{2}$$

Where ω_p and ω_s denote the primary and secondary angular velocity,respectively. The geometric ratio r_g is assumed quasi-stationary and can be described by:

$$r_g = \frac{R_p}{R_s} \tag{3}$$

With r_g is quasi –stationary, the dynamics of slip can be derived using (1) and (3), lead to:

$$\dot{v} = -\frac{\dot{r}_s}{r_g} \tag{4}$$

$$\dot{r}_s = \frac{\dot{\omega}_s\omega_p - \omega_s\dot{\omega}_p}{\omega_p^2} \tag{5}$$

As shown in Figure 3 from the engine side T_e and J_e denote the engine torque and corresponding engine and CVT inertia on the primary shaft respectively, at wheel side T_d and J_s denote the road torque and inertia on the secondary shaft. The dynamic of the primary and secondary shaft of CVT variator can be represented by:

$$\dot{\omega}_p = \frac{T_e - T_{cvt,p}}{J_e} \tag{6}$$

$$\dot{\omega}_s = \frac{T_d - T_{cvt,s}}{J_s} \tag{7}$$

The $T_{cvt,p}$ and $T_{cvt,s}$ denote the torque on the primary and secondary shaft respectively. That torques is transmitted via belt can be calculated according to:

$$T_{cvt,p,s} = \frac{2F_s R_{p,s} \mu_{eff}(\upsilon, r_g)}{\cos\beta} \tag{8}$$

Substituting Equation (1), (2), (3), (4), and (5) leads to:

$$\dot{\nu} = \frac{1}{\omega_p}\left(-\frac{2F_s R_{p,s}\mu_{eff}(\upsilon, r_g)}{\cos(\beta) J_d r_g} + \frac{T_d}{J_d r_g}\right) + \frac{(1-\nu)}{\omega_p}\left(-\frac{2F_s R_{p,s}\mu_{eff}(\upsilon, r_g)}{\cos(\beta) J_e} + \frac{T_e}{J_e}\right) \tag{9}$$

For control design, the slip dynamic system will be linearized, so the state space illustration of the slip dynamic modeling will be defined. The traction coefficient between the pulley and belt is associated to the slip and the ratio; therefore, it can be described by:

$$\mu_{eff}(\upsilon, r_g) = d_{1i}(r_g)\upsilon + d_{2i}(r_g) \tag{10}$$

Which is a piecewise linear, the micro-slip regime represents by i=1 and i=2 represents the macro-slip regime. The ratio relation is taken account by choice of d_{1i} and d_{2i}. Describing the state vector as $x = v$, input vector $u = [\ F_s\ T_e\ \ T_d]$ and output vector y=x , the dynamics can be presented , when the linearzed around a definite working point x=v_0 ,with the linearized model a state space illustration of the slip dynamic model will be described as follow:

$$\dot{x} = A_s x + B_s u \tag{11}$$

$$y = C_s x \tag{12}$$

$$\dot{\omega}_p = \frac{T_e - T_{cvt,p}}{J_e} \tag{13}$$

$$A = \frac{1}{\omega_{p0}}\left[-\frac{T_e}{J_e} - \sigma_0\Phi_0 F_0 k_{1i} + \frac{\sigma_0 F_0 r_{g0} k_2 i}{J_e}\right] \tag{14}$$

$$B = \frac{1}{\omega_{p0}}\begin{bmatrix} -\sigma_0\Phi_0 k_{2,i} - \sigma_0\Phi_0 \nu_0 k_{1,i} + \dfrac{\sigma_0 r_{g0}\nu_0 k_{2,i}}{J_e} \\ \dfrac{(1-\nu_0)}{J_e} \\ \dfrac{1}{J_d r_{g0}} \end{bmatrix}^T \tag{15}$$

$$C = [1] \tag{16}$$

$$\sigma_0 = \frac{2R_{s0}}{\cos\beta} \tag{17}$$

$$\Phi_0 = \left(\frac{r_{g0}}{j_e} + \frac{1}{j_d r_{g0}} \right) \tag{18}$$

The derived slip dynamic will be used for the controller design in next section. The model has 3 inputs F_s, T_e and T_d, but only the secondary clamping force F_s can be controlled. The input torque T_e is commanded by the driver via the throttle pedal and the output torque T_d is specified by the road conditions. Therefore they can be considered as disturbances on the system.

