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ENHANCING ENERGY-EFFICIENT WATER PUMPING WITH INTELLIGENT CONTROL: A COMPARATIVE STUDY OF ADVANCED FUZZY LOGIC AND PID CONTROLLERS ON SIMULINK/MATLAB

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ABSTRACT
Water resources are crucial for social and economic development, human needs, and food production. However, with water scarcity on the rise, minimizing waste during pumping is vital. Using DC motors for pumping offers a solution for sustainable and efficient water management. This study explores intelligent control strategies to enhance energy efficiency in water pumping systems, comparing Advanced Fuzzy Logic and PID Controllers through simulation. The research aims to optimize the control approach for water pumping operations, improving energy efficiency and system performance. Simulation results indicate that both controllers effectively regulate water pumping operations. The Advanced Fuzzy Logic Controller offer better response to setpoints, with minimal overshoot 0,7%, fast settling time 0.052 Seconds, Rise Time 0.048 Seconds, Time Peak 0.05 Seconds and no steady-state error, Compared to PID Controller with Overshoot 10%, Settling Time 0.23 Seconds, Rise Time 0.048 Seconds, Time Peak 0.078 Second and no steady-state error Moreover, the Advanced Fuzzy Logic Controller performs overall better performance in terms of energy efficiency and robustness compared to the PID controller. The findings suggest that the energy efficiency of water pumping systems can be significantly increased by utilizing Advanced Fuzzy Logic Controller approaches, specifically the Advanced Fuzzy Logic Controller. This study contributes to developing control methods for sustainable water management systems with potential uses in agriculture, irrigation, and water distribution.

Keywords: Advanced Fuzzy Logic Control, PID Control, Energy efficiency, Water pumping, Simulink/MATLAB

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INTRODUCTION

DC motors are devices that generate mechanical energy by means of the current that results from a wire coil inside the motor (Osman et al., 2022). They can deliver strong beginning torque and the ability to control speed over a broad range. DC motors are now again increasing in popularity as highly practical equipment. They are commonly used in various applications, such as industrial, automobile, and home appliances (Kumar et al., 2014).

Implementing DC motors for water pumping has emerged as a possible solution to the growing need for resource sustainability and efficient water pumping. DC motors are reliable, efficient, and controllable in terms of controlling speed. Due to its superior electrical properties, such as high starting and accelerating torque, quick response performance, and simple linear control, high-performance DC motor drives are employed increasingly frequently in factories (Akpama et al., 2021). DC motors require a controller to increase their efficiency because without using a controller, a DC motor has a long response to reach a set point, which will later affect the level of efficiency (Guo & Mohamed, 2020)

There are many different methods for controlling the DC motor, including PI, PID, and fuzzy logic controllers. This is because all control systems have issues with undesirable overshoot, prolonged settling times, vibrations, and stability when changing states. Real-world systems are not linear, which makes correct modelling challenging and expensive (Akpama et al., 2021). With its three-term functionality that can handle transient and steady-state responses, proportional-integral-derivative (PID) control offers an easy-to-understand and highly effective solution to many real-world issues. PID controllers are, therefore, often used in traditional speed control loops. Traditional PID controllers suffer from unwanted overshoots, slow response, sensitivity to controller gains, and rapid changes in load torque. Two major issues with motor control are the unstable behaviour of the motor parameters under operating conditions and noise in the system. Therefore, employing standard methods to regulate motion in complex, nonlinear, and time-varying systems becomes difficult. To achieve an ideal state under field conditions, tuning the PID controller's parameters is obviously necessary (Sharma & Palwalia, 2018).

It makes an adaptive Fuzzy Logic Controller based on PID superior to conventional PID controllers. These advantages such as cheaper to develop, covering a wider range of operating conditions (Al-Odienat & Al-Lawama, 2008), not needing an accurate mathematical model, and being more robust than a PID controller (Eltamaly, 2018).

Akpama et al presents. The dynamic behaviour of the motor was assessed in terms of transient response, such as settling time and peak overshoot for both the Fuzzy Logic Controller (FLC) and PID controller. It was found that the Fuzzy Logic Controller (FLC) offers faster dynamic response and better motor performance than traditional PID Controllers. When a disturbance, such as a change in the applied load condition, the Fuzzy Logic Controller (FLC) offers better resilience and a quicker transient reaction. This demonstrates how effectively a DC motor pump can replace an AC motor pump (Akpama et al., 2021).

