

Parameter Estimation and Comparative Analysis of Control Design Techniques for BLDC Hub Motor

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Abstract—Brushless DC (BLDC) motors have become the optimal choice for high-precision controller implementation in industrial applications. This paper presents a detailed analysis of a hub BLDC motor used in low power electric vehicles right from parameter estimation to the implementation of speed control techniques. The parameter estimation is followed by the development of the mathematical model of the BLDC motor. The conventional PID technique and the genetic algorithm-based tuning are applied to the mathematical model. Further physical model of the motor is constructed and simulated for broadly 3 control methods: Conventional PID, Genetic algorithm, and self-tuning Fuzzy logic method. The purpose of the research is to provide a comparative analysis of these control strategies and to identify the optimal one for speed-control of the BLDC hub motor. Results show that the proposed, adaptive Fuzzy logic technique is the best control design for practical implementation.

Index Terms—Brushless DC Motor (BLDC), Mathematical Modelling, Genetic Algorithm (GA), PID, MATLAB, Simulink, Fuzzy Logic, Self-Tuning PID Controller

I. INTRODUCTION

High-performance motor drives are indispensable to the ever-growing fields of industrial control, robotics, aviation, and especially to the future of travel i.e. 'Electric Vehicle Systems.' The use of electric motors follows from this industrial requirement. Conventional DC motors are the first choice owing to the excellent on-field characteristics but have a serious limitation when it comes to power dissipation [1]. This is mainly due to the frictional and consequently, heat losses, in the brushes, whereas unwanted electric

discharges in the commutator arrangement [1]. As an alternative, induction motors are used in varied applications but problems arise when it comes to requirements of a high-power factor, a high starting torque, and high-speed control.

Considering these issues, the highly efficient 'Brushless DC motor' is the optimal choice, as it provides high torque to weight ratio, more torque per Watt (increased efficiency), less noise, elimination of sparks, and increased reliability. The commutation is done by solid-state switches and the motor is driven by DC voltage. The rotor position is determined by Hall sensors [2] or even otherwise by sensor-less techniques [3]. This establishes the commutation instants. The present paper emphasizes on the use of the BLDC 'Hub' motor in particular by providing its detailed study right from parameter estimation to speed control. Considering the requirements of the control mechanism for the BLDC hub motor, the PID (Proportional Integral Derivative) was the first choice as presented further, owing to its accuracy, integrity, stability, and feasibility. The heuristic approach of Ziegler-Nichols for tuning the PID gains is widely used but it has serious limitations when it comes to robustness, instability, and universal applications across all systems. Thus, this paper brings out novel techniques of tuning the controller like the Genetic algorithm and self-tuning Fuzzy logic control. The genetic algorithm-based approach facilitates achieving the required performance of the system in terms of well-defined cost (objective) functions which are minimized over several

iterations. This has an edge over the auto/manual tuning method which requires adjusting the performance now and then. The paper exploits this advantage of evolutionary algorithms for controller designing [4]. The Fuzzy logic-based [5] technique is also dealt with, in this paper to a great detail which creates an adaptive logic controller for the motor. This ensures that the system is controlled well even in cases of uncertainties in parameters and nonlinearities in the environment. The paper aims at providing a comparative analysis of these varied control techniques to attain an optimal solution.

Similar to many contemporary studies regarding the BLDC motor, the unavailability of motor parameters was the principal challenge in this research. The only available information was the current rating 10A, Voltage rating 24V and the number of pole pairs 10. To study the motor behavior and to obtain the speed vs torque and motor efficiency, the Drum Break arrangement was designed. Using this experimental set-up the torque, speed, and current were observed, by using these parameters the following parameters were derived mathematically: moment of inertia (J), friction coefficient (B), back EMF (Electromotive Force) voltage constant (K_e) and torque constant (K_t). Further, this knowledge of parameter values was used to construct the mathematical as well as the physical model of the BLDC motor in MATLAB-Simulink. The mathematical model was tuned using a linearized method coupled with manual ones and separately by genetic algorithms to obtain the values of K_p , K_i , and K_d . The validity of this tuning was tested by simulating the physical model, for these values of PID constants. The physical model was further tuned using the adaptive fuzzy-logic technique.

