Design and Control of ESC-Driven BLDC Propulsion System for Quadcopter Drone

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***Abstract*—The design and control of an Electronic Speed Controller (ESC) driven Brushless Direct Current (BLDC) propulsion system for a quadcopter drone focuses on achieving stable flight, high efficiency, and precise manoeuvrability. In a quadcopter configuration, four BLDC motors are mounted symmetrically on a cross-frame structure, where each motor–propeller pair generates controlled thrust. The ESC plays a critical role by converting the DC supply from the battery into a three-phase AC signal required to drive the BLDC motor using high-frequency switching techniques such as Pulse Width Modulation (PWM). This project emphasizes the modelling, design, and implementation of a closed-loop control strategy to regulate motor speed and thrust based on pilot commands and onboard sensor feedback. The propulsion system integrates a lithium-polymer (Li-Po) battery, power distribution board, ESCs, BLDC motors, propellers, and a flight controller equipped with inertial sensors such as accelerometers and gyroscopes. A proportional–integral–derivative (PID) control algorithm is implemented in the flight controller to maintain roll, pitch, and yaw stability by dynamically adjusting individual motor speeds. The ESC firmware ensures rapid commutation, reduced switching losses, and thermal protection for reliable performance. System analysis includes thrust-to-weight ratio optimization, efficiency evaluation, and dynamic response testing under varying load conditions. The proposed system enhances flight endurance, improves response time, and ensures stable hovering and agile manoeuvring. By optimizing motor selection, ESC rating, and control parameters, the quadcopter achieves reliable propulsion performance suitable for surveillance, mapping, and autonomous navigation applications. This study demonstrates the practical integration of power electronics and control systems in modern unmanned aerial vehicle (UAV) technology.**

***Keywords*—Electronic Speed Controller (ESC), BLDC Motor, Quadcopter Drone, Propulsion System, Pulse Width Modulation (PWM), PID Control, Flight Controller, UAV Stability, Power Electronics, Thrust Optimization.**

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), particularly quadcopters, have gained significant attention in surveillance, mapping, agriculture, delivery systems, and defence applications. The performance of a quadcopter mainly depends on the efficiency and dynamic response of its propulsion system. A quadcopter consists of four Brushless Direct Current (BLDC) motors driven by Electronic Speed Controllers (ESCs), which regulate motor speed through high-frequency switching techniques. The propulsion system must provide sufficient thrust-to-weight ratio while ensuring stable roll, pitch, and yaw motion control.

BLDC motors are widely preferred over brushed motors due to their high efficiency, better torque-to-weight ratio, reduced maintenance, and longer operational life. The ESC acts as a power electronic interface that converts DC supply from a lithium-polymer (Li-Po) battery into three-phase AC signals required for electronic commutation. As reported in [1], proper motor–ESC matching significantly improves efficiency and reduces switching losses.

Accurate control of motor speed is achieved using Pulse Width Modulation (PWM) signals generated by a microcontroller-based flight controller. Closed-loop control algorithms such as Proportional–Integral–Derivative (PID) controllers are implemented to maintain flight stability. Optimized PID tuning improves quadcopter stabilization under disturbances [2].

A. BLDC Motor and ESC Operation

A BLDC motor operates on electronic commutation rather than mechanical brushes. It consists of a permanent magnet rotor and a stator with three-phase windings. The ESC generates sequential switching signals to energize stator windings based on rotor position feedback or sensorless back-EMF detection methods. The ESC receives throttle commands from the flight controller in the form of PWM signals. Based on the duty cycle of the PWM signal, the ESC adjusts the effective voltage applied to the motor, thereby controlling its speed. As per Zhang et al. [3], sensorless commutation reduces system complexity and weight in UAV applications. The efficiency of the propulsion system depends on switching frequency, MOSFET selection, thermal design, and current rating. Proper ESC rating prevents overheating and ensures reliable operation during high-load conditions.

