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Performance evaluation of BLDC motor drive mounted in aerial vehicle (drone) using adaptive neuro-fuzzy

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ABSTRACT

The development of autonomous drones equipped with cameras and various sensors has paved the way for their application in agriculture and perimeter security. These aerial drones require specific power, acceleration, high torque, and efficiency to meet the demands of agricultural tasks, utilizing built-in brushless DC (BLDC) motors. However, a common challenge drone’s face is maintaining the desired speed for extended periods. Enhancing the performance of BLDC motors through advanced controllers is crucial to address this issue. This research paper proposes optimizing the size and speed of brushless DC motors for aerial vehicles using an adaptive fuzzy inference system and supervised learning techniques. When these drones carry loads, the BLDC motors must dynamically adjust the drone's speed. During this phase, the motors must control their speed and torque using artificial intelligence controllers like adaptive neuro-fuzzy inference systems (ANFIS) to enhance the drone's functionality, resilience, and safety. This research has conducted analyses focused on improving the performance of BLDC motors explicitly personalized for unmanned aerial vehicle (UAVs). The proposed method will be implemented using MATLAB/Simulink, expecting to significantly enhance the BLDC motor's performance compared to conventional controllers. Comparative analyses will be conducted between traditional and ANFIS controllers to validate the effectiveness of the proposed approach.

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1. INTRODUCTION

Today, the use of small unmanned aerial vehicles (UAVs) in agriculture is expanding quickly. Drones are semi-automated machines that are gradually evolving into fully automatic machines. These machines have great potential for spatial data collection related to agriculture and planning. While modern drones are global positioning system (GPS) - based autonomous aerial vehicles, UAVs were the first remote-controlled devices flown by a pilot from the ground. The cameras, sensors, and controlling equipment will be different for the different types of drones like Fixed-wing, helicopter, and multi-copter, which come under the UAV group. In recent years, drones have gained attention due to their mechanical simplicity and extensive application in industries like aerial photography with a modest mission weight. However, various issues have arisen, as long-distance flights require heavy equipment [1]. In these types of applications, the built-in brushless DC (BLDC) Motor is mounted to the aerial vehicles so that the speed of the machine needs to be controlled as per the load distribution. The recent technology has extended aerial vehicle time as much as feasible through drone lightning and effective BLDC motor control. Therefore, there is a need to develop associated technologies if a drone cracks, leading to motor destruction that results in significant financial losses [2], [3]. Additionally, research is being conducted to enhance the drone's size to carry significant mission weights such as courier and pesticide spraying. Recently, drones have been used in many areas, including surveillance, agriculture, and logistics [4]. The logistics industry is expected to actively adopt the drone delivery service in the future due to its capacity for cost reduction and quick delivery. Furthermore, employing drones is a crucial part of precision agriculture, which boosts agriculture for pesticide application [5], [6]. In recent years, the BLDC motor stator manufacture involved automating the winding of copper wires on the stator core using various techniques. Due to the stator core's small size and the use of a copper conductor with a narrow diameter, the automation process is challenging in the case of an ultra-compact BLDC motor.

The BLDC speed can be controlled using a variety of control techniques. Traditional control methods were employed with proportional-integral-derivative (PID) and proportional-integral (PI). These controllers are well known for their fast response, short settling and fast rising times, reduced overshoot, and low affordable prices. The most significant disadvantage is that the system reaction slows when the desired value changes due to these controllers under dynamic load conditions [7]–[9]. According to the literature review, multidisciplinary research in electrical, electromagnetics, electronics, and mechanics is required to look at UVA mounted with electric motors applications. This proposed methodology proposes a design for an artificially intelligent unmanned aerial vehicle. The fuzzy logic controller (FLC) membership rules must provide control signals to solve the system more quickly than traditional control methods like PI and PID [10]–[12]. The neural networks will test and train the input data to ensure the system is accurate.

