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# Performance Analysis of ANFIS-PID Controller based Speed Regulation and Harmonic Reduction in BLDC Motor Application

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**ABSTRACT-** This study focuses on assessing the performance of a Proportional-Integral-Derivative (PID) controller integrated with an Adaptive Neuro-Fuzzy Inference System (ANFIS) in the context of speed regulation and harmonic reduction in Brushless DC (BLDC) motor applications. Rising BLDC motor speed elevates Total harmonic distortion (THD) due to non-linearity. THD reduction is vital for efficiency, reliability, and compliance in applications like electric vehicles, HVAC, and industrial automation, ensuring optimal performance and longevity. Through simulation-based design and implementation, the effectiveness of the ANFIS-PID controller is evaluated for achieving precise speed control and reducing harmonic distortions in a virtual environment. Various conventional control topologies are considered, with the ANFIS-PID controller demonstrating superior performance. The synergy of adaptive fuzzy logic and classic control components allows the ANFIS-PID controller to outperform others, particularly in dynamic conditions and varying motor characteristics, offering enhanced speed regulation and harmonic reduction in BLDC motor applications. Detailed simulations in MATLAB/Simulink software thoroughly assess the controller's dynamic response and its ability to accurately regulate BLDC motor speed while concurrently reducing harmonic distortions.

**Keywords:** BLDC Motor, Speed Controller, Current Controller, ANFIS-PID Controller, Power Quality, Harmonic Distortions.

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## 1. INTRODUCTION

Brushless DC (BLDC) motors are widely embraced across diverse applications due to their efficiency and reliability. The speed characteristics of BLDC motors are pivotal in determining their performance in various operational scenarios. As defined in [1], a "Brushless DC (BLDC) motor" is a specific type of DC motor utilizing electronic commutation instead of brushes. The permanent magnet within a BLDC motor manifests a trapezoidal back electromotive force (EMF) [2]. BLDC motors offer advantages such as high efficiency, compact dimensions, and reduced noise [3], making them preferred for fans and high-end pumps. [4] Suggests using hall position sensors in a closed-loop system to regulate BLDC motor speed. Jianwen Shao [5] introduced a direct back-EMF-sensing method in 2006, eliminating duty-cycle restrictions during high-side-switch PWM on-time. J. X. Shen and K. J. Tseng [6] presented equations in 2003 for error calculation related to motor parameters and load. Mohamed A. Awadallah et al. [7] proposed two approaches in 2005 for automated identification of inter-turn short circuits in CSI-powered PM BLDC motors. Work by K. Wang, M. A. Rahman, and J. X. Shen in 2010 aimed to improve third harmonic back-EMF through stator topology changes [8].[9]-[10] extensively discusses tuning techniques for the PI controller, advocating a trial-and-error approach to determine its parameter gain for achieving desired outcomes, as suggested in [11]. Despite the accuracy of output parameter values with fuzzy logic controllers, it's crucial to note that the mentioned controllers have not consistently regulated speed or adequately reduced harmonic distortions, impacting overall power quality within the system [12]-[13]. As the speed of a BLDC motor rises, Total Harmonic Distortion (THD) increases due to factors like non-linearity's and switching losses. THD reduction is vital in BLDC motor applications for enhanced efficiency, smoother operation, reduced electromagnetic interference, prolonged lifespan and regulatory compliance. Controlling THD ensures optimal performance, minimizes energy losses, and maintains reliability, crucial in diverse applications like electric vehicles, HVAC systems, and industrial automation where BLDC motors are prevalent. Efficient THD management enhances system integrity, mitigates operational disruptions, and promotes cost-effective, sustainable utilization of BLDC motors in various sectors. To address the challenges mentioned, this research proposes an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based controller for BLDC motor speed regulation. A comparative study in [14] evaluates the effectiveness of a fuzzy

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controller, a mathematical model, and an ANFIS controller for BLDC motor control. Torque ripple reduction is explored in [15] using a torque controller with unconventional back EMF and [17] employs *dq* reference frame and indirect stator flux control. Speed control via a Hall Effect sensor is discussed in [16]. This study emphasizes hybrid PD-ANFIS and PI-ANFIS controllers, with the ANFIS-PID controller emerging as superior, providing precise and responsive speed regulation with reduced harmonic distortions in dynamic conditions and varying motor characteristics [14, 15, 16, 17]. This research investigates the ANFIS-PID controller's efficacy in regulating speed and reducing harmonics in BLDC motors. ANFIS-PID merges adaptive neuro-fuzzy inference and PID control, promising enhanced motor performance and energy efficiency. Such advancements are pivotal for industries relying on BLDC motors for precise and reliable operations. The research structure comprises an introduction *(Section-1)*, system configuration evaluation *(Section-2)*, existing and proposed controllers *(Section-3)*, simulation results and discussion *(Section 4)*, and research conclusion *(Section 5)*.