The secondary pressure cylinder is connected to the line pressure and is concerned to the secondary clamping force F_s. The PWM signal duty cycle is accountable of the secondary pressure determination which sets up the clamping force, or the line pressure. The line pressure is bounded between 6.6 and 4.2[bar] and can be considered linear variation to the duty cycle. Due to the complex and time wasting dynamic modeling of line pressure system, Frequency Response Function (FRF) measurement is preceded by Bonson et al. [3]. The system estimation from duty cycle as input and the line pressure as the output can presented by a third order low pass filter with cut – off frequency of 6 [Hz].

4. The Control Design of Slip Dynamic Model

Due to the slip dynamics relays on the many variables, it is difficult to design a controller which is capable of achievement the demanded performance. So, the linearizing of the slip dynamics is done in different working points. The controller of slip can be designed according to the linearized slip dynamic model and the evaluated the clamping force system transfer function. In this section, Adaptive Fuzzy logic control and Linear Quadratic Regulator (LQR) are proposed and explained. The reference point of the slip controller is chosen at the turning point between the micro-and macro slip region, based on the Figure 2. Slip reference point is taken depend on the ratio as shown in Table 1.

Table 1. Reference Point of Slip Dependent on the Ratio

Ratio [-]	v_{ref} [%]
0.43	2.5
1	1.5
2.25	1.5

4.1. Fuzzy PID (FPID) Control

Fuzzy control offers a formal methodology to characterize, manipulate, and implement a human's heuristic knowledge about control a system. As shown in Figure 4, the fuzzy controller block diagram is presented, which illustrates a fuzzy controller embedded in a closed-loop control system. The plant outputs are represented by *y(t),* its inputs are represented by *u(t)*, and *r(t)* is the reference input to the fuzzy controller.

The fuzzy controller consists of four main components: (1) "the rule-base" holds the knowledge, in the shape of a group of rules, to achieve the best control the system. (2) The inference mechanism estimates which control rules are applicable at the current time and then makes a decision what the plant input should be. (3) The fuzzification interface adapts the inputs to can be construed and compared to the rules in the rule-base and (4) the defuzzification interface changes the conclusions reached by the inference mechanism into the inputs to the plant [10].

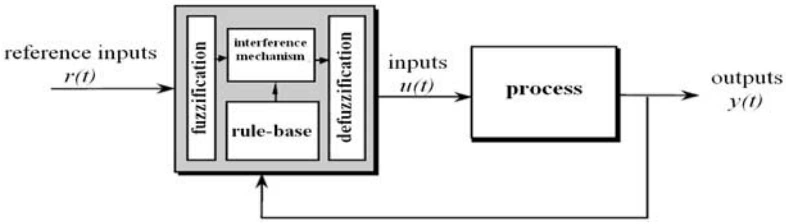

Figure 4. Fuzzy Logic Control Architecture

Table 2. Adaptive Fuzzy Logic Control Rule Base

e / Δe	*N*	*P*
N	LN	Z
P	Z	LP

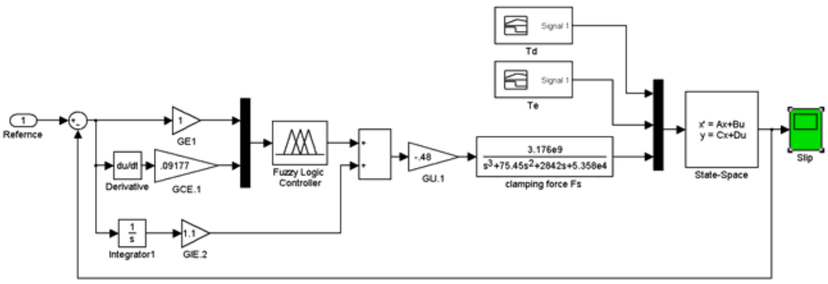

Figure 5(a). Simulink model of the proposed Adaptive Fuzzy logic control for slip model