B. Control Strategy for Quadcopter Stabilization

Quadcopter motion is controlled by varying the speed of individual motors. Roll, pitch, and yaw are achieved by differential thrust control. A closed-loop feedback system is implemented using data from an Inertial Measurement Unit (IMU) consisting of accelerometers and gyroscopes. The PID controller continuously compares desired orientation with actual orientation and generates corrective motor speed commands. According to [4], PID-based stabilization provides robust control with low computational complexity. The mathematical model of quadcopter dynamics is derived using Newton–Euler equations. Control inputs are mapped to motor angular velocities, ensuring stable hovering and smooth manoeuvrability.

II. LITERATURE SURVEY

Research on quadcopter propulsion systems has significantly expanded due to the growing demand for efficient and stable UAV platforms. Early studies by Pounds et al. explored the basic dynamics of quadrotor UAVs and emphasized the importance of accurate thrust modelling for stable flight control [21]. Their work laid the foundation for understanding motor–propeller interaction in multirotor systems.

BLDC motors and Electronic Speed Controllers (ESCs) have been widely adopted in UAV applications due to their high efficiency and reliability. Kim et al. conducted a comparative analysis between brushed and brushless motors in small UAVs and reported that BLDC motors offer higher power efficiency and lower maintenance requirements compared to brushed motors [22]. Additionally, BLDC motors with sensorless operation were shown to reduce system weight and enhance reliability [23].

Control strategies for quadcopters have been extensively studied. Mahony et al. proposed a nonlinear control framework for multirotor UAVs using feedback linearization that significantly improved attitude stability during aggressive manoeuvres [24]. Madani and Benallegue introduced backstepping control for a quadrotor, demonstrating improved stabilization performance compared to conventional PID controllers [25]. However, PID remains prevalent in propulsion control due to its simplicity and satisfactory performance in practical implementations [26].

Several researchers have focused on the integration of ESCs with flight controllers for optimized performance. Zhang et al. evaluated sensorless BLDC control techniques embedded in ESCs and reported that advanced commutation algorithms can reduce torque ripple and improve motor efficiency [27]. Furthermore, the work by Singh et al. discussed hardware considerations, including ESC current ratings and thermal management, highlighting their critical role in system reliability [28]. Overall, existing literature establishes the effectiveness of BLDC–ESC propulsion systems and control strategies, while also identifying areas for improved control algorithms and energy-efficient design.

III. BLOCK DIAGRAM

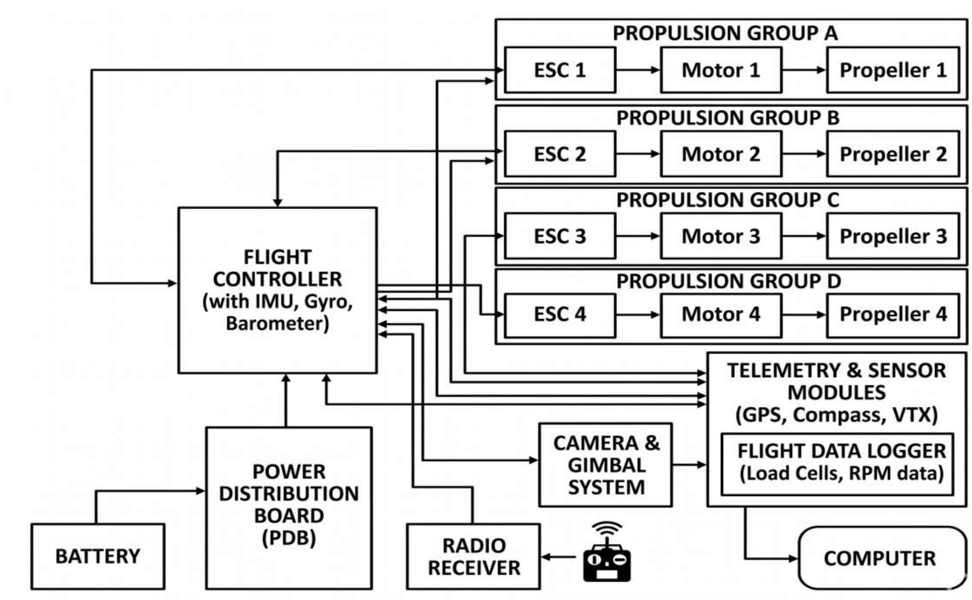

Figure 1:block diagram of Quadcopter drone

The block diagram illustrates the overall architecture of the ESC-driven BLDC propulsion system used in the quadcopter drone. The system consists of a lithium-polymer (Li-Po) battery, power distribution board, flight controller, inertial measurement unit (IMU), electronic speed controllers (ESCs), BLDC motors, and propellers.