When this control technique is applied to dynamic systems, the online tuning of gains employs intelligent control mechanisms. These combinations ensure excellent performance with improved steady-state response, rise and settling time, and minimal overshoot [13]. Fuzzy logic neural networks were used in designing and developing the adaptive neuro-fuzzy inference systems (ANFIS) controllers for the brushless DC motor (BLDCM), which will be mounted in aerial vehicles to increase the speed and torque. The fuzzy inference systems (FIS) and artificial neural networks (ANN) are combined with the concepts of the intelligent control system by the ANFIS controllers. The neural network's hidden layers will serve as membership functions for rules in the fuzzy control. The fuzzy logic controller develops the membership functions with the help of IF-THEN rules. To manage the speed and torque of the BLDC motor, the projected ANFIS controllers are finally applied to practice. MATLAB/Simulink is used to design and characterize the performance of ANFIS controllers of BLDC motors [14]–[16].

2. LITERATURE SURVEY

In this paper author have explained that a Swiss startup business designed, commercialized, and piloted the first authorized drone system to apply pesticides in Europe automatically. The article's main point is that sprayer drones make the air relevant for agricultural activities and processes in unique, fundamentally valuable, and commercially viable ways. The authors presented in [1], [3], and [17] that the impressive performance of unmanned aerial vehicles (UAV) in various commercial and military applications subjected to rotor control of the motor. The UAV's rotors are necessary to ensure stability and safe flight while carrying out its desired load. The BLDC motor has a significant impact on regulating the UAV's dynamics and performance.

The authors have define about the drones [2] are as used for external control in agriculture using cameras, different sensors, and autonomous flight capabilities. But flying with heavy equipment makes it challenging to fly for an extended period. Therefore, improving the flying time by making the drone lighter and effectively controlling the BLDC motor. This means that the motor dissipates most of the energy during drone flying needs improvement. The motor winding should be automated with copper using various techniques to overcome this issue. Then the weight of the motor becomes light and becomes more effective. The brushless DC motors, compared to conventional motor drives, are more complex to build, efficient, quieter, and reliable. It has a facility for its multivariable system, nonlinear control, and robust coupling system. To increase power factor and reduce switching losses, this research suggests designing neuro-fuzzy controllers for switching multiple converters. Compared to traditional controllers, this controller will improve in reducing current ripples in time and torque. The proposed ANFIS is now trained to deliver the required control commands by modifying the fuzzy membership functions.

3. BLDC MOTOR MATHEMATICAL MODEL

Figure 1 shows that BLDC motor windings provide the electromagnetic field (EMF) in the shape of the trapezoidal magnetic field created by the concept of mutual induction. A similar three-phase BLDC motor equivalent circuit is also shown in Figure 2. According to from (1) to (14) have been derived for the Figure 2. In addition, Figure 1 shows the rotor's back-induced EMF and correlations.

$$V_{ab} = R(i_a - i_b) + (L - M)\frac{d(i_a - i_b)}{dt} + e_{ab} \quad (1)$$

$$V_{bc} = R(i_b - i_c) + (L - M)\frac{d(i_b - i_c)}{dt} + e_{bc} \quad (2)$$

$$V_{ca} = R(i_c - i_a) + (L - M)\frac{d(i_c - i_a)}{dt} + e_{ca} \quad (3)$$

$$\frac{di_a}{dt} = \frac{R}{L}i_a + \frac{2}{3L}(V_{ab} - e_{ab}) + \frac{1}{3L} + (e_{bc} - e_{bc}) \quad (4)$$

$$\frac{di_b}{dt} = \frac{R}{L}i_b + \frac{2}{3L}(V_{ab} - e_{ab}) + \frac{1}{3L} + (e_{bc} - e_{bc}) \quad (5)$$