## 2. SYSTEM CONFIGURATION

The research detailed in Lu H et al. (2008) and Yashoda M et al. (2016) compares the effectiveness of a fuzzy controller and a mathematical model of a BLDC motor controlled by an ANFIS controller. The mathematical model assumes uniform phase resistance, consistent inductances, ideal power semiconductor device characteristics, minimal iron losses, and an unsaturated motor.

*Figure 1* illustrates the BLDC servomotor drive system circuitry, providing a visual representation of the established mathematical model. The system includes a primary DC source, transformed into AC through an inverter. Speed regulation provides switching signals to the inverter circuit. Different controllers, outlined in subsequent sections, are employed to regulate this speed. These controllers play a crucial role in maintaining optimal performance and efficiency of the system. Detailed descriptions of these controllers and their functions are provided in the following sections for comprehensive understanding and implementation within the system.

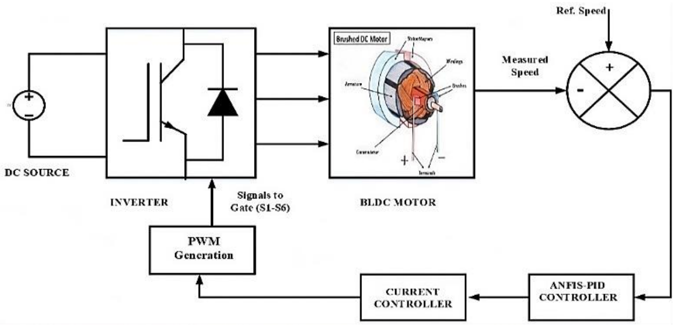



**Figure 1:** Schematic Representation of proposed System

The voltage equations for line-to-line configurations are succinctly represented using matrix expressions as follows:

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

The currents in phases a, b, and c are $i_a$, $i_b$, and $i_c$, while the reverse EMFs are $e_a$, $e_b$, and $e_c$. Self- and mutual-inductance per phase are denoted by L and M, and stator winding resistance per phase is R. The motor's electromotive force (EMF) is expressed mathematically as:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} = K_t I \quad (2)$$

Considering the torque constant ($K_t$) and angular velocity in radians per second, the equation becomes $i_a = i_b = i_c = I$, maintaining equilibrium between torques from inertia and the imposed load.

$$T_e = T_L + \frac{J_M d_\omega}{dt} + B_M \omega \quad (3)$$

Load torque ($T_L$), inertia ($J_M$), and frictional constants ($B_M$ and $B_L$) are represented in BLDC servomotors. Alternative expressions for load torque considering friction and load inertia are as follows:

$$T_L = J_L \frac{d\omega}{dt} + B_L \omega \quad (4)$$

The motor's generated output power is given by

$$P = T_e \omega \quad (5)$$

$$E = e_a = e_b = e_c = K_b \omega \quad (6)$$

In BLDC servomotor systems, essential parameters like back electromotive force (EMF) denoted as E, the back EMF constant ($K_b$), and angular velocity (ω) are pivotal. Additional critical motor parameters encompass phase inductance, phase resistance, load inertia ($J_M$), load friction ($J_L$), load damping ($B_M$), and load friction ($B_L$). Changes in parameters such as R, $J_M$, $J_L$, $B_M$, and $B_L$ directly influence the BLDC system's speed response. Previous attempts with controllers like PI, FLC, ANFIS, ANFIS-PD, ANFIS-PI, and PID have shown unsatisfactory results in maintaining good power quality. To address this, a novel topology, the ANFIS-PID controller, is introduced for improved performance, as described in the following sections.

## 3. PROPOSED ANFIS-PID CONTROLLER

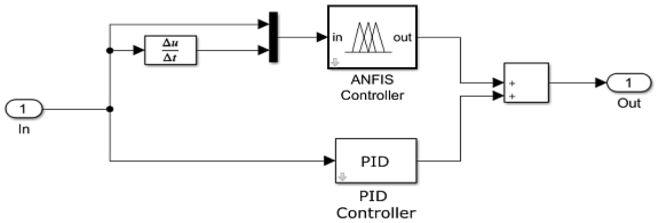



**Figure 2**. Simulink model of ANFIS-PID controller

The ANFIS-PID controller, illustrated in *figure-2*, seamlessly integrates ANFIS with PID control.