Li et al. present. Results show that the Fuzzy PID has a reasonably good anti-disturbance capacity and outperforms the regular PID in terms of adjustment time, rising time, peak overshoot, and peak time (Li & Gong, 2022). Somwanshi et al. The superiority of the Fuzzy-PID Controller was evident, particularly in terms of robustness to parameter variations (Somwanshi et al., 2019).

The study presents the design of an Advanced Fuzzy Logic Controller to regulate the motor's speed. The main problem in the PID Controller is parameter tuning, which can be solved by utilizing optimization techniques or algorithms. To resolve this issue, fuzzy logic can automatically adjust the PID parameters in real-time. Forty-nine rules are formulated with various membership functions to generate equations for speed control and parameter tuning of PID. The motor speed is controlled by continuously adjusting the motor armature voltage. MATLAB/Simulink software is utilized for simulation in this study. Two controllers, a PID controller and an Advanced Fuzzy Logic Controller, are developed for comparison.

While recent studies have highlighted the superiority of fuzzy logic-based controllers over traditional PID controllers in terms of dynamic response and resilience (Akpama et al., 2021; Li & Gong, 2022; Somwanshi et al., 2019), the practical implementation of advanced fuzzy logic controllers in real-world water pumping systems warrants further examination. Potential challenges, including computational complexity and sensitivity to environmental factors, need to be thoroughly addressed to ensure the viability and scalability of such control systems (Khairudin et al., 2019; Hakim et al., 2024; Flores et al., 2023).

In this study, propose an Advanced Fuzzy Logic Controller for water pumping systems that aims and focusing to improve energy efficiency and performance. While our controller shows promising results in simulation studies, it is important to acknowledge its limitations and consider potential challenges associated with its real-world implementation. By addressing these challenges, we aim to enhance the practical relevance and applicability of our proposed controller in real-world water pumping systems.

METHOD

In this study, we implemented an Advanced Fuzzy Logic Controller (AFLC) in a water pumping system to enhance energy efficiency, with a focus on improving speed response. The AFLC was compared to a conventional PID controller to evaluate its performance in achieving these objectives. While the AFLC demonstrated superior energy efficiency and control precision, an important aspect that we considered was its ability to maintain speed response under varying system parameters and environmental conditions.

To address potential limitations regarding the robustness and scalability of the AFLC, our method included conducting comprehensive tests to evaluate its speed response and energy efficiency under different scenarios. We subjected the controller to varying pump speeds and environmental conditions especially torque response in variation load, to assess its performance over time.

The data obtained from these tests supported the AFLC's effectiveness in enhancing energy efficiency, especially in speed response systems. This suggests that the AFLC has the potential to perform well in real-world applications, maintaining stable speed response and improving energy efficiency over long periods of time.

By demonstrating the AFLC's robustness and scalability in achieving these objectives, our study provides valuable insights for future research. This includes further analysis of the AFLC's performance under different operating conditions and its potential for long-term stability in real-world applications, particularly in enhancing energy efficiency in speed response systems.

DC Motor Modelling

It is well accepted that a linear relationship exists between the torque produced by a DC motor, the armature current, and the magnetic field intensity. The torque (T) of the motor and the armature current (i) are directly related, assuming that the magnetic field stays constant (Somwanshi et al., 2019). Eq. (2.1) illustrates how this relationship is characterized by a constant variable (Kt), the torque constant. These motors are frequently referred to as armature-driven motors.

$$T = Kt \; x \; i \qquad (2.1)$$

Eq. (2.1) shows that the back electromotive force (EMF) (e) is directly connected to the shaft's rotational motion (θ) through a constant factor (K_b), also called the electromotive force constant.

$$e = Kb \; x \; \theta \qquad (2.2)$$

The subsequent governing equations are obtained by using Newton's second law, as expressed in Eq. (2.3), and Kirchhoff's mesh law, as stated in Eq. (2.4)(Ramadan et al., 2014).

