Investigations of BLDC motor speed characteristics via THD under conventional and advanced hybrid controllers

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ABSTRACT

This project investigates brushless direct current (BLDC) motor speed control through total harmonic distortion (THD) analysis, employing proportional integral (PI), fuzzy logic (FLC), adaptive neuro-fuzzy inference system (ANFIS), and an innovative hybrid ANFIS-PD/PI controller. Considering the vital role of BLDC motors in precision-dependent industries like robotics, electric vehicles, and industrial automation, our primary focus is on understanding BLDC motor operation and recognizing THD's significance as a performance metric. Controllers are meticulously implemented in real-time, fine-tuned, and optimized to achieve desired speed characteristics, incorporating considerations like response time, accuracy, and energy efficiency. The project's core involves THD analysis, quantifying harmonic content in the BLDC motor's speed waveform. This facilitates a comprehensive comparative evaluation of controller performance, assessing their capability to maintain speed stability and influence power quality. The discussion covers the merits and limitations of each controller, with a special emphasis on the hybrid ANFIS-PD/PI controller, seamlessly blending ANFIS adaptability with PD/PI control stability. Results illustrate the hybrid controller's excellence in optimizing BLDC motor speed control, demonstrating superior performance in speed accuracy, disturbance rejection, and THD reduction. These findings drive advancements in motor control technology, providing practical guidance for selecting controllers tailored to specific application requirements. Simulation results can be analyzed using MATLAB/Simulink 2018a Software.

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1. INTRODUCTION

The current period is characterized by the industrial revolution, primarily initiated by the invention of the motor. A wide range of applications are associated with the DC and AC motors. In the realm of DC motors, there is a variety suitable for different applications. However, industrial setups typically employ two primary types of DC motors. As proposed in [1], the term "brushless direct current (BLDC) motor" refers to a particular type of DC motor that uses an electronic commutation system rather than brushes for commutation. The permanent magnet is the part of BLDC motor with the appearance of the back electromotive force (EMF) which is trapezoidal. As proposed in [2], the current technology is mostly compressed of BLDC related terminology in the whole world. BLDC motors, distinguished by their brushless and commutators-free design, demand minimal maintenance and operate with significantly reduced noise levels compared to DC motors. These motors leverage rotor magnets to generate the necessary magnetic flux, leading to enhanced efficiency. Furthermore, BLDC motors offer numerous advantages, including high efficiency,

compact dimensions, and reduced noise levels [3]. Due to the higher efficiency and reliability BLDCs are adopted in the fans and high-end pumps. Brown [4], to regulate the speed of BLDC motor an employment of hall position sensors in a closed loop system is implemented. In 2006, Shao [5] introduced an upgraded direct back-EMF-sensing method. This advancement allowed for the detection of back EMF during the high-side-switch PWM on-time. The duty-cycle restriction is eliminated by this scheme. In 2003, Shen *et al.* [6] presented equations for error calculation that were specifically related to motor parameters and load. For the automated identification and precise localization of inter-turn short circuits occurring within the stator winding of current source inverter (CSI)-powered permanent-magnet (PM) brushless DC motors. Awadallah *et al.* [7] introduced two different schemes in 2005. In 2010, Wang *et al.* [8] published a paper with the main objective of improving the third harmonic back-EMF, primarily by altering the stator topology. Wu *et al.* [9] proposed a novel control strategy for dealing with torque pulsation problem caused by traditional control method for Brushless DC (BLDC) motor and to achieve high precision and good stability. Tan and Atherton [10] had a detailed discussion of tuning techniques for the proportional integral (PI) controller. The adoption of a trial-and-error approach for figuring out the parameter gain of the PI controller results from the various tuning techniques that are advised in [11] in order to achieve the desired results. To obtain nearly rectangular currents in the motor, a pulse-width modulator (PWM) current controller or a hysteresis current controller is typically used. The following method uses fuzzy logic to regulate the speed of BLDC motors. Fuzzy logic, which Lotfi Zadeh introduced in 1965, has since been applied in a number of disciplines, including artificial intelligence and control theory. When a fuzzy logic controller is used, the output parameter values are accurate. The flexibility and convenience of the fuzzy logic controller make it a widely adopted choice [12], [13]. Adaptive neuro-fuzzy inference system (ANFIS), the fuzzy controller, and specific expert systems are just a few examples of artificial intelligence-based controllers that are widely used in a variety of applications. But all of the above-mentioned controllers have not attained regulated speed and there are less reductions in the harmonic distortions which effects the power quality in the system. Therefore, in order to overcome these issues, in this research endeavor, an ANFIS-based controller is proposed for the speed regulation of BLDC motors. ANFIS, characterized as a rule-based system, exhibits remarkable stability and faster response times with reduced steady-state error, outperforming fuzzy logic controllers. The study shown in [14] compares the effectiveness of a fuzzy controller and a mathematical model of a BLDC motor controlled by an ANFIS controller. Additionally, efforts are made to minimize torque ripple by employing a torque controller for BLDC motors using an unconventional back EMF in [15].
Another approach involves speed control via a hall effect sensor fixed within the stator of a BLDC motor, as discussed in [16]. As proposed in [17] for reducing the torque ripples, dq reference frame and indirect control of stator flux is employed. This study places significant emphasis on the analysis and integration of proportional integral derivative (PID), proportional derivative (PD), PI, and ANFIS controllers, resulting in the development of hybrid PD-ANFIS and PI-ANFIS controllers tailored for BLDC motor speed regulation. The organization of this research work is as follows, section 1 describes the introduction of this work, section 2 evaluates the configuration of the system, section 3 describes the exsting controlling topologies and proposed controller. Section 4 depicts the simulation-based results and discussion and section 5 ends with concluding the proposed work.

2. SYSTEM CONFIGURATION

The research depicted in [14], [15] assesses the efficiency of a fuzzy controller versus a mathematical model of a BLDC motor under the control of an ANFIS controller. This mathematical framework is established upon several core assumptions, including uniform phase resistance across all stator phase windings, consistent self and mutual inductances, ideal properties of power semiconductor devices, minimal iron losses, and an unsaturated motor. Figure 1 illustrates the circuit of the BLDC servomotor drive system.

The voltage equations for line-to-line configurations are succinctly represented using matrix expressions as (1).