Fuzzy logic generates linguistic rules, refined by a neural network through training data, while the PID algorithm computes control signals based on the current error, accumulated past errors, and anticipated future error rate. Operating in a closed-loop system, the controller continuously adjusts the BLDC motor's speed to match a desired set point. The ANFIS adapts its fuzzy logic rules based on the error signal, leveraging historical data for enhanced responses.

## 4. SIMULATION BASED RESULTS

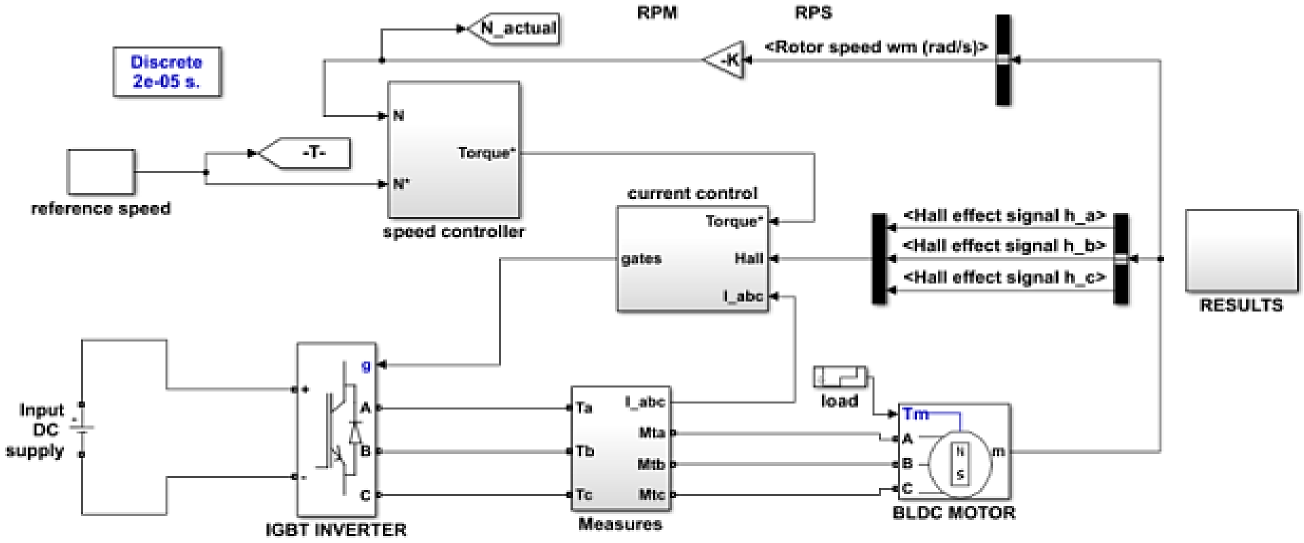
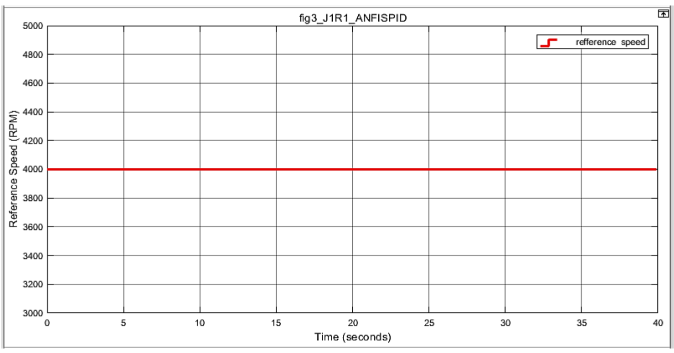


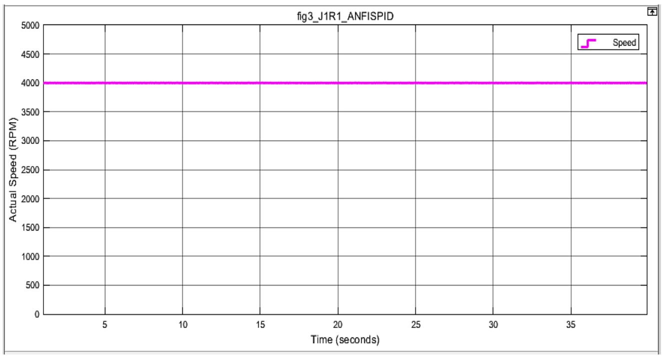

**Figure 3**. Simulink Mode of Proposed System

Simulation results affirm the ANFIS-PID controller's effectiveness in BLDC motor speed control.