The Li-Po battery serves as the primary DC power source for the system. The battery output is connected to the Power Distribution Board (PDB), which distributes regulated DC power to the four ESC units. Each ESC is responsible for driving one BLDC motor. The ESC converts DC supply into controlled three-phase AC signals using a MOSFET-based inverter circuit. This process is achieved through high-frequency Pulse Width Modulation (PWM) switching.

The flight controller acts as the central processing unit of the quadcopter. It receives orientation and motion data from the IMU sensors, which include accelerometers and gyroscopes. Based on the desired flight command and real-time feedback, the flight controller generates PWM control signals for each ESC.

Each ESC independently controls the speed of its corresponding BLDC motor. By varying motor speeds, the quadcopter achieves roll, pitch, yaw, and throttle control. The propellers convert rotational motion of the BLDC motors into thrust force required for lift and manoeuvrability. Thus, the system operates in a closed-loop control configuration, ensuring stable flight, precise speed regulation, and efficient propulsion performance.

IV. METHODOLOGY

The methodology adopted for the design and control of the ESC-driven BLDC propulsion system consists of system modelling, hardware selection, control algorithm implementation, and performance validation. The complete workflow is divided into analytical design and experimental validation phases.

Initially, thrust requirements were calculated based on the total take-off weight (TTOW) of the quadcopter. A minimum thrust-to-weight ratio of 2:1 was considered for stable hovering and manoeuvrability. Based on this requirement, appropriate BLDC motors and propellers were selected using manufacturer thrust curves. As suggested in [1], proper matching of motor KV rating and propeller size improves propulsion efficiency.

In the second stage, ESC selection was performed considering maximum continuous current, voltage rating, switching frequency, and thermal limits. The ESC converts DC supply into three-phase AC using a MOSFET-based inverter topology. PWM signals generated by the flight controller regulate motor speed by varying duty cycle.

The third stage involved mathematical modelling of quadcopter dynamics using Newton–Euler equations. The relationship between motor angular velocity (ω) and generated thrust (T) is expressed as:

$$T = K_t \omega^2 \qquad (4.1)$$

where K_t is the thrust coefficient. Control inputs for roll, pitch, and yaw were derived from differential motor speeds.

A closed-loop PID controller was implemented to maintain attitude stability. The controller continuously compares desired orientation with real-time IMU feedback and adjusts motor speeds accordingly. As reported in [2], PID control provides reliable stabilization with low computational complexity. Finally, system validation was performed through simulation and experimental testing. Parameters such as motor speed response, current consumption, temperature rise, and flight stability were analysed under varying load conditions.

V. RESULT ANALYSIS

The system was validated through a comprehensive Simulink-based simulation model, analyzing gate pulse generation, commutation logic, and Simulink circuit under dynamic load conditions.