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} R & -R & 0 \\ 0 & R & -R \\ -R & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & M-L & 0 \\ 0 & L-M & M-L \\ M-L & 0 & L-M \end{bmatrix} \times \frac{di}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix} \tag{1}$$

Considering the negligible impact of mutual inductance compared to self-inductance, the previously mentioned matrix equation can be reformulated as (1).

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} R & -R & 0 \\ 0 & R & -R \\ -R & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & -L & 0 \\ 0 & L & -L \\ -L & 0 & L \end{bmatrix} \times \frac{di}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix} \quad (2)$$

Where i_a, i_b, and i_c represent the phase currents of phases a, b, and c, and e_a, e_b, and e_c stand for the back EMFs of phases a, b, and c, respectively. Self- and mutual-inductance per phase are denoted by the letters L and M, respectively. Stator winding resistance per phase is denoted by the letter R. The EMF produced by the motor can be mathematically articulated as (3).

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} = K_t I \quad (3)$$

When the torque constant, represented as "Kt," and angular velocity denoted in radians per second, are taken into account, the resulting equation is $i_a=i_b=i_c=I$. To maintain equilibrium between the counteracting torques originating from inertia and the imposed load, this electromagnetic torque can likewise be represented as (4).

$$T_e = T_L + \frac{J_M d\omega}{dt} + B_M \omega \quad (4)$$

Here, load torque is depicted with TL, inertia depicted by JM and frictional constant is denoted by BM associated with BLDC servomotors. Alternative ways to express the load torque in relation to the components of friction and load inertia are as (5).

$$T_L = J_L \frac{d\omega}{dt} + B_L \omega \quad (5)$$

The motor's generated output power is given by (6) and (7).

$$P = T_e \omega \quad (6)$$

$$E = e_a = e_b = e_c = K_b \omega \quad (7)$$

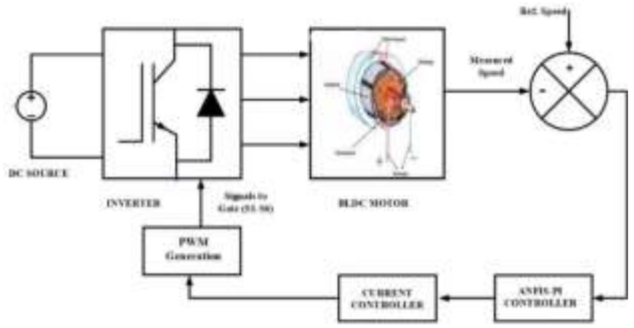


Figure 1. Schematic representation of proposed system

Back EMF per phase, the back EMF constant (Kb), and angular velocity (expressed in radians per second) are all represented by the letters E, Kb, and ω, respectively. The motor's parameters encompass inductance and resistance at phase, inertia, and friction characteristics of the BLDC servomotor, as well as those of the load. For the design of conventional controllers like P, PI, and PID controllers, precise determination of these factors is essential. During operational conditions, variations in R, JM, JL, BM, and BL have a direct impact on the speed of response of the BLDC system. The settling time for the speed response will be prolonged by raising the values of the energy-storing inertia components JM and JL; however, the deceleration time of the speed response will be sped up by raising the values of the power-using friction components BM and BL. Another parameter that could alter in real-world use is the BLDC servomotor's phase resistance. The addition of terminal resistance, modifications to the resistance of the phase windings, and changes in the on-state resistance of insulated gate bipolar transistor (IGBT) switches caused by temperature changes are a few of the variables that can cause these variations. The speed response of the BLDC servomotor drive system can be significantly affected by these variations in phase resistance.

The BLDC servomotor's varying inertia, friction, and phase resistance may work together to produce significant overshoots, which are typically undesirable in many control applications. In order to improve response times, reduce overshoot, and reduce steady-state errors, the BLDC servomotor drive system must implement suitable controllers, such as PID or FLC controllers.

2.1. PI controller

A large number of industrial control systems use PID controllers [7]–[9] because they require little parameter tuning. When the system receives a step reference input, PID controllers have the ability to predict output variations resulting from derivative action, eliminating steady-state errors through integral action. With only parameters taken from the system's step response as a source of input, the Ziegler-Nichols method stands out as the most popular PID tuning method [18]–[22].

2.2. Fuzzy logic controller

The signals generated by the fuzzy controller and the reference current controller are combined to create a control system signal that is sent through the gate driver circuit. For the BLDC motor current to match the reference current value produced by the speed controller, the current control loop must be in control. Figure 2 shows the fundamental design of a fuzzy logic controller. Fuzzification, a fuzzy rule-base, a fuzzy inference engine, and defuzzification are its four key components.

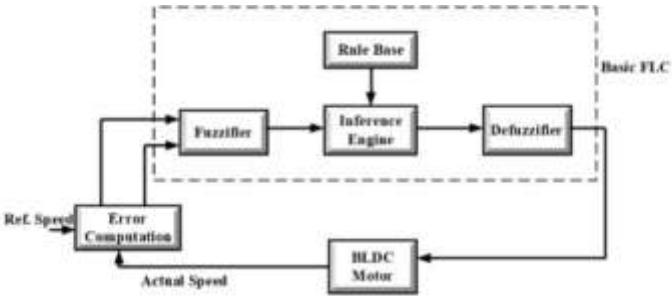


Figure 2. Block diagram of FLC based system

The fuzzy controller takes error (e) and the rate of error change (ce) as inputs, producing an output representing a shift in duty cycle (dc). The difference between the reference speed and the actual speed in this context serves as the definition of error, whereas the difference between the current error and the error that came before it serves as the definition of error change. An output can be positive or negative and is denoted by the letter "dc," which stands for a shift in the duty cycle. If-then rules are just one example of a linguistic term that is used in fuzzy logic and is typically expressed through logical implications. These regulations outline a set of values known as fuzzy membership functions. Triangles, trapezoids, and bell curves are just a few examples of the shapes that these membership functions can take [23]–[26].

2.3. ANFIS controller

ANFIS, a neuro-fuzzy technique that combines neural networks and fuzzy inference systems, is the main tool used in the research. The basic structure of ANFIS controller is depicted in Figure 3. The flexibility of neural networks and fuzzy logic's ability to deal with uncertainty and imprecision are both demonstrated by the ANFIS controller. In this hybrid model, the fuzzy model, including all of its variables and rules, is used as input and successfully models the output data [27]–[30].