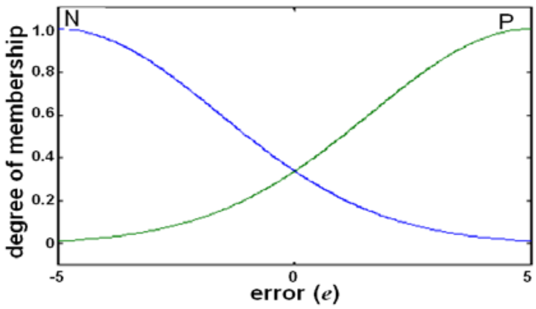

Figure 5(b)

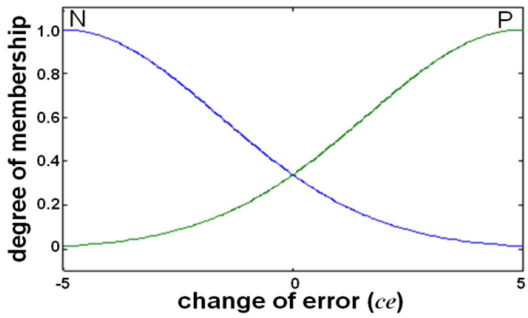

Figure 5(c)

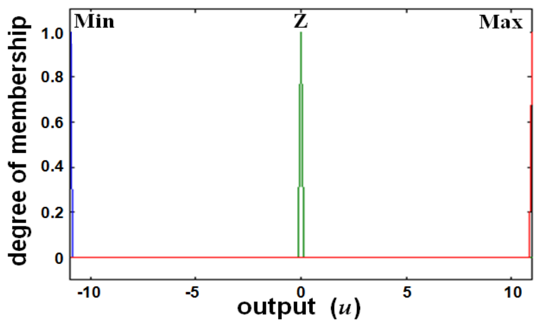

Figure 5(d)

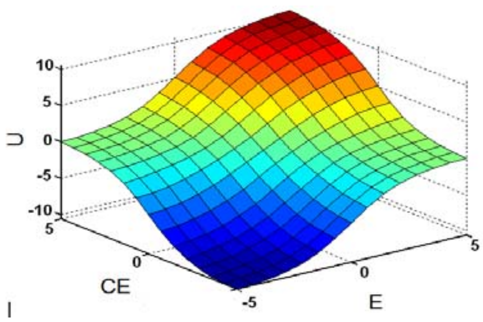

Figure 5(e). The rules, member functions and surface of the proposed adaptive Fuzzy logic control

4.2. LQR Controller

The design of optimal control systems is an important function of control engineering. The intention of design is to recognize a system with realistic components that will provides the desired operating performance.

The design of a system must be based on minimizing a performances index. Systems that are adjusted to provide minimum performance index are often called optimal control system shown in Figure 6. Linear-quadratic-regulator (LQR) is an element of optimal control strategy which has been widely developed and used in different applications. LQR design is based on the selection of feedback gains *K* such that the cost function *J* is minimized. This ensures that the gain selection is optimal for the cost function specified [11].

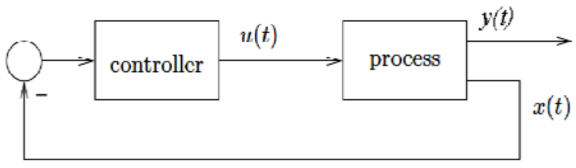

Figure 6. Linear Quadratic Regulator (LQR) with State Feedback

Table 3. Variation of the feedback gain K for various operating point

Ratio r_g[-]	*K*
0.43	-0.5424
1	-0.74246
2.25	-0.912

For design LQR controller, the Matlab lqr function can be used to calculate the value of the vector of feedback gain *K* which represented the feedback control law. That achieved by selecting output and input weight matrices *Q* and *R*, as *R* = 1 and *Q* = *ρ*CT*C* where *CT* is the matrix transpose of *C* from state Equation (14). The control signal can be adjusted by regulating the value of ρ in Q matrix which is done in m-file code.

R = 1;

Q = ρ [1];*

[K, S, e] = lqr [A, B, Q, R];

So, by adjusted the value of *ρ* = 800, the following values of matrix *K* are obtained. If *ρ* is increased even higher, the response of system will be improved, but the values of *ρ* = 800 is chosen due to it is achieved the desired requirements. The value of feedback matrix *K* are vary with different operating point of ratio r_g, that demonstrated by the Table 3.