According to (1) and (5) can be represented in the spate space representation of the BLDC motor, and the new equations can be written as (6) to (8). The torque equation for the three-phase BLDCM is written as (9).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + (L - M)\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \psi_e \omega_m \begin{bmatrix} f(\phi_e) \\ (\ \phi_e - \frac{2\pi}{3}) \\ f\left(\pi_e + \frac{2\pi}{3}\right) \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} T_a \\ T_b \\ T_c \end{bmatrix} = \tau_t i_a \begin{bmatrix} f(\phi_e) \\ (\ \phi_e - \frac{2\pi}{3}) \\ f\left(\pi_e + \frac{2\pi}{3}\right) \end{bmatrix} \quad (8)$$

$$T_e = T_a + T_b + T_c \quad (9)$$

The peak stator current is an electric source to control the closed loop. A field weakening control block using the reactive power and the current square waveform of a BLDC motor is shown in Figure 1. Figure 3 displays the overall system block diagram for the BLDC motor's speed regulation. The ANFIS controllers are designed to estimate the speed of the BLDC motor through the outer loop, and the inverter is employed in the inner loop. The speed regulation equations of the BLDCM can be written as (10), and the flux produced in the BLDC motor can be expressed as (11).

$$T_e - T_l = J\frac{d\omega_m}{dt} + \mu_f + \omega_m \quad (10)$$

$$\phi_e = \frac{P}{2}\varphi_m \quad (11)$$

The EMF weakens in the motor due to poor current, torque, and dynamic speed. Therefore, the stator current is on the d-axis, and the reactive power is on the q-axis. The stator current opposing the electromotive force is also computed. The above BLDC motor equations are written as state-space representations and shown in (12) and (13).

$$\begin{bmatrix} i_a \\ i_b \\ \omega_m \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{\mu_f}{J} \end{bmatrix} + \begin{bmatrix} i_a \\ i_b \\ \omega_m \end{bmatrix} + \begin{bmatrix} \frac{2}{3L} & \frac{1}{3L} & 0 \\ -\frac{1}{3L} & \frac{1}{3L} & 0 \\ 0 & 0 & \frac{1}{J} \end{bmatrix} \begin{bmatrix} V_{ab} - e_{ab} \\ V_{bc} - e_{bc} \\ T_e - T_l \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \\ \omega_m \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -1 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ \omega_m \end{bmatrix} \quad (13)$$

Figure 1 depicts a typical BLDC motor for unmanned aerial vehicles. Electric motors with brushless DC drives (BLDC) are renowned for their outstanding efficiency, dependability, and high-power density. The block diagram of the BLDC Motor is shown in the Figure 3. However, the limitations of BLDC motors include complicated motor control due to the magnets. The speed rotation and the torque relationship are shown in Figure 4. Figure 5 illustrates how brushless D.C. motors may have an inner or outer rotor structure. First, the difference in rotating inertia between the outer and inner rotors reduces torque ripple, which offers stability and smooth functioning even at low speeds. Second, an external BLDC rotor's outside diameter is frequently more critical than an internal rotor design [18].

The exterior design also features a more significant air gap region, enabling more force production. The method of the BLDC Motor with the suitable winding structure is shown in Figure 5. A Hall Effect estimator, which has two functions, is used in the process. First, the inverter detects the position of the rotor and uses it as a switch for communication and a position estimator.