The proposed circuit, illustrated in *figure-3*, is supplied with a 20V DC input. Since the BLDC motor requires AC power, an inverter is employed to convert the DC supply. Speed regulation, utilizing controllers like PI, FLC, ANFIS, ANFIS-PD, ANFIS-PI, and ANFIS-PID, generates switching pulses for the inverter. The regulated current, serving as the basis for the Hysteresis controller, directs the switching pulses to the Inverter Circuit. System responses are recorded and analyzed under various operational conditions, including speed changes, load disturbances, BLDC servomotor's phase resistance modifications, and system inertia changes, assessing controller performance across different speed ratings and load scenarios.




(a)

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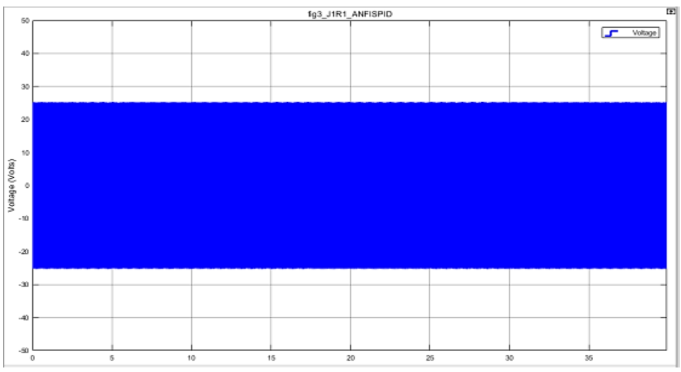


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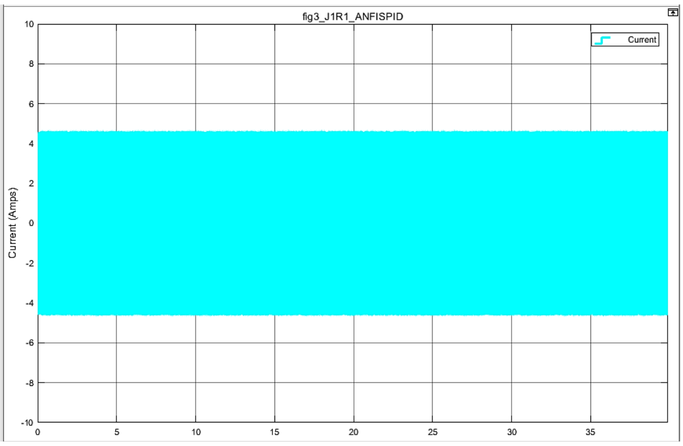
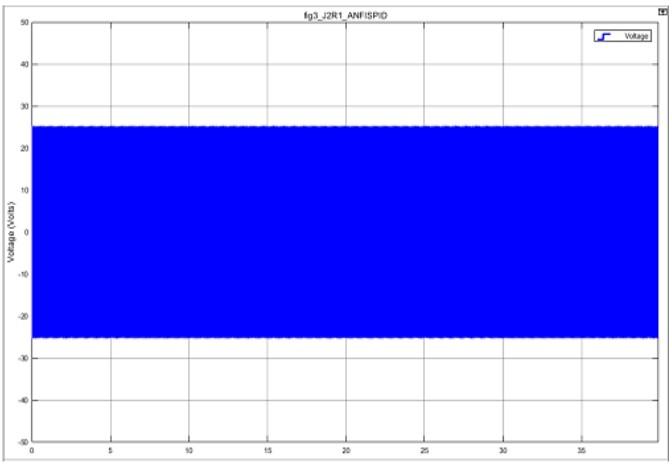



(d)

**Figure 4.** Case-1 $J_1R_1$ NO LOAD condition Results (a) Reference Speed (b) Actual Speed (c) Voltage (d) Current

In this case-1, the system performance is evaluated at No-Load Condition with $J_1R_1$ whereas $J_1$ = 350e-6 kg-m$^2$ and $R_1$ = 0.57 Ω depicted in *fig 4(a-d)*. Reference speed is considered as Constant *i.e.*, 4000 rpm and the obtained measured speed is similar to the speed of reference. But the settling time of this ANFIS-PID 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 5A, but it has the reduced harmonic distortions compared to the other controllers.