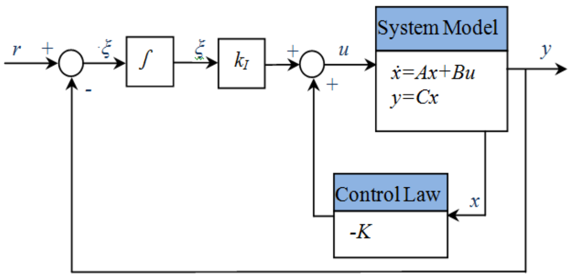

Figure 7. Linear Quadratic Regulator (LQR) with State Feedback

In order to diminish the steady state error of the system output and tracking reference inputs the internal model design technique used, the basic principle of design the internal model is to insert an integrator in the feedforward path between the error comparator ant the plant and a value of constant gain k_I should be put after the integrator. With a full-state feedback controller all the states are feedback. The steady-state value of the states should be calculated, multiply that by the chosen gain K, and added to the error comparator and k_I used a new value as the control signal for computing the input. The integral gain k_I can be obtained by using m-file code. The block diagram of the method used in simulation model is done by exported both value of feedback gain matrix K and integral gain k_I, as shown in Figure 7. The Simulink model of slip dynamic with LQR control and using internal model design technique is shown in Figure 8.

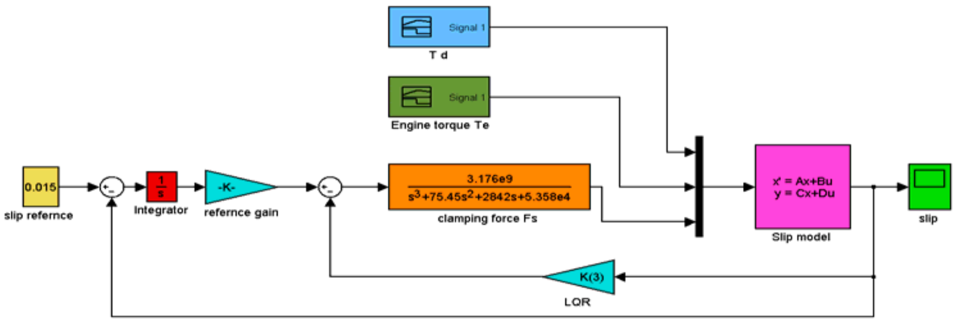

Figure 8. Simulink Model of Slip Dynamic with LQR Control and using Internal Model Design Technique

5. Simulation Results and Discussion

In order to investigate and evaluation the performance of the proposed two controllers (LQR, adaptive fuzzy logic control) and compared with PI to validate the robustness of the proposed control strategy, the simulation test is conducted.

As shown in Figure 7, the response of proposed control system with PI, Adaptive fuzzy logic and the linear quadratic regulator (LQR) are demonstrated. According to the Figure 7, the results obviously appeared that Adaptive Fuzzy logic control has the fastest response with the rising time of 0.116 [s] and settling time of 2.14 [s]. For the percent of overshoot (%), LQR has the minim value 0.5% which achieves the desired requirement of controller design. In addition the LQR controller tends to generate very small steady state error (Ess), is within the limit 0.01%. This can be signifying that LQR controller has the ability to attenuate the effect of disturbances in the system.

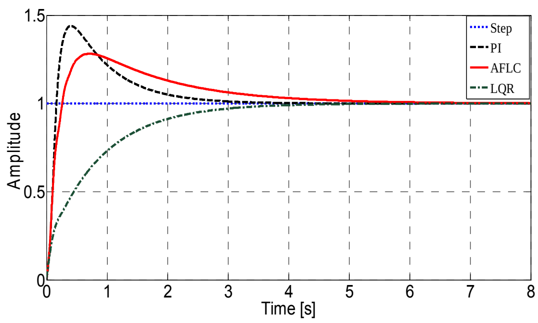

Figure 9. Step Response of Slip Model with LQR, Adaptive Fuzzy Logic and PI Control