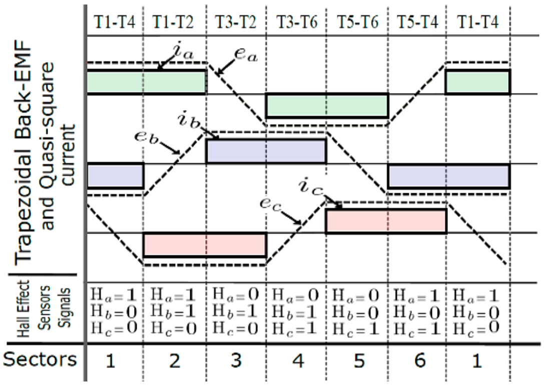


Figure 1. Trapezoidal EMF with the hall sensor pattern

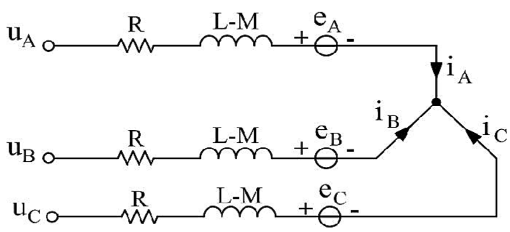


Figure 2. Equivalent circuit of 3-phase BLDCM

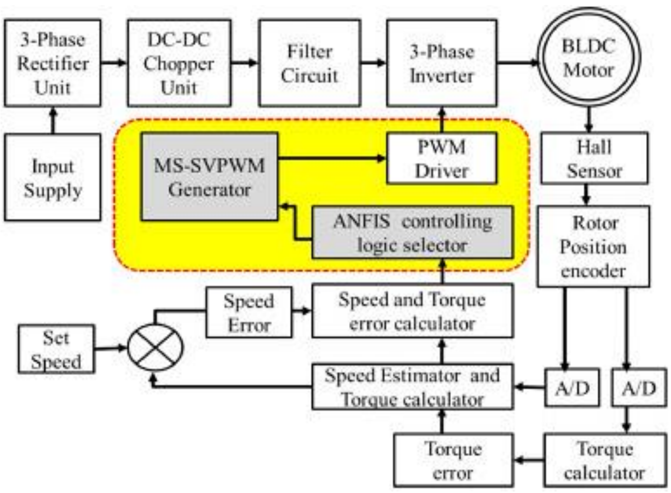


Figure 3. Overall system block diagram in BLDC motor

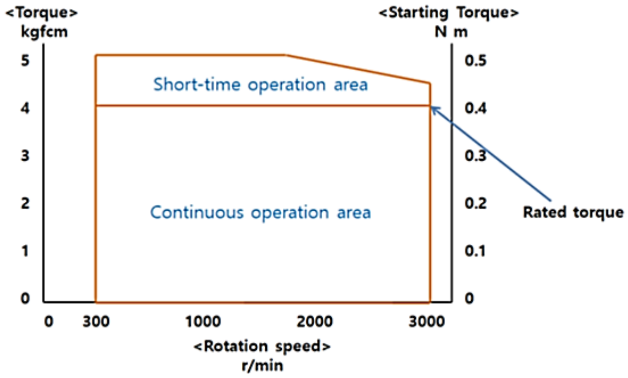


Figure 4. Rotation speed concerning the torque of the BLDC motor

Figure 5. Design of BLDC motor for unmanned aerial vehicles

4. PROPOSED ANFIS-BASED CONTROL

A network design consists of fixed node links by which nodes have been connected with an adaptive network. Moreover, nodes have been adaptable overall in the system. Every layer's output depends on node-related factors and the rule of learning how these factors must be changed to reduce the predefined error measure, which is shown in Figure 6.

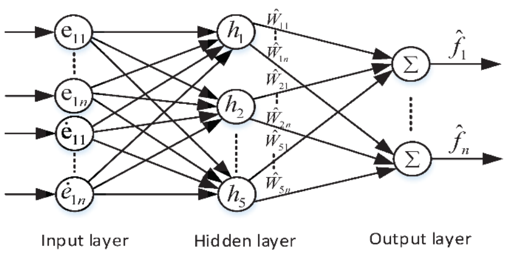


Figure 6. Adaptive neural network

The controller structure comprises five layers which are illustrated in [19], [20]:

- Layer 1 is known as the input layer, and its function is to *i* and is written as (14) and (15).

$$O_i^1 = \mu_{Ai}(x)\ \forall\ i = 1,2 \quad (14)$$

$$O_i^1 = \mu_{Bi}(y)\ \forall\ i = 3,4 \quad (15)$$

where μ_{Ai}, μ_{Bi} , are the variables for the A_i and B_i, and O_i^1 is the triangular shape of the function.