2.4. ANFIS PD controller

Within the realm of BLDC motor speed control, the ANFIS-PD controller holds a specialized role. This controller combines the adaptability of neural networks with the interpretability of FLC to effectively govern the speed of the BLDC motor. ANFIS PD controllers rely on feedback from the motor's current speed and the desired reference speed to compute a control signal. The proportional (P) component plays a pivotal role in ensuring the motor attains and sustains the desired speed, while the derivative (D) component acts to dampen any speed oscillations, thereby enhancing system stability. This ANFIS-based approach possesses the capability to adapt for varying load conditions and nonlinearities, ultimately optimizing BLDC motor speed control with a high degree of precision and efficiency [31]-[34].

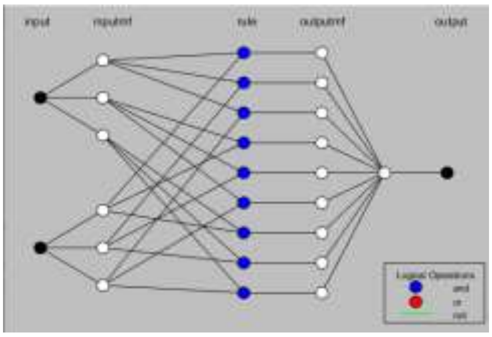


Figure 3. Structure of ANFIS controller

3. PROPOSED ANFIS-PI CONTROLLER

The ANFIS-PI controller is engineered for the precise control of (BLDC motors. Its functionality commences with the acquisition of input data, typically comprising the desired speed (reference) and the current motor speed. The controller calculates the error as the difference between these two values. The ANFIS-PI controller in the project aims to optimize BLDC motor speed control by employing ANFIS and PI control techniques. ANFIS combines the learning capabilities of neural networks with the interpretability of fuzzy logic to enhance controller performance. By integrating PI control with ANFIS, the hybrid ANFIS-PI controller leverages both approaches, offering improved adaptability and precise speed regulation for the BLDC motor. Additionally, ANFIS-PI controllers often incorporate adaptive learning mechanisms to continually fine-tune their fuzzy rule parameters and membership functions, ensuring optimal and adaptive speed control of BLDC motors in various applications such as robotics and industrial automation [35], [36]. Figures 4-6 depict the internal structure of the ANFIS controller and the error changes in the errors and outputs provided to the ANFIS controller.

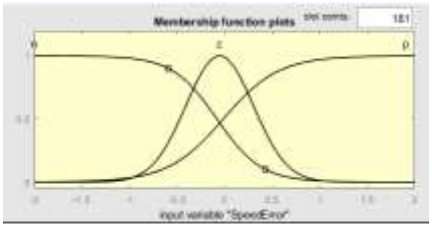


Figure 4. Input 1

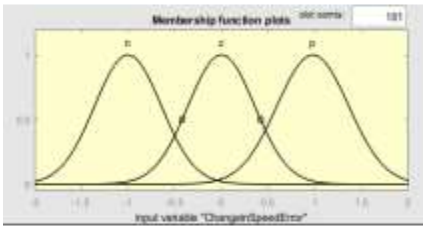


Figure 5. Input 2

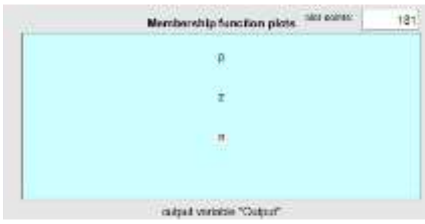


Figure 6. Output 2

4. SIMULATION AND RESULTS

Simulation results of the ANFIS-PI controller applied to BLDC motor speed control validate its effectiveness. The Simulink model and proposed control circuit is depicted in Figures 7 and 8. Across diverse conditions, the ANFIS-PI controller showcases accurate speed tracking, minimizing overshoot and steady-state error. It exhibits better performance than conventional PID control in terms of response time and disturbance elimination. The performance of the different controller has evaluated in the total harmonic distortions(THDs) values which are given in the below mentioned Tables 1 and 2. The adaptability of the ANFIS component allows the controller to adapt to changing motor characteristics and disturbances, enhancing overall system stability and accuracy. These results suggest that the ANFIS-PI controller is a promising solution for BLDC motor speed control, particularly in applications where precise and adaptive control is essential, such as robotics and industrial automation.

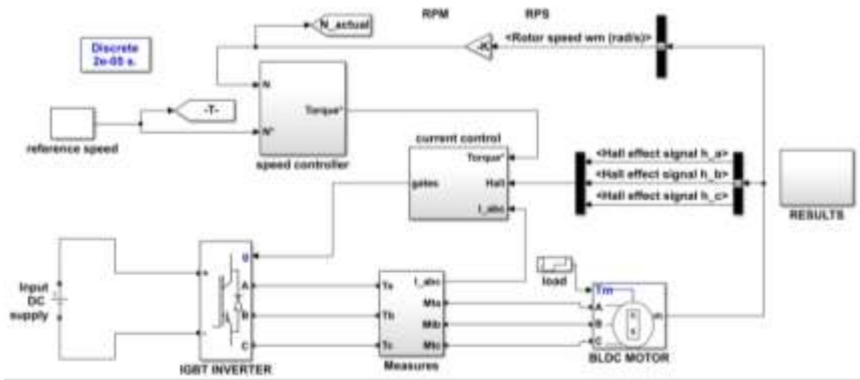


Figure 7. Simulink mode of proposed system

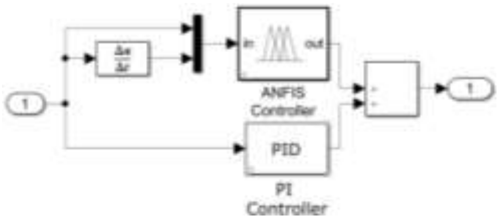


Figure 8. ANFIS-PI based controller

4.1. ANFIS-PI related simulation results

The DC input supply to this proposed circuit is taken as 20 V depicted in Figure 9. The equivalent reference speed given to the system is shown in Figure 9(a), the corresponding actual speed obtained is shown in Figure 9(b) and respective voltage and current waveforms of the system are shown in Figure 9(c) and Figure 9(d) respectively. The obtaining supply from the source is DC but the BLDC Motor requires AC, so in order to convert DC power into AC power and inverter is employed. The switching pulses to this inverter is considered by regulating the speed with different controllers like PI, FLC, ANFIS, ANFIS-PD and ANFIS-PI which the regulated speed is then fed back to current regulation process. The regulated current serves as the basis for generating switching pulses via the hysteresis controller, which are then directed to the inverter circuit. Responses of the system are recorded and analyzed under a wide range of condition operations, such as reference speed changes, load disturbances, modifications to the BLDC servomotor's phase resistance, and changes in system inertia. The proposed controller's performance has been assessed at various speed ratings. Mainly 3-cases like at no load, full load and reduced loads are considered which are then sub-divided into sub-cases based on change in inertia and resistance.