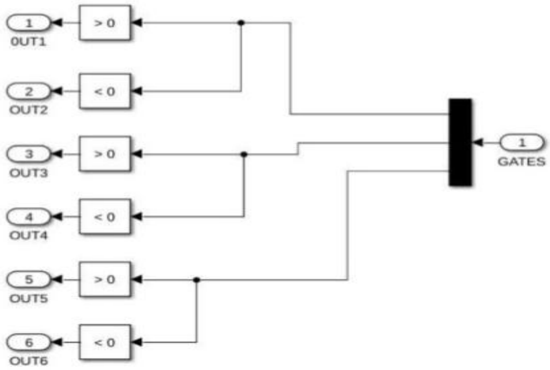

Figure 2: analyzing gate pulse generation

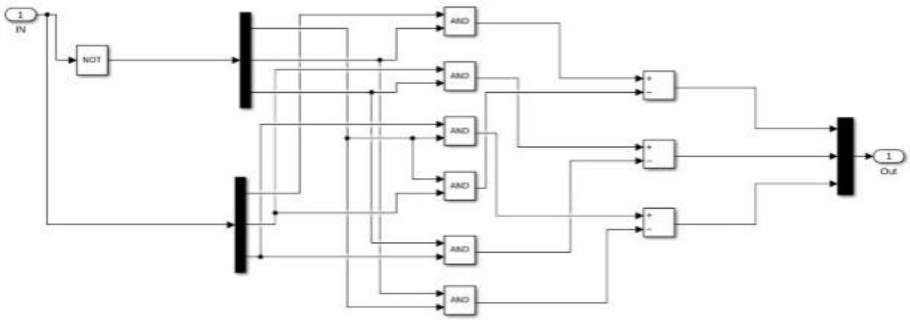

Figure 3: Commutation logic

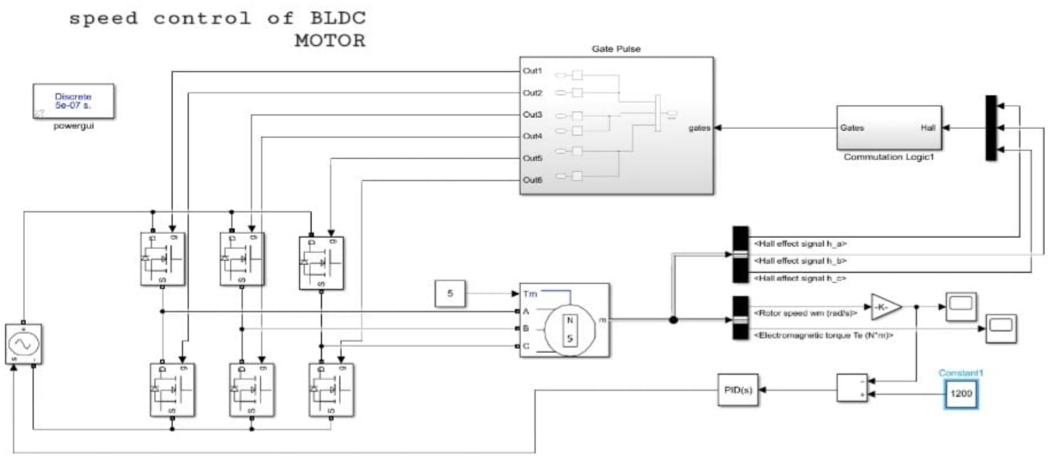

Figure 4: MATLAB Simulink circuit under dynamic load conditions

The rotor speed response demonstrates that the BLDC motor accelerates rapidly and reaches the desired reference speed with minimal overshoot and a fast settling time. This confirms that the PID controller is accurately tuned and capable of maintaining stable operation during transient conditions. The steady-state speed remains constant, indicating excellent regulation performance.

The electromagnetic torque characteristics exhibit a high initial peak during startup to meet acceleration demands, followed by a rapid reduction and stabilization with minor ripples. These torque ripples are inherent to electronic commutation in BLDC motors but remain within acceptable operational limits, ensuring smooth thrust generation suitable for aerial applications.