- Layer 2: This layer is the rule node, and its output is the product of its two inputs from layer 1. Through this layer, the weight of the two inputs is determined in (16) so that:

$$W_i = \mu_{Ai}(x)\ \mathrm{X}\ \mu_{Bi}(y)\ \forall\ i = 1,2 \quad (16)$$

- Layer 3: The normalized ring strength is derived using the average nodes (17), so N is as:

$$\overline{W_i} = \frac{W_i}{W_1+W_2}\ \forall\ i = 1,2 \quad (17)$$

- Layer 4: This layer generates the product of the two inputs. The linear function of the input signals x and y, one of the nodes, is given by (18) and (19).

$$O_i^4 = \overline{W_i} Z_i = \overline{W}(p_i x + q_i y + r_i) \quad (18)$$

$$O_i^5 = \sum_i \overline{W_i}\, Z_i \quad (19)$$

- Layer 5: It is also referred to as the summation layer and is the final controller layer. Σ designates the single node, which is in charge of adding up all incoming signals.

The proposed ANFIS is now trained to deliver the required control commands by modifying the fuzzy membership functions. These membership options are chosen after many trial-and-error iterations or based on the designer's prior expertise [21]. Chain rule and gradient have been essential learning rules for adaptive networks. Furthermore, FLC is well-known for dealing with complex, non-linear, and well-characterized systems. However, ANN has proven reliable in speed, and adaption.

5. NEURO-FUZZY CONTROLLER FRAMEWORK

It has been sensible to use the integration to minimize the drawbacks of artificial intelligence controllers, leading to Neuro-fuzzy controllers. A hybrid architecture includes a hidden layer among the input and output nodes, which control and communicate the decision. Fuzzy interference, defuzzification, and fuzzification components are included in the controller architecture shown in Figure 7. In this article, NFC uses the E as a speed error and the rate of change in error (ΔE) as input signals in both cases, which were computed using a comparator [22]. Qualitative fuzzy has been applied using non-linear quantization and membership function to calculate the two input signals using the fuzzy technique membership function (MF).

MF is used in Figure 7 in this illustration. Insight-variable only possesses big negative (NB) and zero error (ZE) membership functions because of supervisory and adaption learning. The system evaluates the negative fuzzy controller (NFC) concert regarding error difference and error, and it generates a signal of pressure in the form of +1, [-1+1], and -1.

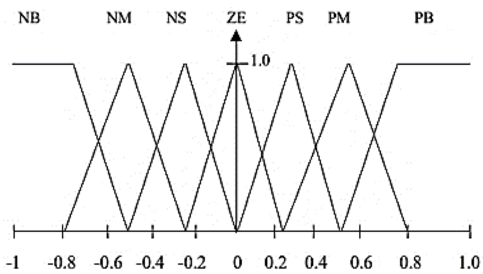


Figure 7. Input/output membership functions

5.1. Converter design for BLDC motor

The bidirectional DC-DC converter maintains a consistent DC voltage under various speed conditions while controlling the BLDC motor [23]. The algorithm creates the two current loops and keeps the DC voltage constant while generating the current reference I_{ref}. A PI controller is designed in the hybrid energy storage system (HESS) to build the current as the reference I_{ref}. The above table contains the equation created for reference current I_{ref} . Kp, and $K_{.I.}$ are the gains of proportional and integral, respectively. The value of the K_p, $K_{.I.}$ can be determined using the Ziegler-Nichols method. The reset flip-flop, or S.R., is the component that receives the controller's signal. Based on the reference current I_{ref}, the battery and supercapacitor will be operated by the controlled signal delivered in (20) by the reference current I_{ref}. The battery will be in the charging mode if the actual signal is less than I_{ref} and the discharging method if the current value exceeds I_{ref}. The speed control of the BLDC motor is the main theme of this paper [24].

$$I_{ref} = \left(K_P + \frac{K_I}{S}\right) \mathrm{X}\ \mathrm{V_{error}} \tag{20}$$

The PID controllers' tuning will decide the performance and speed efficiency of the BLDC motor. Therefore, the PID tuning will determine the ideal performance of the BLDC motor. In general, tuning the PID controllers is very difficult due to its rules and trial-error methods like the Ziegler Nichols method, which may take more time and damage the hardware during the process of controlling. Consequently, the ways that depend on rule-based systems will not support the delay in time. Due to these disadvantages in PID controllers.