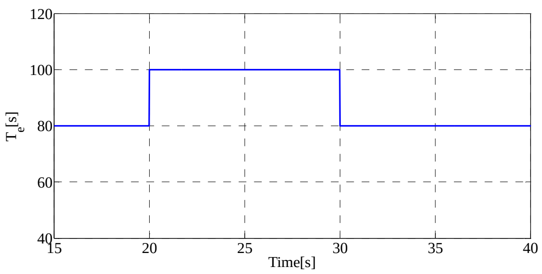

Figure 10(a). The engine torque T_e disturbance

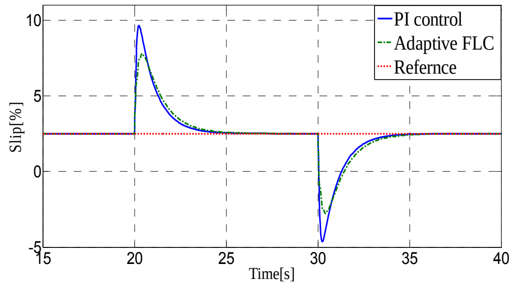

Figure 10(b). Response of the slip model with PI control and AFLC

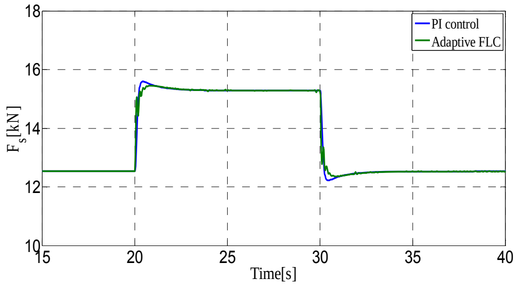

Figure 10(c). Response of the Clamping Force F_S with PI Control and AFLC

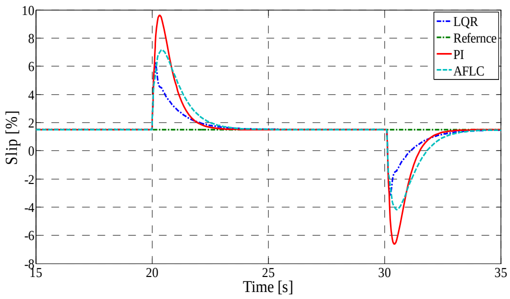

Figure 11(a). Response of the slip model with PI control, AFLC and LQR control

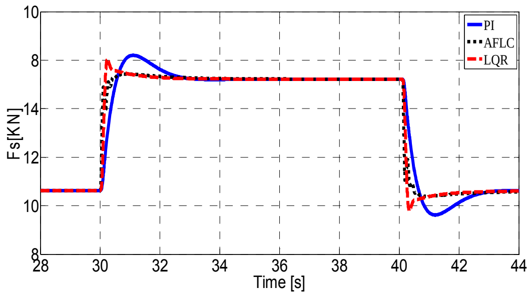

Figure 11(b). Response of clamping force F_S with PI control, AFLC and LQR control

From Figure 9, 10, and 11, it can be realized that Adaptive Fuzzy logic control and LQR controllers are adequate to utilize in the control of slip dynamic model system and gave the similar results as the PI controller. Whatever, due to the higher gain of LQR controller, the clamping forces are reached to a much higher level during suddenly changing torque compared to the clamping forces based on PI controller and Adaptive Fuzzy logic controller.

However, the results proven that Adaptive Fuzzy logic controller and LQR controller are give significant performance better than PI control in slip control of CVT.

6. Conclusion

In this paper, two controllers, Adaptive Fuzzy logic and LQR for slip control in CVT are proposed and tested by simulation using MATLAB. Also the two controllers are compared with PI control. Based on the result and the analysis, the control of approach fuzzy PID control and LQR is capable on controlling the slip on the variator of CVT. The slip controller based on fuzzy PID and LQR control design afford better disturbance alleviation, which caused by torque peaks, compared to PI controller. Simulation and analysis results show that a better performance is achieved by the LQR with respect to both adaptive fuzzy control strategy and PI controllers in controlling the slip, so the improved efficiency for CVT is maintained and the improved efficiency for CVT is achieved by controlling the clamping force and prevents excess slip.

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