$$J \frac{d^2}{dt^2} + b \frac{d\theta}{dt} = \text{Kt x i} \qquad (2.3)$$

$$La\ x\ \frac{di}{dt} + Ra\ x\ i = V - K\frac{d\theta}{dt} \quad (2.4)$$

(J) is the rotor's moment of inertia; (b) is the motor's viscous friction constant; (L_a) is the electrical inductance; (R_a) is the electrical resistance; and (V) is the voltage source. Eq. (2.5) and (2.6) demonstrate how the modelling equations can be represented in terms of Laplace variables by utilizing the Laplace transform(Nassim & Abdelkader, 2021) (Goswami & Joshi, 2018).

$$s(j.s + b)\ x\ \Theta(s) = Kt\ x\ I(s) \quad (2.5)$$

$$s(La.s + Ra)\ x\ I(s) = V(s) - Kb\ x\ s.\Theta(s) \quad (2.6)$$

After removing I(s) from Eq. (2.7), the rotational speed was considered the input and the armature voltage output, resulting in the derivation of the open-loop transfer function.

$$G(s) = \frac{\Theta(s)}{V(s)} = \frac{Kt}{(j.s + b)(La.s + Ra) + Kt\ x\ Kb}\left[\frac{rad/sec}{V}\right] \quad (2.7)$$

Table 1. Parameters of the DC Motor

Parameter	Value	Unit
Armature Resistance (R_a)	4.0	Ohms (Ω))
Armature Inductance (L_a)	0.3	Henry (H)
Torque Constant (K_t)	0.24	N-m/A
Input Voltage (V_a)	60	Volts (V)
Frictional Coefficient (B)	0.0011	N-m/(rad/sec)
Moment of Inertia (J)	0.0043	$kg.m^2$
Rated Speed (Nm)	5000	RPM
Back Emf Constant (K_b)	0.24	V/(rad/sec)

Using the parameters of our engine, which are in the table above in equation (2.7), we obtain the following equation:

$$G(s) = \frac{\Theta(s)}{V(s)} = \frac{0.24}{(0.0043s + 0.0011)(0.3s + 4) + 0.24\ x\ 0.24}\left[\frac{rad/sec}{V}\right] \quad (2.8)$$

The equation mentioned earlier can be subsequently translated using the Simulink figure below.

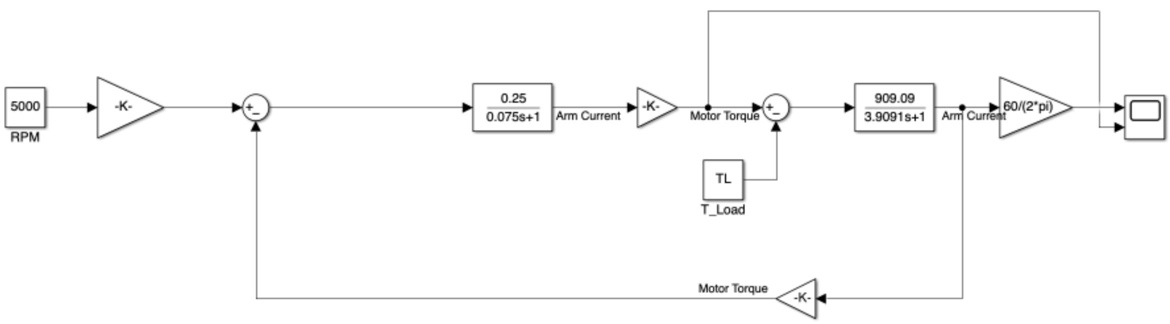

Figure 1. Representation of a DC motor in Simulink

Controller Design

PID Controller Design

The function of the PID controller is mainly to adjust an appropriate proportional gain (KP), integral gain (KI) and differential gain (KD) in order to achieve optimal control performance. General Structure of PID Controller:

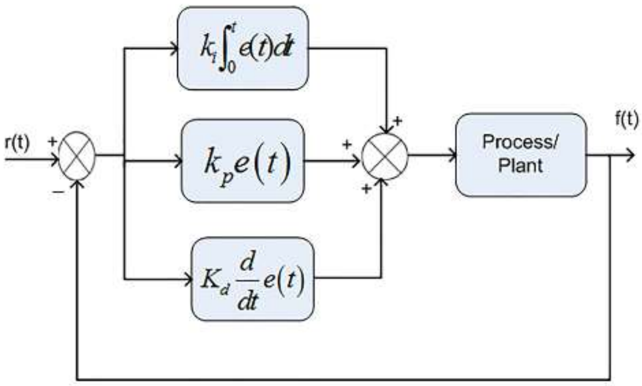

Figure 2. General Structure of PID Controller

The error at time t, or the difference between the set point and the current process value, is represented by e(t), whilst the control signal applied to the system is indicated by u(t). The gains connected to the proportional, integral, and derivative components are denoted by K_p, K_i, and K_d, respectively. It is important that tuning is frequently necessary in order to determine the values of K_p, K_i, and K_d. This system tuning procedure can be carried out by systematic system experimentation or based on experience and techniques like Ziegler-Nichols (Daraz et al., 2020) or by system experiments; in our case, we will use the "self-tuning method"; the values obtained are Kp = 12, Ki = 10, Kd = 0.2.