In this case-1, the system performance is evaluated at no-load condition with J1R1 whereas J1=350e-6 kg-m2 and R1=0.57Ω depicted in Figure 9. The equivalent reference speed given to the system is shown in Figure 9(a), the corresponding actual speed obtained is shown in Figure 9(b) and respective voltage and current waveforms of the system are shown in Figure 9(c) and Figure 9(d) respectively. The reference speedisconsidered as constant i.e., 4,000 rpm and the obtained measured speed is similar to the speed of reference. But the settling time of this ANFIS-PI based system is more compared to the other conventional controllers based systems. In this, the output voltage of the inverter is equal to 25V, whereas the amplitude of current is 5 A, but it has the reduced harmonic distortions compared to the other controllers, the obtained THD value is shown in the comparison Table 1.

In this case-2, the system performance is evaluated at no-load condition with J2R1 whereas J1=560e-6 kg-m2 and R1=0.57Ω depicted in Figure 10. The equivalent reference speed given to the system is shown in Figure 10(a), the corresponding actual speed obtained is shown in Figure 10(b) and respective voltage and current waveforms of the system are shown in Figure 10(c) and Figure 10(d) respectively. The reference speed is considered as constant i.e., 4,000 rpm and the obtained measured speed are similar to speed of reference. But the settling time of this ANFIS-PI based system is more compared to the other conventional controllers based systems. In this, the output voltage of inverter is equal to 25 V, whereas the amplitude of current is 5 A but it has the reduced harmonic distortions compared to the other controllers, the obtained THD value is shown in the Table 1.

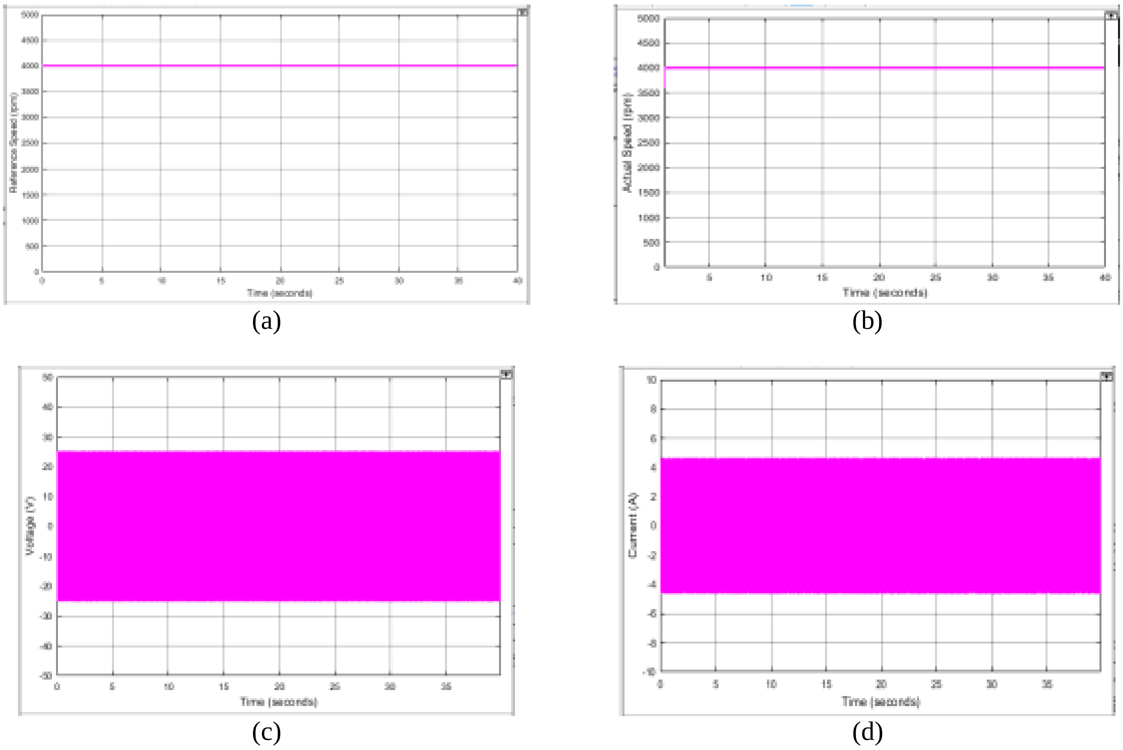


Figure 9. Case-1-J1R1 no load condition results: (a) reference speed, (b) actual speed, (c) voltage, and (d) current