6. RESULT ANALYSIS AND DISCUSSION

Electrical/mechanical restrictions and performance requirements are considered during the design phase. The "Kv" word should be identified since drone applications frequently employ it. "Kv" refers to the motor's constant rotational speed when the voltage is 1 V DC. The unit of "Kv" is rpm/V. When 1 V is supplied to an unloaded BLDC motor, the number of rotor rotations per minute is measured. The unloaded motor speed will be 11.1×500=5550 rpm if the battery voltage is 3S (3.7 V × 3=11.1 V) and the motor is a 500 Kv BLDC. The speed of the BLDC motor will drop when a propeller is used in an unmanned aerial vehicle. To overcome this, the stator and rotor of the motor should be the perfect design.

The parameters of the BLDC Motor is shown in Table 1. In this paper, we employed ANFIS controllers to build a self-adaptive NFC for the BLDC motor, which will be used in UAVs. The ANN and the fuzzy logic combination will be termed the ANFIS, which implements ANFIS architecture. The proposed controller associates the FLC and N.N. structure to design an intelligent UAV control system. The fuzzy rules and membership functions will be noted as nodes in the hidden layers. The prototype of the BLDC motor setup in UAV is shown in Figure 8 and simulated in MATLAB, which is shown in Figure 9. The suggested controller is initially built from the IF-THEN rule to the BLDC drive system. Figures 10 and 11 clarifies the performance of the BLDC motor drive with several controllers and is compared at various speeds. The reference speed in this simulation portion is low, from 0 to 0.35 seconds. At 0.35 seconds, the motor's rotor abruptly rises to a slight overshoot with the ANFIS, but the voltage increases steadily. This dynamic power increases by 0.6 at 0.05 seconds, causing the corresponding speed to reach its maximum and the reference torque to remain at 20 nm. When the active power maintains the constant, the speed of the BLDC motor will be uniformly increasing.

Table 1. Parameter of BLDC motor

Parameter	Value	Parameter	Value
Resistance of Stator R_s	2.65 ohm	Damping Viscus	0.01 Nm.sec
Inductance of Stator L_s	8.5 mh	Number of Poles	4
Voltage (V_{DC})	210 V	TL	0.7 [N.m]
Back EMF	50 V	HP	3
Inertia	7.5×10-3 Kgm.m^2	Rated Speed	3000 (RPM)

The performance of the BLDC motor based on different controllers is evaluated by time domain specification as in Table 2**.** It has been shown that ANFIS performs better than the other two methods. Additionally, it is claimed that when the UAV is coupled with the maximum load, the NFC and PID controllers reject load disturbance at different rates. It has been discovered that NFC is more robust than other controllers and rejects load disturbances better than PID controllers with reduced ripple. This work is evaluated from the references. According to the results, back EMFs have a higher harmonic content than phase-induced voltages, which resemble trapezoidal wave shapes. However, it is well known that phase voltages contribute significantly to torque ripple. Therefore, the back EMF waveforms are appropriate for this excitation type since the motor is designed to be actuated in a six-step pulse. BLDC motor rotation at various speeds is currently being tested with the speed controllers that were developed. Figure 10 illustrates the output responses of a BLDC motor that is not under load. The desired speed rises at a rate of 3350 rpm for 0.3 seconds after 0.4 seconds, then falls back to the predetermined level of 3000 rpm. ANFIS produces better performance compared to the traditional PID. The performance of the BLDC motor drive with NFC controller is shown in Figures 11(a)-11(c) when the reference torque is changed from low to high at different speeds. According to the input data, NFC provides a good reaction concerning optimized ripple. The NFC will notice that whenever the torque changes unexpectedly, the simulation results show an overshoot (in moments of a sudden change in speed) and will be minimized. Finally, three-phase BLDC motor voltages at various speeds and torques are noted. Recent development in agriculture applications shows that UAVs are an initial technology to increase agricultural productivity using aircraft. Manufacturing of stator of existing BLDC motors has automated the winding to optimize its core with a small diameter construction known as ultra-compact BLDC motors.