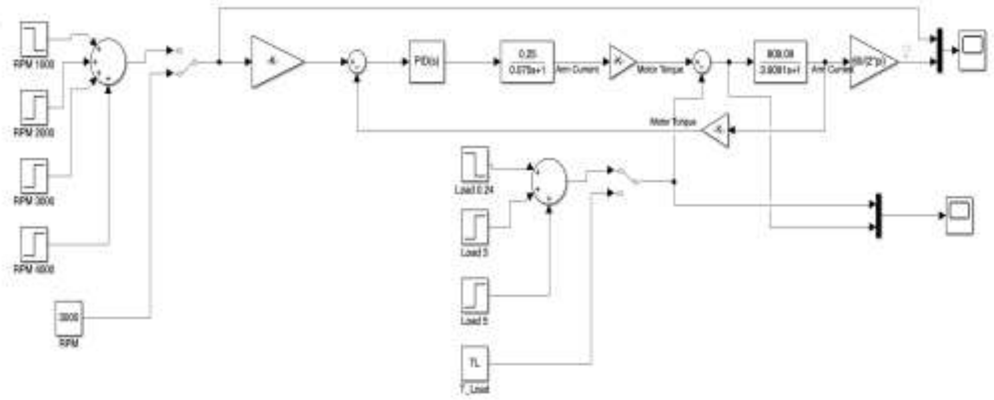

Figure 3. Design PID Controller system on Simulink/MATLAB

Advanced Fuzzy Logic Controller

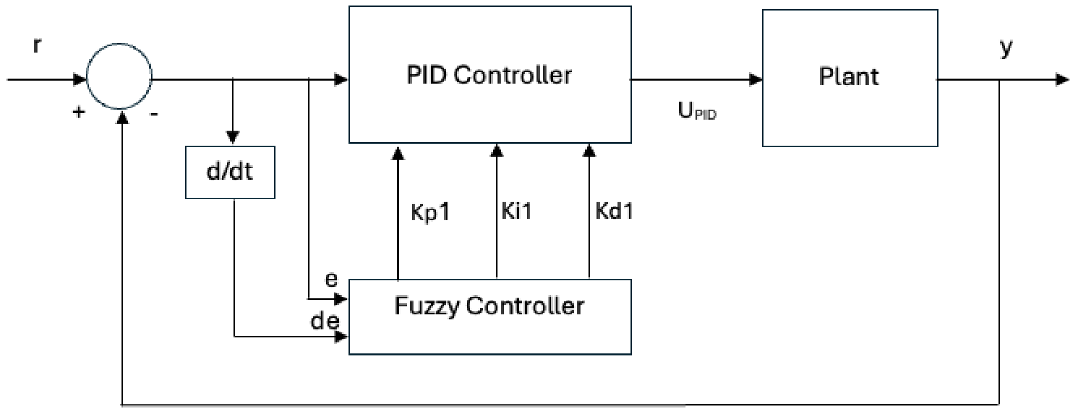

Figure 4. Structure of Advanced Fuzzy Logic Controller

A PID controller's performance can only be improved by optimizing its parameters. Ziegler Nichols and the self-tuning method presented a popular method for fine-tuning the PID controller to improve performance through parameter optimization (Huang et al., 2022). With the help of the fuzzy structure, approximate relationships between the input and the desired output can be expressed in linguistic words. A group of fuzzy components are used to depict the relationship. If-then rules link a potential response to an approximation of the system's state.