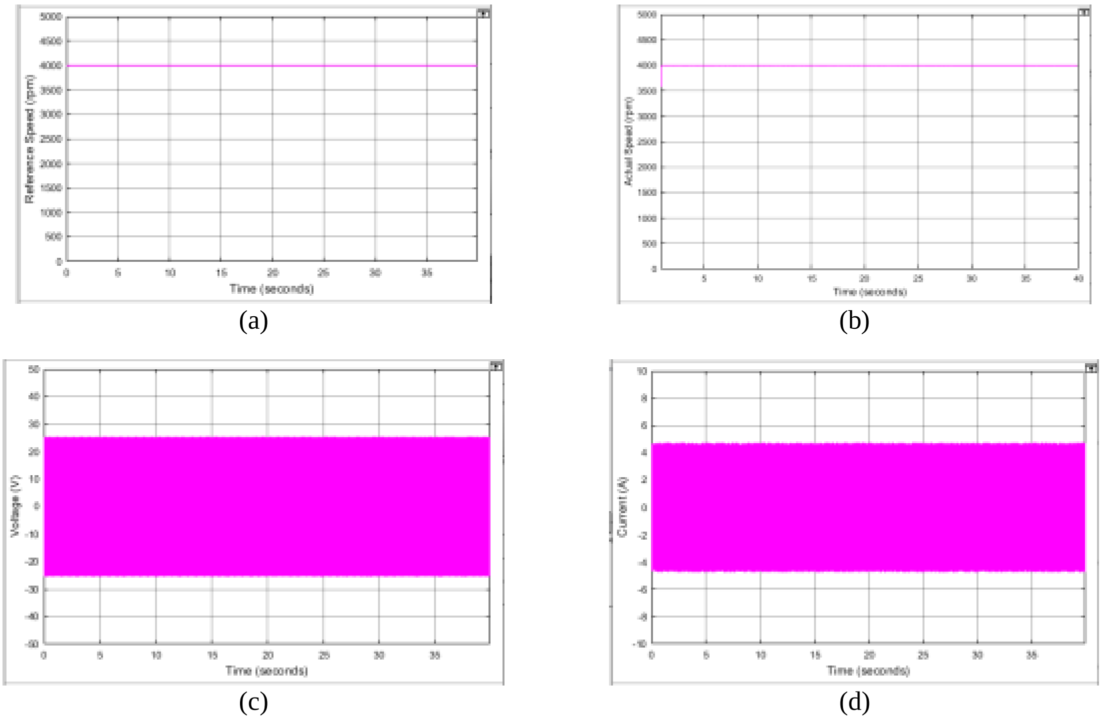


Figure 10. Case-2- J2R1 no load condition results: (a) reference speed, (b) actual speed, (c) voltage, and (d) current

In this case-3, the system performance is evaluated at no-load condition with J2R2 whereas J2=560e-6 kg-m2 and R2=1.14Ω depicted in Figure 11. The equivalent reference speed given to the system is shown in Figure 11(a), the corresponding actual speed obtained is shown in Figure 11(b) and respective voltage and current waveforms of the system are shown in Figure 11(c) and Figure 11(d) respectively. The reference speed is considered as constant i.e., 4,000 rpm and the obtained measured speed is equal to the reference speed. But the settling time of this ANFIS-PI based system is more compared to the other conventional controllers based systems. In this, the output voltage of inverter is equal to 25 V, whereas the amplitude of current is 5 A but it has the reduced harmonic distortions compared to the other controllers, the obtained THD value is shown in the Table 1.

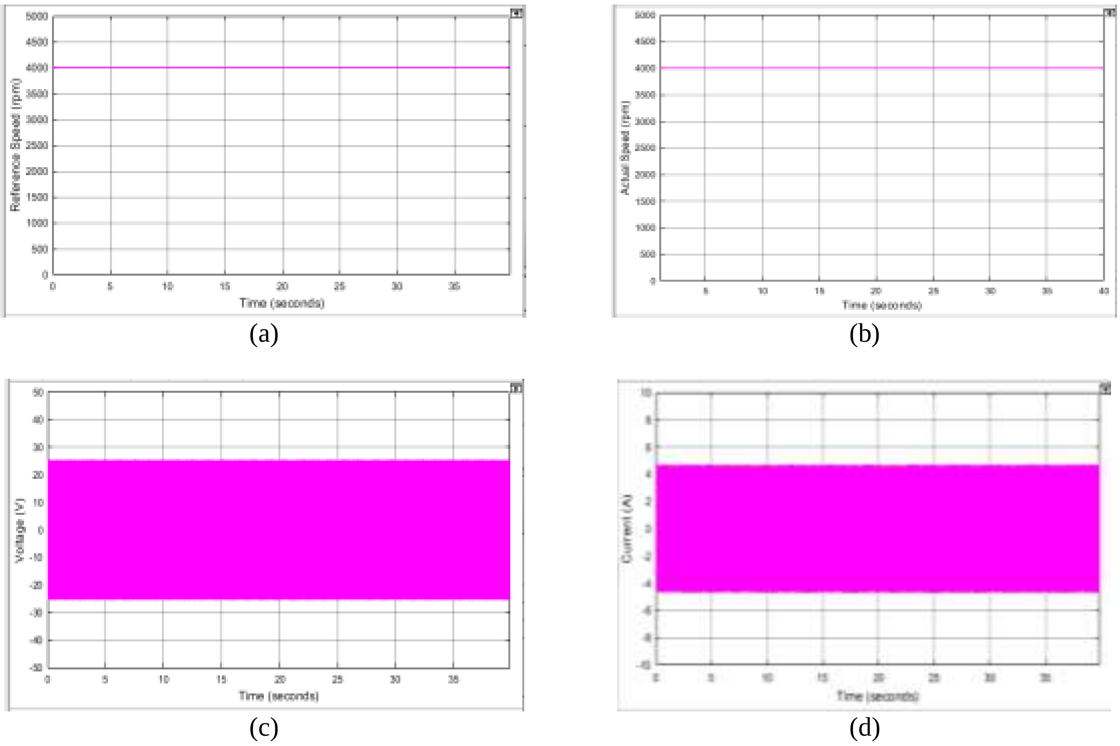
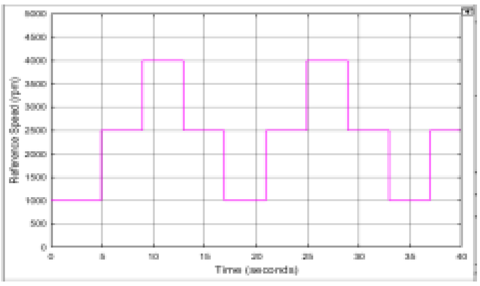


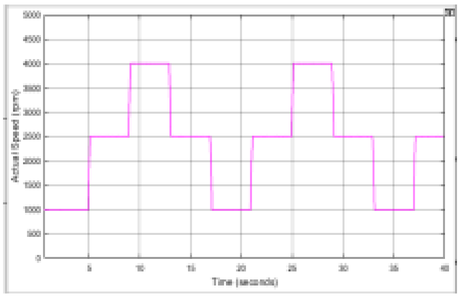
Figure 11. Case-3 J2R2 no load condition results: (a) reference speed, (b) actual speed, (c) voltage, and (d) current