The same findings have been evaluated for another two cases under same conditions with same reference speed and actual speed taken for Case-1, considering Case-2 as $J_2R_1$ ($J_1$ = 560e-6 kg-m2, $R_1$ = 0.57 Ω) and Case-3 as $J_2R_2$ ($J_2$ = 560e-6 kg-m2, $R_2$ = 1.14Ω) depicted in *fig-5(a-b)* and in *fig-6(a-b)* respectively. The obtained THD value for these cases is shown in the below comparison *table-2*.




(a)

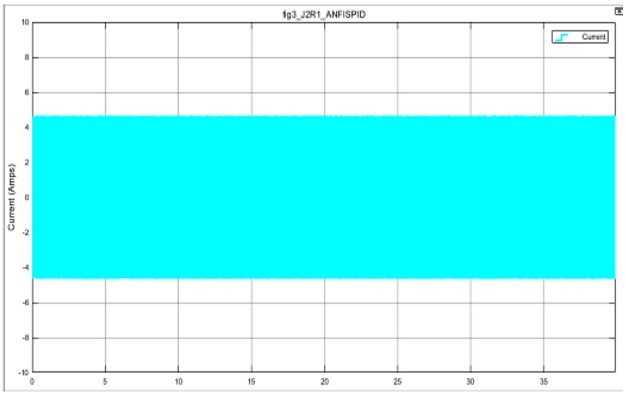



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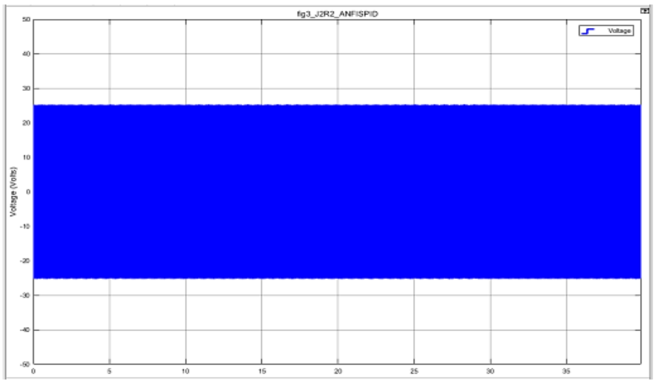
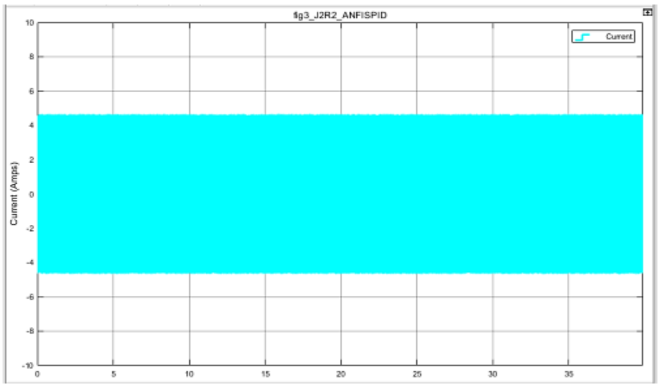
**Figure 5**. Case-2 $J_2R_1$ NO LOAD condition Results (a) Voltage (b) Current




(a)




(b)

**Figure 6**. Case-3 $J_2R_2$ NO LOAD condition results (a) Voltage (b) Current

In Case-4, the system is assessed under Full Load Condition with $J_1R_1$ ($J_1$ = 350e-6 kg-m2, $R_1$ = 0.57Ω) in *fig-7(a-e)*. The reference speed varies from 1000 to 2500 to 4000 to 2500 to 1000 rpm. The measured speed matches the reference, and the speed regulation (error) is depicted in the simulation results. However, the settling time for this ANFIS-PID system is higher compared to other conventional controllers. The inverter output voltage is 25V, with 5A current amplitude and reduced harmonic distortions, as indicated by the THD value in Comparison *table-2.*

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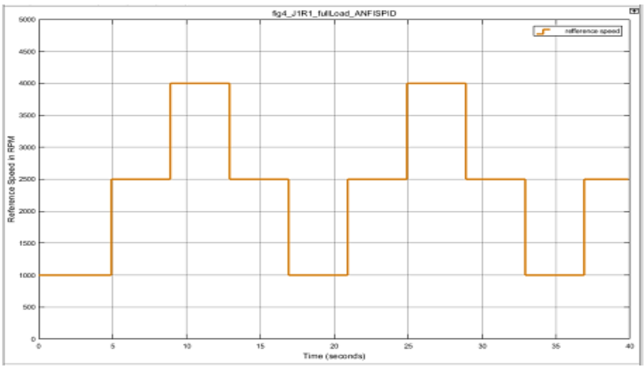