The structure of an Advanced Fuzzy Logic Controller comprises two segments: Conventional PID Controller and Fuzzy Logic Controller (FLC); K_{p1}, K_{i1}, and K_{d1} are the preliminary values parameters of Conventional PID Controller K_{p2}, K_{i2}, and K_{d2} are the gain outputs of Fuzzy Logic Controller (FLC), The equation of tuned parameters will be in Eq. 3.1:

$$Kp = K_{p1} \times K_{p2}$$
$$Ki = K_{i1} \times K_{i2} \quad (3.1)$$
$$Kd = K_{d1} \times K_{d2}$$

The output of the control action of the Conventional PID Controller after tunning with the Fuzzy Logic Controller (FLC) will be in equation (3.2).

$$U_{PID} = Kp\, e(t) + Ki \int e(t) + Kd \frac{de(t)}{dt} \quad (3.2)$$

Design of Fuzzy Rule Base

A rule base refers to a collection of decision-making logics that aim to replicate the cognitive process of human judgment-making (Varshney, 2023). The rule base is constructed by utilizing the inputs and their related outputs, specifically determining the desired outputs for a given set of inputs (Tripathy et al., 2022). Seven membership functions are considered for inputs and seven membership functions for output; thus, it will give a total of 49 rules:

Table 2. Fuzzy Rules for Kp

e/de	NB	NM	NS	Z	PS	PM	PB
NB	PB	PM	PS	NB	NB	NB	NB
NM	PM	PS	Z	PS	NB	NS	Z
NS	PB	PM	PS	PM	PS	PM	PB
Z	PB	PM	PS	Z	PS	PM	PB
PS	PB	PM	PS	NS	PS	PM	PB

e/de	NB	NM	NS	Z	PS	PM	PB
PM	Z	NS	NM	NS	Z	PS	PM
PB	NB	NB	NB	NS	PS	PM	PB

Table 3. Fuzzy Rules for Ki

e/de	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	Z
NM	PB	PB	PB	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NS	NM
Z	NM	NS	Z	Z	Z	NS	NM
PS	NM	NS	Z	PS	PS	PM	PB
PM	Z	Z	PS	PM	PM	PB	PB
PB	Z	PS	PB	PB	PB	PB	PB

Table 4. Fuzzy Rules for Kd

e/de	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	Z
NM	PM	PM	PS	PS	PS	Z	Z
NS	PM	PS	Z	Z	Z	NS	NM
Z	PS	PS	Z	Z	Z	NM	NB
PS	NM	NS	Z	Z	Z	PS	PM
PM	Z	Z	PS	PM	PB	PB	PB
PB	Z	PS	PB	PB	PB	PB	PB

Simulink diagram of the DC motor in series with Advanced Fuzzy Logic Controller

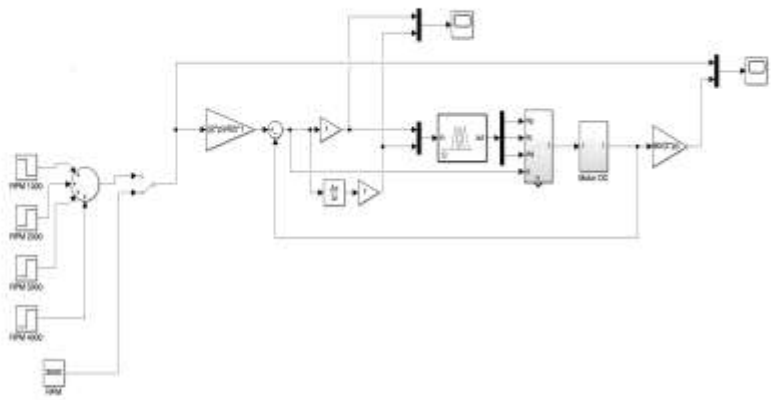

Figure 5. Design of Advanced Fuzzy Logic Controller on Simulink/MATLAB

RESULTS AND DISCUSSION

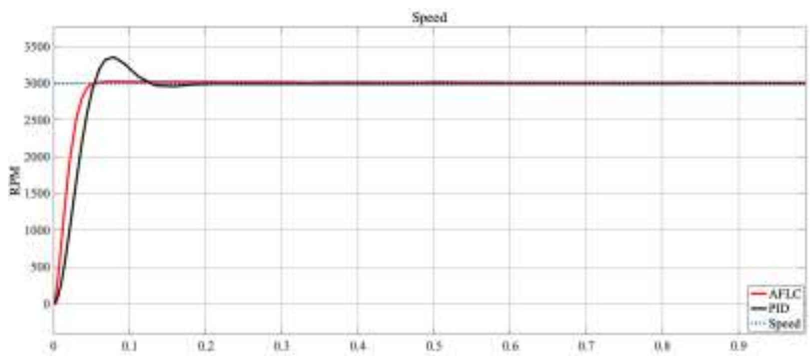

Figure 6. Step Response plotted for the DC Motor with Advanced Fuzzy Logic Controller Method and PID Controller Method