II. EXPERIMENTAL SETUP

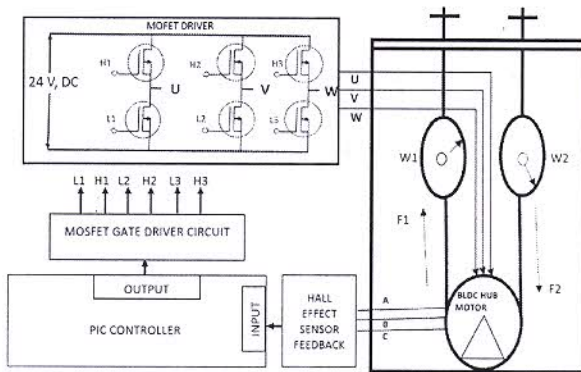


Fig. 1. Experimental setup of BLDC hub motor

To rotate the motor continuously the controller energizes the motor winding by solid-state switches as shown in Fig. 1. In the proposed experimental set up BLDC hub motor is operated in three-phase. The experimental setup is implemented using the BLDC hub motor driver circuit,

which includes the MOSFET driver circuit, electronic controller, Hall Effect sensor, and brake drum arrangement. Hall Effect sensors are present in the BLDC hub motor, which provides the position of the rotor. The speed of the BLDC hub motor can be increased or decreased based on the requirements by using the electronic circuit. Using brake drum arrangement the BLDC hub motor parameters are derived and calculated. Also, using this set up the back EMF voltage and phase current waveforms are observed on the oscilloscope for different loading conditions. Also, the efficiency of the motor was calculated by calculating the input and output power of the motor.

The experimental setup is controlled by using the PIC (Peripheral Interface Controller) controller. Hall Sensor signals are input to the controller, which generates the PWM (Pulse Width Modulation) pulses through which the commutation sequence is obtained. On completion of each cycle, the PIC controller generates six PWM signals which are the inputs to MOSFET driver IC.

The duty cycle of the PWM signal is controlled by the PIC controller which corresponds to the throttle voltage amplitude required to maintain the desired speed. The trapezoidal back EMF wave-forms are generated by the inverter circuit. Torque is generated by the interaction between the magnetic field generated by the stator coils and the permanent magnet.

TABLE I
PARAMETER TABLE

Parameter	Value	Unit	Symbol
Per phase resistance	0.155	Ohm	R_a
Per phase inductance	0.161	mH	L_a
Moment of Inertia	4.88e-4	Nm/s ²	J
Damping coefficient	5.15e-3	Nms/rad	B
Torque constant	0.2969	Nm/A	K_t
Back EMF constant	0.1546	Vs/rad	K_e/K_b
Max. Flux linkage	16.765	mWb	Ψ_m
Number of pole pairs	10	-	PP

A. Motor Gear Ratio

A planetary gear or epicyclic gear arrangement consists of three kinds of gears sun, planet and ring mounted in such a way that the center of planet gear revolves around that of sun. A carrier connects the centers of all three planetary gears and rotates to carry the planet gear around the sun gear. To analyze the action of the gear train on the input and output torque, speed it is necessary to calculate the gear ratio. Many configurations can be created by locking one kind of gear and using others for input and output [6]. For the ring gear locked with sun gear as input and carrier output, which is the kind of operation in this study, the gear ratio is given by:

$$GearRatio = 1 + \frac{N_r}{N_s} \quad (1)$$

N_r is the number of teeth on the ring gear and N_s is the

number of teeth on the sun gear. For this motor, $N_r=93$ and $N_s=23$. Hence the gear ratio is 4.57.