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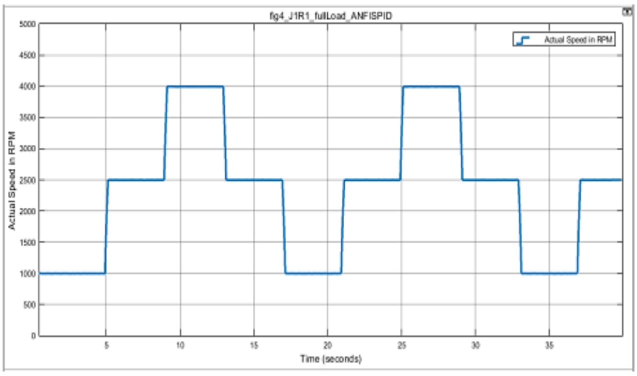


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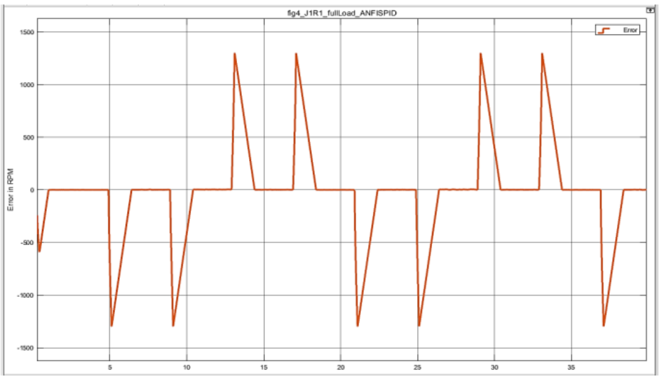


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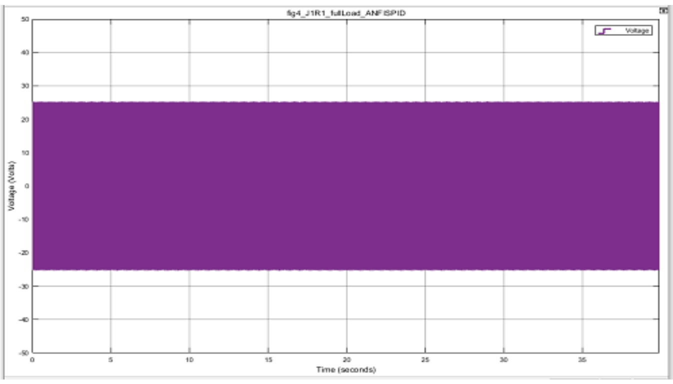


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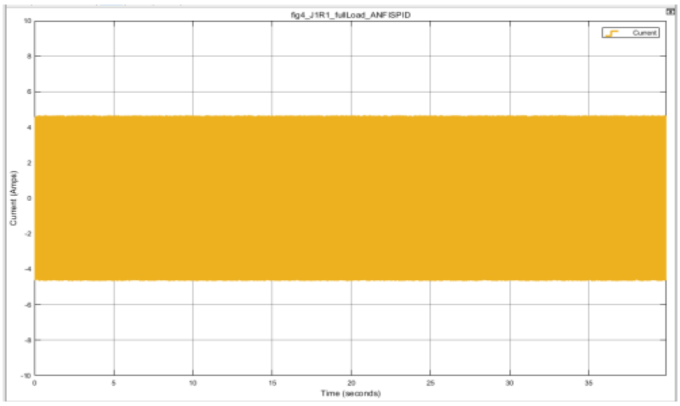
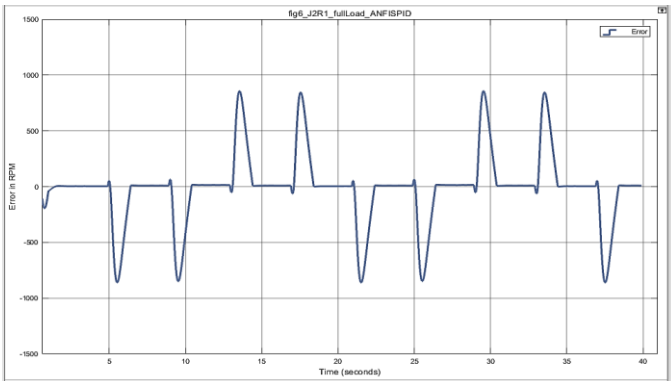