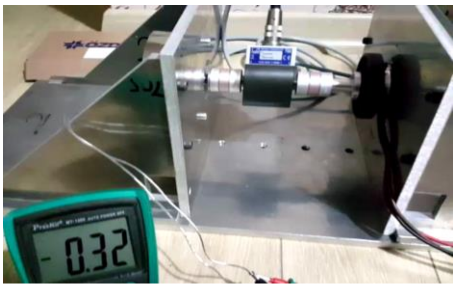


Figure 8. BLDC motor test setup (dyno) picture

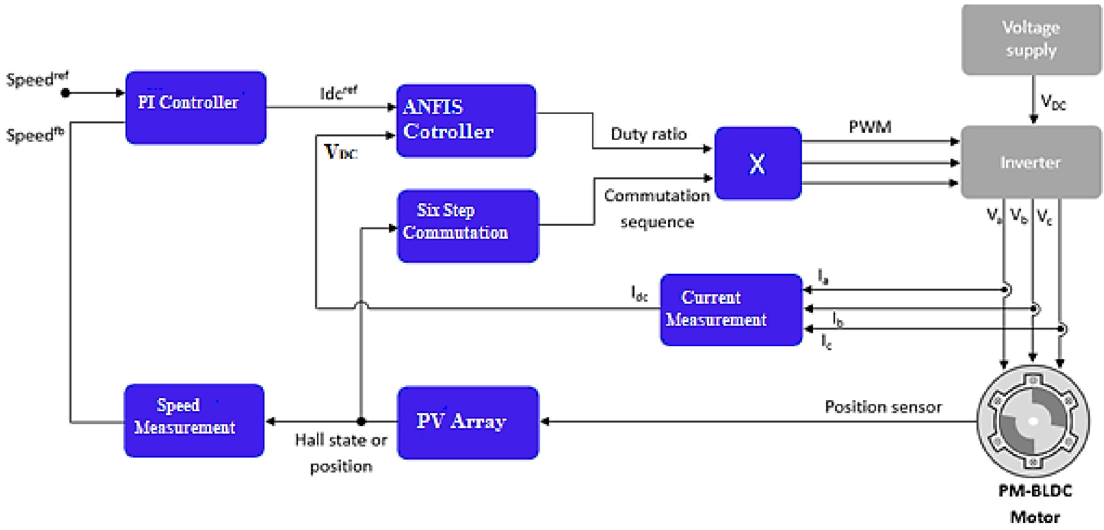


Figure 9. MATLAB design of ANFIS-based BLDCM

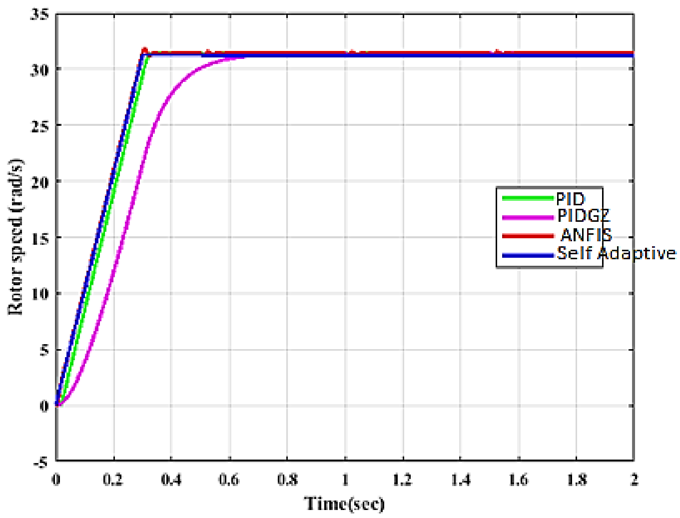
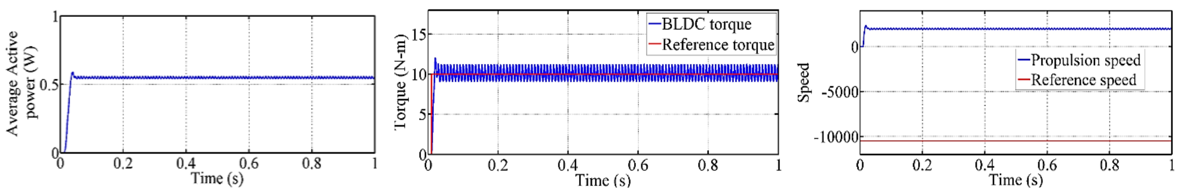


Figure 10. MATLAB designed output with ANFIS Controller for BLDC motor



(a) (b) (c)

Figure 11. Various parameter diagrams of BLDCM designed in MATLAB with ANFIS controller:
(a) active power, (b) reference speed and propulsion speed, and (c) reference torque and BLDCM torque

Additionally, motor manufacturers concentrate on speed and torque. The existing Arial vehicles are designed with fixed speed and torque. This paper proposes that the UAVs' performance has increased by increasing the speed and torque. Therefore, these issues must be resolved to enhance motor performance. During the dynamometer testing of the BLDC motor, a dynamic torque sensor and an electromagnetic power brake are employed as a passive load [25].

A typical six-step excitation voltage during the test has been conducted. The assessment is executed over a wide range of speed and torque to determine the motor and driver efficiency. The results show that the BLDC motor efficiency is optimized across a wide speed operating range, enabling it to attain the highest efficiency in unmanned aerial vehicle applications. The torque and current are optimized from this Table 2 for 0.1% variations.

Table 2. Comparison of the BLDC motor parameters with the various controllers

Parameters		GA	PSO	ANFIS*