Table 5. Characteristics Response from Advanced Fuzzy Logic Controller Method and PID Controller method

Characteristics	Advanced Fuzzy Logic Controller (AFLC)	PID Controller (Self-Tuning)
Rise Time (t_r)	0.048 Seconds	0.048 Seconds
Maximum Overshoot (M_p)	0,7 %	10%
Time Peak (T_p)	0.05 Seconds	0.078 Seconds
Settling Time (t_s)	0.052 Seconds	0.23 Seconds
Steady State Error (SSE)	0	0

The advanced fuzzy logic controller responds better to the motor when it is run at 3000 RPM regularly. This includes improvements in all parameters related to rise time, settling time, and overshoot. Figure 4.1 illustrates how the system is tested for tracking reference speed values, and Table 4.1 displays the parameter's outcome.

The next test involves varying the speed of the DC motor every two seconds at four different speeds (RPM 1000, 2000, 3000, and 4000) to see the response generated by the advanced fuzzy logic controller and PID Controller that has been designed. The advanced fuzzy Logic controller generates a response as needed, namely having a low overshoot value, the same rise time, and a fast settling time, as seen in Table 4.1. additionally, this advanced fuzzy Logic controller responds consistently to any changes that have occurred

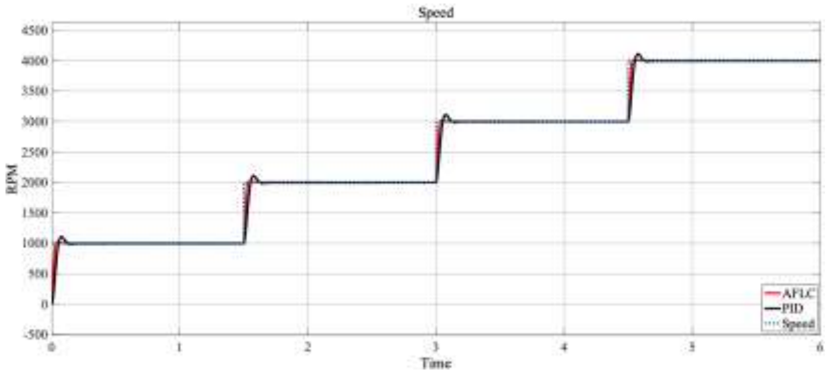

Figure 7. Speed Response at variable load conditions on both controller

Both of the controllers might experience rapid load disturbances. At the onset, a load torque of 0.24 N-m is applied, followed by subsequent instances at t = 2 and t = 4 seconds, where the load torque experiences rapid increments to 3 N-m and 5 N-m, respectively. Figure 8 and Figure 9 illustrate the reaction of a system that incorporates an advanced Fuzzy Logic control and PID Controller mechanism,