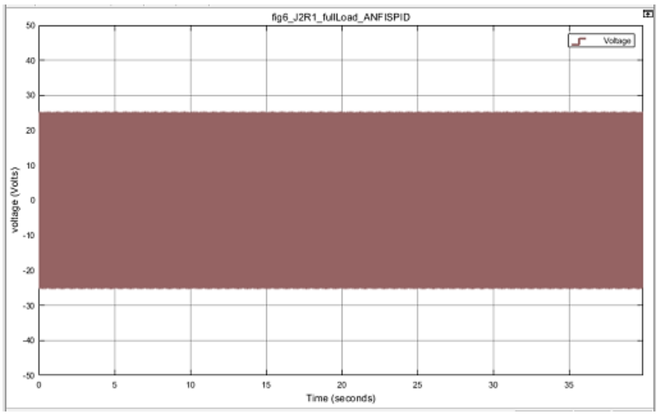

(e)

**Figure 7.** Case-4 $J_1R_1$ FULL LOAD condition results (a) Reference Speed (b) Actual Speed (c) Error (d) Voltage (e) Current

The same findings have been evaluated for another two cases under same conditions with same reference speed and actual speed taken for Case-4, considering Case-5 being as J2R1 (J2 = 560e-6 kg-m2, R1 = 0.57 Ω) and Case-6 as J2R2 (J2 = 560e-6 kg-m2, R2 = 1.14Ω) depicted in *fig-8(a-c)* and in *fig-9(a-c)* respectively. The obtained THD value for these cases is shown in the below comparison *table-2*.




(a)

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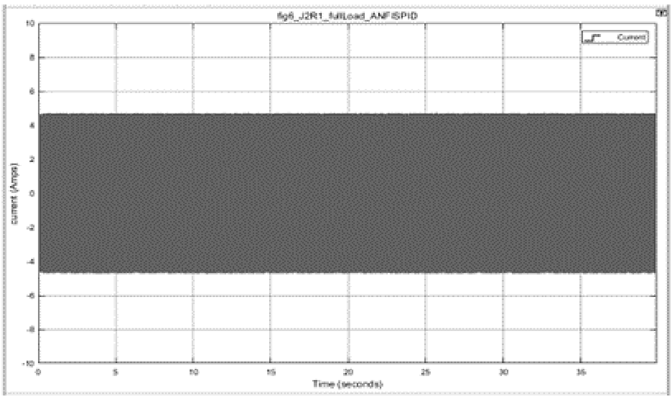
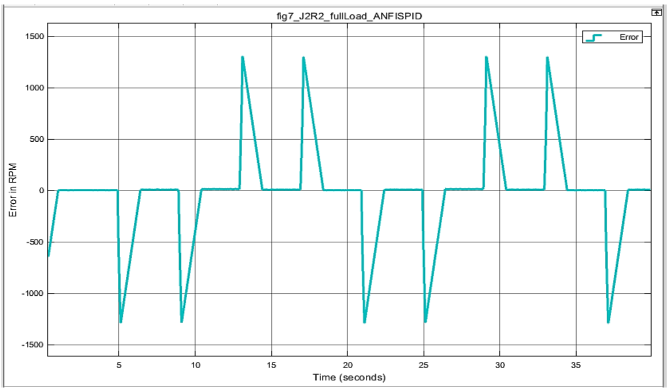
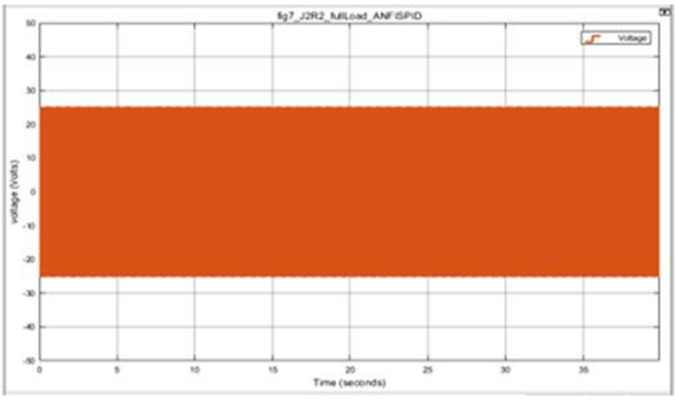



(c)

**Figure 8.** Case-5 $J_2R_1$ FULL LOAD condition results (a) Error (b) Voltage (c) Current




(a)