Rise time	0-700 RPM	0.002	0.001	0
	700-900RPM	0.001	0	0
Settling time	0-700 RPM	0.016	0.011	0.002
	700-900RPM	0.002	0.001	0
Steady-state error	0-700 RPM	0.93%	0.96%	0.99%
	700-900RPM	0.93%	0.99%	0.99%
Startup torque	0-700 RPM	2.2 NM	1.2 NM	0.2 NM
	700-900RPM	0.8 NM	0.5 NM	0.1 NM
Start-up current	0-700 RPM	2A	1A	0.2A
	700-900RPM	0.5A	0.3A	0.1A
Speed variation		0.2%	0.1%	0.1%
Power factor		1	1	1
DC voltage		800 V_{dc}	850 V_{dc}	900V_{dc}

7. CONCLUSION

This proposed methodology presents the design and development of a brushless D.C. motor mounted on aerial vehicles with simulation. According to the simulation results, the suggested self-adaptive ANFIS enhances the brushless D.C. motor performance under various dynamic load conditions while ensuring stability in unexpected disturbances. This paper project proposes to build a 650 W, 3500 rpm, 225 KV, 5 kg BLDC motor. Since motors consume most of the battery's stored energy, the effectiveness of an unmanned aerial vehicle's overall system depends on the efficiency of the motor's energy conversion. Thus, increasing and optimizing BLDC motor efficiency throughout the test is essential. Also, the characteristic curves of the BLDC motor and propeller load should be considered jointly. The conclusions demonstrate that system efficiency may be achieved and the propeller works smoothly. Furthermore, this objective is accomplished throughout an extensive speed range, as verified by the simulation and experimental findings.

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