In this case-4, the system performance is evaluated at full load condition with J1R1 whereas J1=350e-6 kg-m2 and R1=0.57Ω depicted in Figures 12. The equivalent reference speed given to the system is shown in Figure 12(a), the corresponding actual speed obtained is shown in Figure 12(b), the error obtained is shown in Figure 12(c) and respective voltage and current waveforms of the system are shown in Figure 12(d) and Figure 12(e) respectively. The reference speed is considered as varied i.e., 1,000–2,500–4,000–2,500–1,000 rpm with respect to the timings and the obtained measured speed is same as reference speed. The difference in the speed regulation i.e., error is also shown in simulation results Figure 12. But the settling time of this ANFIS-PI based system is more compared to the other conventional controllers based systems. In this, the output voltage of inverter is equal to 25 V, whereas the amplitude of current is 5 A but it has the reduced harmonic distortions compared to the other controllers, the obtained THD value is shown in theTable 1.

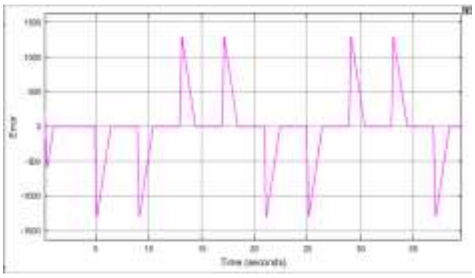
In this case-5, the system performance is evaluated at reduced load condition with J1R1 whereas J1=350e-6 kg-m2 and R1=0.57Ω depicted in Figure 13. The equivalent reference speed given to the system is shown in Figure 13(a), the corresponding actual speed obtained is shown in Figure 13(b), the error obtained is shown in Figure 13(c) and respective voltage and current waveforms of the system are shown in Figure 13(d) and Figure 13(e) respectively. The reference speed is consider as varied i.e., 1,000–2,500–4,000–2,500–1,000 rpm with respect to the timings and the obtained measured speed is same as reference speed. The difference in the speed regulation i.e., error is also shown in simulation results Figure 13. But the settling time of this ANFIS-PI based system is more compared to the other conventional controllers based systems. In this, the output voltage of inverter is equal to 25 V, whereas the amplitude of current is 5 A but it has the reduced harmonic distortions compared to the other controllers, the obtained THD value is shown in the Table 1.



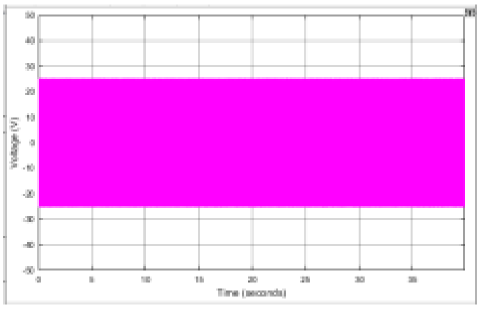
(a)



(b)



(c)



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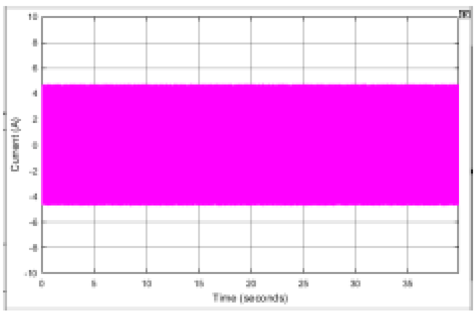
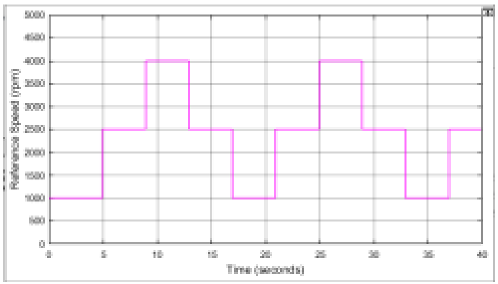
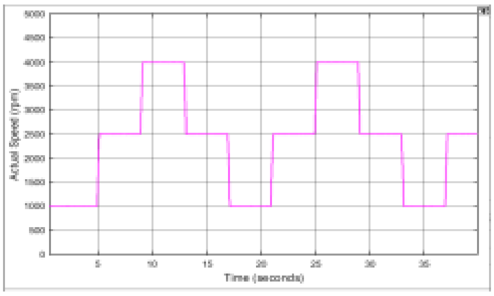


(e)

Figure 12. Case-4- J1R1 full load condition results: (a) reference speed, (b) actual speed, (c) error, (d) voltage, and (e) current



(a)



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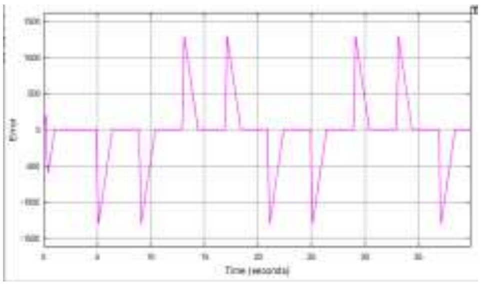

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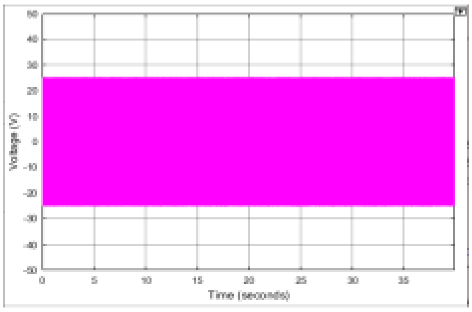
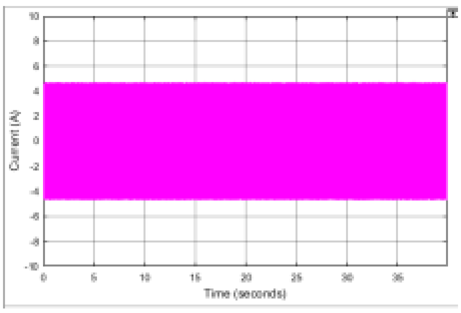