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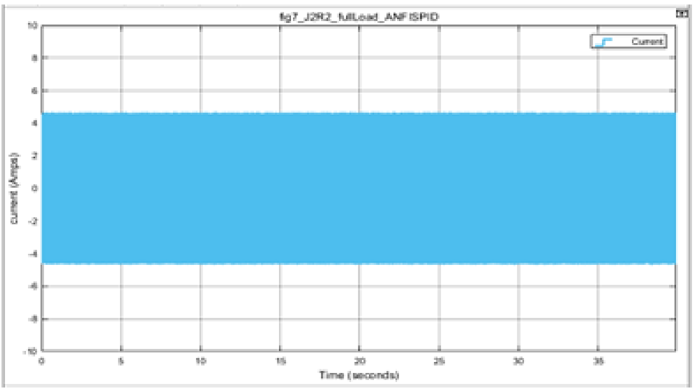


(c)

**Figure 9.** Case-6 $J_2R_2$ REDUCED LOAD condition results (a) Error (b) Voltage (c) Current

## 4.1. THD Vs Speed Characteristics

This study evaluates the system's performance at varying speeds (4000-1000 rpm), as shown in *table-1*. The speed directly correlates with the obtained Total Harmonic Distortion (THD). Notably, the ANFIS-PID-based system consistently outperforms other conventional controllers, demonstrating superior speed regulation and enhanced power quality even at increased speeds.

**Table 1. THD Vs Speed Characteristics**

| 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 | %THD With ANFIS PID Controller |
|---|---|---|---|---|---|---|---|
| 1 | J1R1 No Load | 41.86 | 33.34 | 19.59 | 15.20 | 12.36 | 11.60 |
| 2 | J2R1 No Load | 69.03 | 34.72 | 25.46 | 15.67 | 13.25 | 12.25 |
| 3 | J2R2 No Load | 59.28 | 34.01 | 22.06 | 15.94 | 12.99 | 12.00 |
| 4 | J1R1 Full Load | 41.86 | 33.49 | 20.12 | 19.21 | 13.66 | 12.29 |
| 6 | J2R1 Full Load | 69.03 | 34.08 | 23.21 | 19.24 | 14.32 | 13.25 |
| 7 | J2R2 Full Load | 59.28 | 33.84 | 20.99 | 19.72 | 13.68 | 12.08 |

## 4.2. Comparison table of the current THDs with all controllers

In the comparison *table-2* 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 2. Comparison table of the current THDs with all controllers**

| CONTROLLER / SPEED | % THD With PID Controller | % THD With FLC Controller | % THD With ANFIS Controller | % THD With ANFIS PD Controller | % THD With ANFIS PI Controller | % THD With ANFIS PID Controller |
|---|---|---|---|---|---|---|
| 4000 | 41.86 | 33.49 | 20.12 | 19.21 | 13.66 | 12.29 |
| 3500 | 41.76 | 33.4 | 20.07 | 19.17 | 12.99 | 12.19 |
| 3000 | 41.71 | 33.31 | 19.98 | 19.12 | 12.59 | 11.97 |
| 2500 | 41.65 | 33.23 | 19.84 | 19.07 | 12.32 | 11.64 |
| 2000 | 41.58 | 33.14 | 19.75 | 19.01 | 12.30 | 11.37 |

## 6. CONCLUSION

The performance analysis of the ANFIS-PID controller in simulating speed regulation and harmonic reduction in BLDC motor applications has provided valuable insights. The study effectively demonstrated the hybrid controller's efficacy in achieving precise speed regulation while concurrently reducing harmonic distortions. As the need for precise motor control continues to rise across various industries, our research outcomes present significant opportunities for advancing BLDC motor control technology. These advancements hold promise for enhancing performance in sectors such as robotics, electric vehicles, and industrial automation. The adaptive learning capabilities of ANFIS, integrated with the established PID control structure, played a crucial role in adapting to dynamic operating conditions. This unique fusion ensures unparalleled precision and responsiveness. Compared to other controllers, the ANFIS-PID hybrid excels in dynamically adapting to varied motor conditions, achieving superior speed regulation and harmonic reduction. This makes it an optimal choice for advancing Brushless DC motor applications, offering a remarkable balance between adaptability and stability. Simulation results underscored the controller's ability to optimize BLDC motor performance, showcasing improved speed regulation and reduced harmonic distortions in changing reference speeds, with implications for enhanced motor efficiency and reduced electromagnetic interference.

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