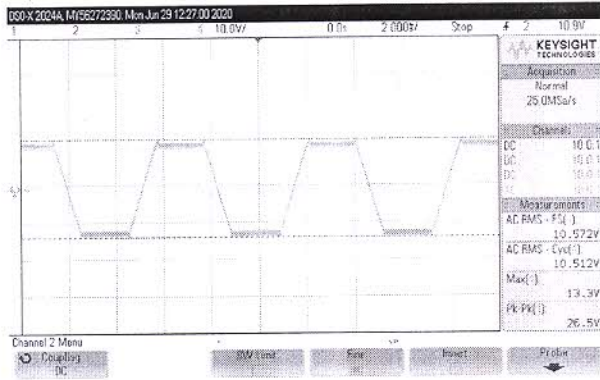


Fig. 2. Peak-Peak Value Of Back EMF

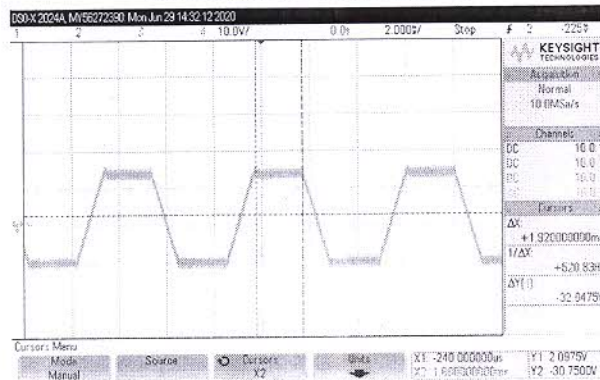


Fig. 3. Time for which Back EMF is constant

B. Speed Calculations

The no-load speed was measured by the tachometer as 215 RPM i.e. 22.51 rad/s. However, this is the output speed of the gear train. Thus to obtain the actual rotor speed, the gear ratio is used. The rotor speed is 4.5 times the measured speed and is hence equal to 102.87 rad/s.

From the back EMF profile obtained on the oscilloscope Fig. 2 - 3 the frequency(f) obtained is 159.72 Hz. The number of pole pairs (P) is 10. Hence the angular speed can be estimated as

$$\omega = \frac{60f}{P} \quad (2)$$

Thus estimated angular speed is 100.3529 rad/s. This is in close agreement to the measured value which validates the correctness of the back-EMF profile.

C. Methods of Parameter Estimation

The per-phase resistance and inductance are measured by simply using the ohmmeter and inductance meter respectively across the line-to-line nodes and dividing the value by two [7]. The torque constant and the back EMF constant are measured according to the definitions which is

- K_t = Ratio of Torque to Phase current

- K_e = Ratio of Peak phase voltage to Angular speed

Of particular interest is the measurement of B and J . The damping coefficient B is calculated by rotating the motor at a constant speed. Thus the torque equation becomes $\tau = B\omega$ and from the known values of torque and angular speed, B can be known [7]. For J , the motor is first run at a steady speed, and then it is switched off. The time taken for the speed to decrease to 36.8% is noted. This time constant is mathematically equal to B/J . Thus, J can be estimated from the known value of the time constant and B [7]. All the parameters are tabulated in Table I.

III. MATHEMATICAL MODEL AND TRANSFER FUNCTION OF BLDC MOTOR

A. Transfer Function Estimation

The transfer function is the important hypothesis of the control system and such types of mathematical models are used in the automation based on the control system. The study assumes that the three-phase BLDC hub motor is controlled in two-phase conduction mode. The equivalent circuit of BLDC Hub Motor is as shown in Fig. 5. At a time only two phases are active either AB or BC or CA, one positive and the other negative.

Once the parameters are known, mathematical modeling is essential to understand the behavior of the system. Thus, it is required to derive the transfer function for the BLDC motor. Generally, the mathematical model of a Brushless DC motor is on the similar lines of that of the brushed conventional DC motor. The significant addition is in the phases involved which directly affect the overall results of the BLDC model. The phase distinctly affects the resistive and the inductive nature of the BLDC arrangement. For BLDC motor the mechanical and electrical time constants are vital modeling parameters. The voltage equation of a brushless DC (BLDC) motor is given by the following equation:

$$V = Ri + L_s \frac{di}{dt} + K_e \omega \quad (3)$$

where V is the phase voltage, R is the phase resistance, L_s is the synchronous inductance, and K_e is the back electromotive force (BEMF) constant. The net torque equation at no load is given by [8]:

$$\tau = J \frac{d\omega}{dt} + B\omega \quad (4)$$

Based on the symmetrical and three-phase arrangement, the transfer function of the BLDC motor is:

$$\frac{\omega}{V}(s) = \frac{K_t}{(JL_s)s^2 + (JR_a + BL_s)s + (BR_a + K_b K_t)} \quad (5)$$

$$\frac{\omega}{V}(s) = \frac{0.2969}{(7.859e - 8)s^2 + (7.649e - 5)s + 0.0467} \quad (6)$$