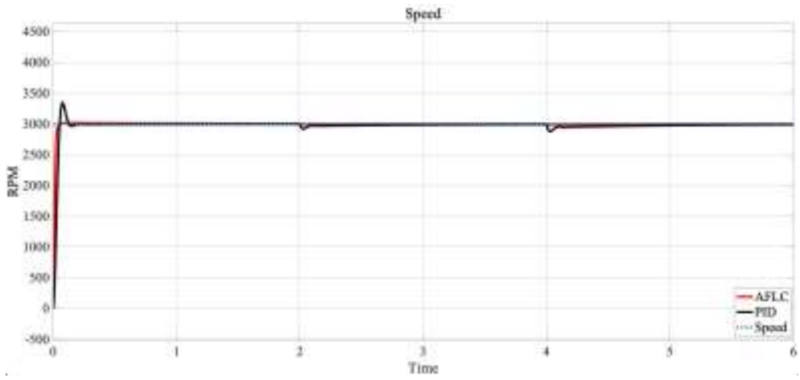

Figure 8. Speed Response at Variable Load Conditions on Both Controller

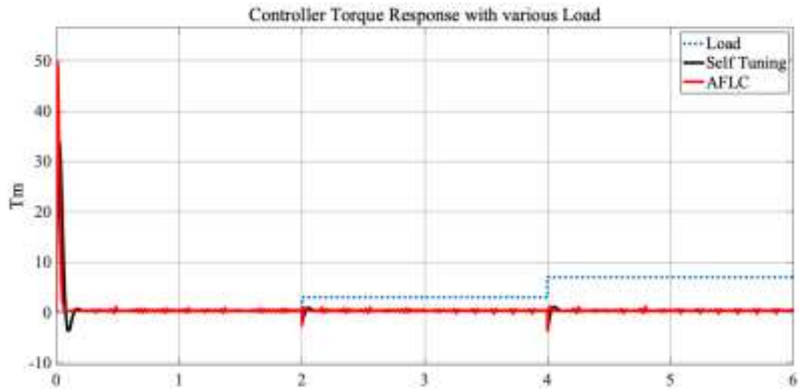

Figure 9. Torque response at variable load conditions on both controller

Figures 8 and 9 show that the scaling factors of the advanced fuzzy logic controller and PID controller automatically adjust all three parameters when the load disturbance occurs at t = 2 seconds and t = 4 seconds. Figure 4.3 compares the motor speed characteristics derived by Advanced Fuzzy Logic controllers with PID controllers. After the system stabilizes, the scaling factors generated by the fuzzy controller return to their initial levels.

For Figure 4.4, when the advanced fuzzy logic controller is loaded, the system will immediately correct the situation again according to the given setpoint compared to the conventional PID controller. However, the advanced fuzzy logic controller compensates with a slight ripple result because the advanced fuzzy logic controller system is multiplied to several PID parameters, one of which is K_d, which will create a ripple system when Kd is multiplied.

While this study has demonstrated the advantages of the Advanced Fuzzy Logic Controller (AFLC) over a conventional PID Controller in improving energy efficiency in water pumping systems, there is a need for further analysis of the long-term stability and robustness of AFLCs in practical applications.

Future research should focus on conducting long-term field tests to assess the performance of AFLCs in real-world scenarios. This could involve monitoring the controller's performance over extended periods, evaluating its ability to maintain stable operation in varying environmental conditions, and assessing any potential degradation in performance over time.

By addressing these concerns, future studies can provide a more comprehensive understanding of the performance of AFLCs in practical applications and ensure their long-term effectiveness in improving energy efficiency in water pumping systems.

CONCLUSION

In a comparative study between the Advanced Fuzzy Logic Controller (AFLC) and a conventional PID Controller to improve energy efficiency in water pumping systems, the AFLC, which regulates input from the PID, shows significant advantages in terms of overshoot, settling time, rise time, and overall performance. Here are the study's conclusions: 1) Overshoot: AFLC produces lower overshoot than conventional PID. This demonstrates AFLC's ability to regulate input more precisely, reducing unwanted spikes in the system. 2) Settling Time: AFLC has a faster settling time than conventional PID. AFLC's ability to adjust inputs quickly and accurately allows the system to reach a steady state more efficiently. 3) Rise Time: AFLC also shows the same rise time as conventional PID. 4) Overall Performance: AFLC consistently performs better than conventional PID in improving energy efficiency in water pumping systems across all aspects assessed. This shows that intelligent controllers such as AFLC can benefit energy-sensitive applications significantly. Thus, in the context of improving energy efficiency in water pumping systems, the use of AFLCs that regulate the input from PIDs can be considered a better option than conventional PIDs based on the results of this comparative study. Advanced Fuzzy Logic Controller control produces a responsive water pump, which can reduce water loss caused by over-pumping or under-pumping. By adjusting the speed appropriately, the pump can maintain stable water pressure and reduce the risk of leaks or wastage of water. By optimizing speed response using precise controls, water pumps can work more efficiently, reducing water loss and minimizing energy consumption. However, the study lacks discussion on potential challenges and drawbacks associated with AFLC implementation, such as computational complexity and sensitivity to environmental factors. Future research should focus on addressing these challenges to ensure the controller's effectiveness in practical settings. Additionally, the study highlights the need for a more thorough analysis of the AFLC's robustness and scalability. Despite these limitations, the AFLC shows promise in enhancing energy efficiency and performance in water pumping systems.

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