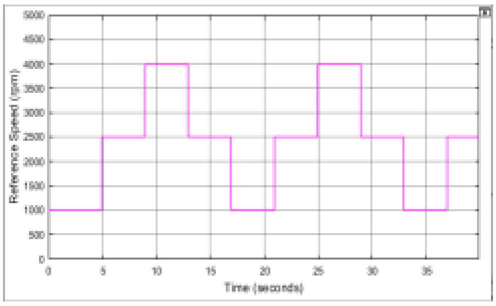
(d)



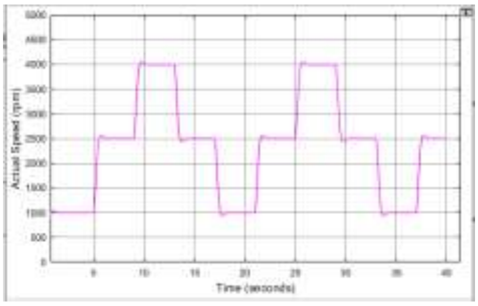
(e)

Figure 13. Case-5-J1R1reduced load condition results: (a) reference speed, (b) actual speed, (c) error, (d) voltage, and (e) current

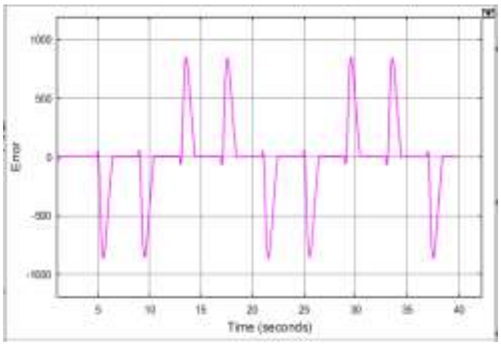
In this case-6, the system performance is evaluated at full load condition with J2R1 whereas J2=560e-6 kg-m2 and R1=0.57Ω depicted in Figure 14. The equivalent reference speed given to the system is shown in Figure 14(a), the corresponding actual speed obtained is shown in Figure 14(b), the error obtained is shown in Figure 14(c) and respective voltage and current waveforms of the system are shown in Figure 14(d) and Figure 14(e) respectively. The reference speed is consider as varied i.e., 1,000–2,500–4,000–2,500–1,000 rpm with respect to the timings and the obtained measured speed is same as reference speed. The difference in the speed regulation i.e., error is also shown in simulation results Figure 14. But the settling time of this ANFIS-PI based system is more compared to the other conventional controllers based systems. In this, the output voltage of inverter is equal to 25 V, whereas the amplitude of current is 5 A but it has the reduced harmonic distortions compared to the other controllers, the obtained THD value is shown in the Table 1.



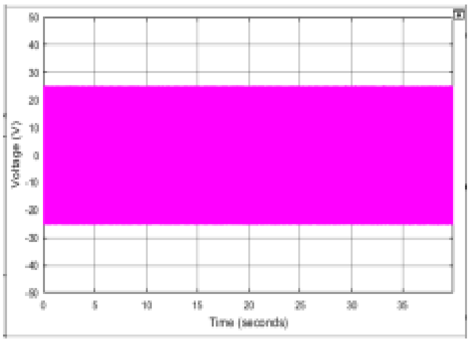
(a)



(b)



(c)



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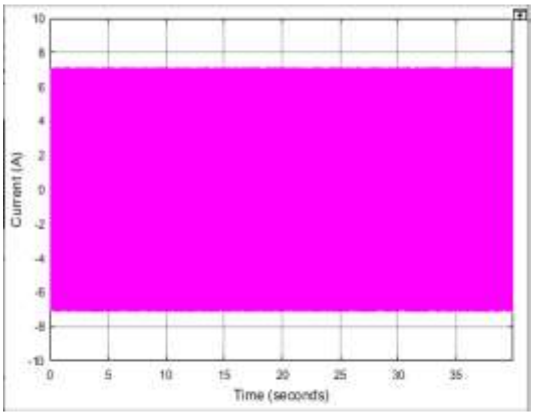

(e)

Figure 14. Case-6 J2R1 full load condition results: (a) reference speed, (b) actual speed, (c) error, (d) voltage, and (e) current

In this case-7, the system performance is evaluated at full load condition with J2R2 whereas J2=560e-6 kg-m2 and R2 1.14Ω depicted in Figure15. The equivalent reference speed given to the system is shown in Figure 15(a), the corresponding actual speed obtained is shown in Figure 15(b), the error obtained is shown in Figure 15(c) and respective voltage and current waveforms of the system are shown in Figure 15(d) and Figure 15(e) respectively. The reference speed is consider as varied i.e., 1,000–2,500–4,000–2,500–1,000 rpm with respect to the timings and the obtained measured speed is same as reference speed. The difference in the speed regulation i.e., error is also shown in simulation results Figure 15. But the settling time of this ANFIS-PI based system is more compared to the other conventional controllers based systems. In this, the output voltage of inverter is equal to 25 V, whereas the amplitude of current is 5 A but it has the reduced harmonic distortions compared to the other controllers, the obtained THD value is shown in the Table 1.