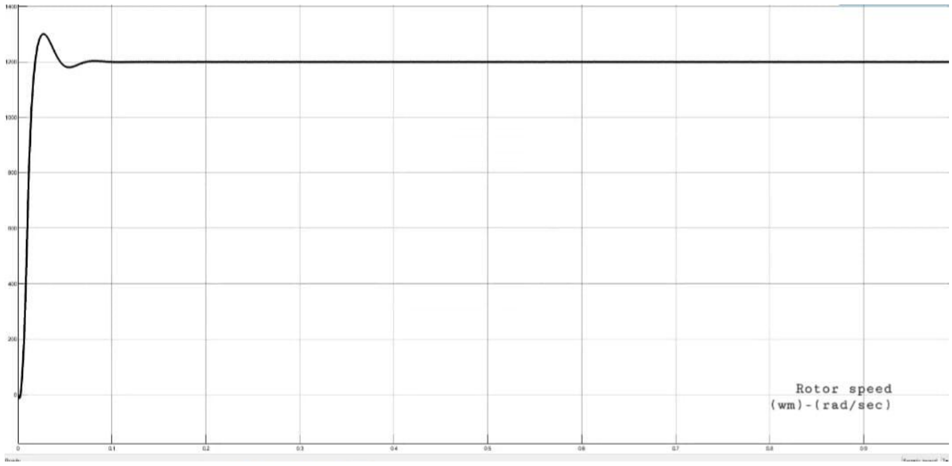

Figure 5 : Steady State speed of BLDC Motor

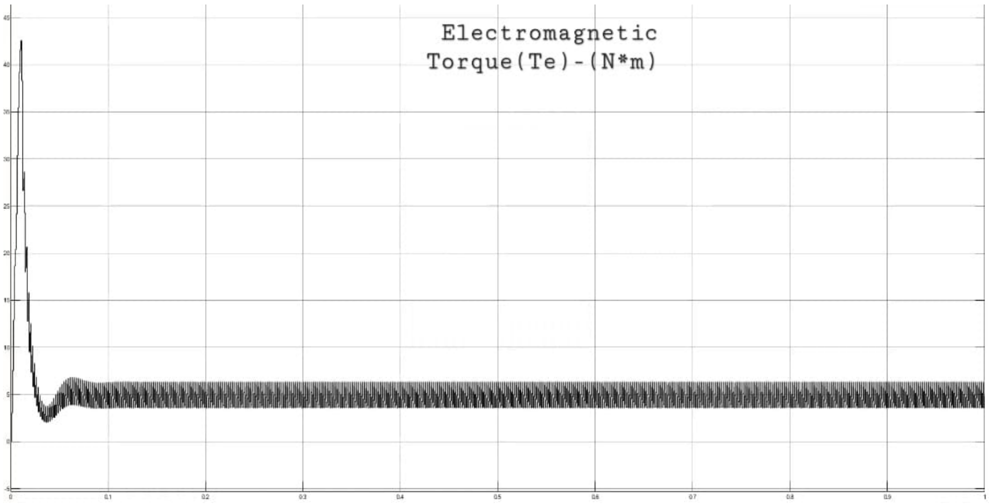

Figure 6: Electromagnetic torque of BLDC Motor

The commutation logic circuit effectively processes Hall sensor inputs to generate precise switching signals for the three-phase inverter. This ensures correct phase energization, leading to efficient torque production and continuous motor rotation. The ESC successfully modulates gate pulses based on real-time feedback, validating the closed-loop control architecture. Scope outputs confirm stable voltage waveforms, synchronized commutation sequences, and efficient power conversion, collectively verifying the system's dynamic responsiveness and reliability for quadcopter propulsion.

VI. CONCLUSION

The design and simulation of the ESC-driven BLDC propulsion system for a quadcopter drone have been successfully implemented and analysed using the developed Simulink model. The system combines a three-phase inverter, electronic speed controller (ESC), commutation logic based on Hall sensor signals, and a closed-loop PID speed control mechanism to achieve efficient and reliable motor operation. From the simulation results, the rotor speed response clearly shows that the motor accelerates rapidly and reaches the desired reference speed with very small overshoot and fast settling time. This indicates that the PID controller is properly tuned and capable of maintaining stable operation under dynamic conditions. The steady-state speed remains constant, confirming good regulation performance.

The electromagnetic torque characteristics demonstrate a high initial peak during startup due to acceleration requirements, followed by a reduction and stabilization with minor ripples. These torque ripples are expected in BLDC motors due to electronic commutation but remain within acceptable limits, ensuring smooth operation suitable for drone applications. The commutation logic circuit effectively processes Hall sensor inputs to generate accurate switching signals for the inverter. This ensures correct phase energization, leading to efficient torque production and continuous rotation of the motor. The ESC successfully controls the motor speed by adjusting gate pulses based on feedback, demonstrating proper closed-loop control functionality.

Overall, the system exhibits good dynamic response, stability, and reliable performance. The results confirm that the designed ESC-driven BLDC propulsion system is well-suited for quadcopter drones, where fast response, precise speed control, and efficient power utilization are critical for stable flight and manoeuvrability.

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