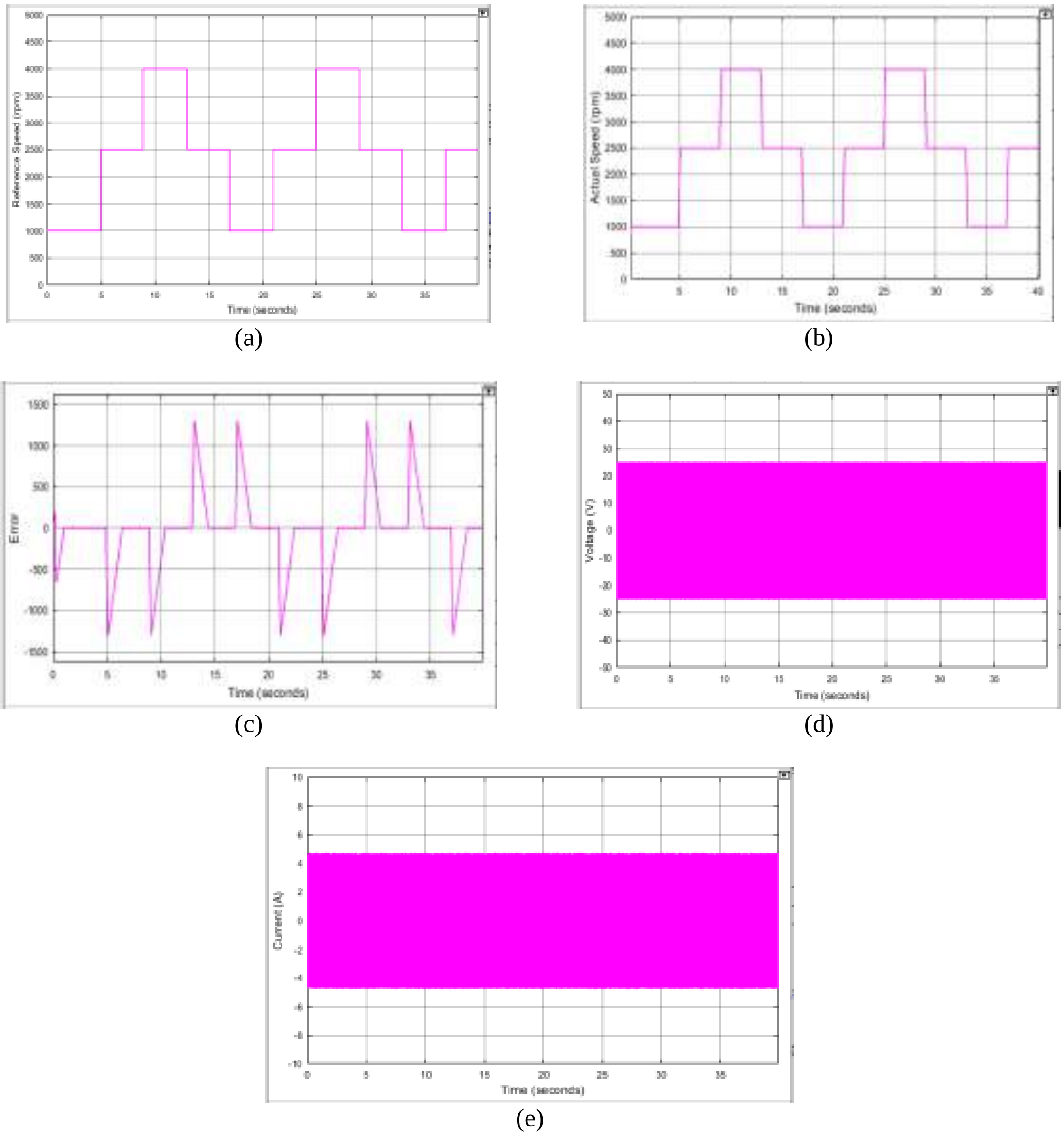

Figure 15. Case-7 J2R2 full load condition results: (a) reference speed, (b) actual speed, (c) error, (d) voltage, and (e) current

4.2 Comparison table of the current THDs with all controllers

In the comparison Table 1 the obtained THD values of current in different controllers is depicted. Among all these controllers, the hybrid ANFIS-PI based system has evaluated the reduced THDs i.e., almost the THD values are below 15%. In light of this, it can be said that the ANFIS-PI-based system has evaluated the better system performance when compared to other controllers while maintaining good power quality throughout the process.

Table 1. The comparison THDs

S.No	Name of the case with parameter variation	% THD with PID controller	% THD with FLC controller	% THD with ANFIS controller	% THD with ANFIS PD controller	% THD with ANFIS PI controller
1	J1R1 no load	41.86 %	33.34 %	19.59 %	15.20 %	12.36 %
2	J2R1 no load	69.03 %	34.72 %	25.46 %	15.67 %	13.25 %
3	J2R2 no load	59.28 %	34.01 %	22.06 %	15.94 %	12.99 %
4	J1R1 full load	41.86 %	33.49 %	20.12 %	19.21 %	13.66 %
5	J1R1 reduced load	54.01 %	34.73 %	26.49 %	16.56 %	12.78 %
6	J2R1 full load	69.03 %	34.08 %	23.21 %	19.24 %	14.32 %
7	J2R2 full load	59.28 %	33.84 %	20.99 %	19.72 %	13.68 %

4.3. THD vs speed characteristics

With varying speeds between 4,000-1,000 rpm, the system's performance is assessed in this work is depicted in Table 2. The speed is directly proportional to the THD obtained. Among all the controllers ANFIS-PI based system has evaluated better performance than the other conventional controllers, even if the speed is increased.

Table 2. Varied speeds vs THDs

Controller Speed (RPM)	% THD with PID controller	% THD with FLC controller	% THD with ANFIS controller	% THD with ANFIS PD controller	% THD with ANFIS PI controller
4,000	41.86	33.49	20.12	19.21	13.660
3,500	41.76	33.4	20.07	19.17	12.990
3,000	41.71	33.31	19.98	19.12	12.590
2,500	41.65	33.23	19.84	19.07	12.320
2,000	41.58	33.14	19.75	19.01	12.300
1,000	41.14	33.05	19.50	18.98	12.298

5. CONCLUSION

Our investigation into BLDC motor speed control, employingTHD analysis with PI, fuzzy logic, ANFIS, and the hybrid ANFIS-PD/PI controller, has yielded valuable insights into motor control technology. The project's objective was to deepen our comprehension of BLDC motor speed characteristics and assess diverse control methodologies for their efficacy. Through rigorous experimentation and analysis, distinct strengths and limitations of each controller emerged. PI control, a conventional method, demonstrated stability but lacked adaptability. Fuzzy logic, while adaptable, faced challenges in precision. ANFIS exhibited promising adaptive capabilities. The standout performer was the hybrid ANFIS-PD/PI controller, seamlessly blending ANFIS adaptability with the stability of PD/PI techniques. It excelled in speed accuracy, disturbance rejection, and THD reduction, presenting a compelling solution for optimizing BLDC motor speed control, especially in applications requiring precision. In the broader motor control context, our project contributes significantly by showcasing the hybrid controller's advantages and offering practical guidance for controller selection based on application requirements. As demand for precise motor control grows across industries, our findings pave the way for advancements in BLDC motor control, benefiting fields like robotics, electric vehicles, and industrial automation. The ANFIS-PI controller, as evidenced by THD values, outperformed conventional controllers, affirming its superior performance in regulating motor speed.

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