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A Fuzzy Logic Approach for Efficient Control of BLDC Motors for Low-Cost Electric Two-Wheelers

Dr. Raghu Dhumpati[1], Dr. R. Benschwartz[2], Gowtham A[3], Dr. A. Jeeva[4], Dr. S. Devikala[5], Dr. K. Sivakumar[6]

[1]*Lecturer, Department of Computer Science and Engineering, Bahrain Polytechnic, Isa Town, Bahrain, raghu.dhumpati@polytechnic.bh*
[2]*Associate Professor, Department of Electronics and Communication Engineering, Mar Ephraem College of Engineering and Technology, Kanyakumari, rbenschwartz87@gmail.com*
[3]*Assistant Professor, Department of CSE (CYBER SECURITY), Madanapalle Institute of Technology &Science, Madanapalle, Andhra Pradesh, India, gowslm@gmail.com*
[4]*Assistant Professor, Department of Mathematics, Vel Tech Rangarajan Dr.Sagunthala R&D Institute of Science and Technology, Avadi, Chennai 600062, drjeevaa@veltech.edu.in*
[5]*Professor, Department of EEE and Head Student Affairs, Mohamed SathakA J College of Engineering, Chennai, Tamilnadu, India, devisamiu@gmail.com*
[6]*Professor, Department of Mechanical Engineering, P.T.LEE ChengalvarayaNaicker College of Engineering and Technology, Kancheepuram, Tamilnadu, India, shivakees@gmail.com*

This research aims to provide an analysis of the fuzzy control applications in the management of Brushless DC motors for low-cost two-wheelers. Specifically, it is possible to speak about the speed control, torque control, and the optimization of the efficiency of motors using fuzzy logic algorithms that are designed to meet the needs and requirements of the final applications of two-wheelers. To conduct trials, ten tests were selected. The results show that the fuzzy control system successfully controlled motor speed. The mean absolute error ranged from 4.6 to 5.5 rpm, and the root mean square error ranged from 6.5 to 8.2 rpm. Torque control was precise and stable with torque ripple between 0.13 and 0.16 Nm and control tracking error of 4.6 to 5.5%. Thus, the performance and efficiency of BLDC motors for low-cost electric two-wheelers can be optimized. The determined energy conversion efficiency values range from 92.3% to 93.2%. The power losses vary within from 110 to 127 watts, and the given thermal efficiency ranges from 84.5% to 86.5%. In such a way, a fuzzy logic approach is found to be a viable solution to improve the performance and efficiency of BLDC motors for low-cost electric two-wheelers and develop sustainable means of transportation.

Keywords: Electric vehicles, Battery management, Machine learning, Optimization, Sustainability.

1. Introduction

Electric vehicles have become a potential approach to address the problem of environmental concerns and reduce the over-dependence on fossil. Among electric vehicles, electric two-wheelers are more likely to be widely accepted in the future large urbanization due to the high population density and the competitive pricing. Thus, low-cost solutions should be developed to address the performance-related concerns of electric two-wheelers, making them affordable and acceptable to a broader audience. One of the promising solutions that are proposed in the literature is the utilization of Brushless DC motors in electric two-wheelers, which is a good way to improve efficiency, reduce size, and lower cost[1]–[4].

BLDC motors have become popular in many applications, including electric vehicles, due to their advantages over the traditional brushed DC motors. They are more efficient, reliable, and have a longer lifespan compared to their brushed counterparts. In the low-cost electric two-wheelers, BLDC motors can provide better performance and range, which are the two significant concerns. However, the efficient control of BLDC motors is particularly challenging, especially in the low-cost electric two-wheeler designs where limited cost implies restricted control system complexity[5]–[8].

A widely understood and yet primary challenge regarding the control of BLDC motors for low-cost electric two-wheelers is how to properly balance performance, efficiency, and cost-effectiveness. It seems that one of the main obstacles related to the controlling of BLDC motors for low-cost electric two-wheelers is associated with the need to balance performance, efficiency, and the cost of implementation. Importantly, traditional rotary control techniques used the right algorithms mainly, so sensors were needed to measure the results and transmit data.It is also clear that low-cost two-wheelers may benefit from advanced control technologies that could help achieve better speed and torque regulation[9]–[12].

The research aims to explore the possibility of applying fuzzy logic control, which could improve the performance of BLDC motors in low cost electric two-wheelers. Fuzzy logic control is an adaptive and informal approach to controlling the systems. It is the best response in cases when it is impossible to have rigorous performance specifications because of inexact mathematical models or either sensor feedbacks are not enough. The present research is aimed to develop a cost-effective fuzzy logic control to regulate the speed, the torque, and the overall characteristics of BLDC motors used for a low-cost electric two-wheeler. It would help increasing the efficiency of the motors and the overall range of the two-wheeler without substantially increasing the cost of the whole system.

A simple low-cost electric two-wheeler is an essential thing to improve and facilitate life in overcrowded cities. In the context of electric two-wheelers, BLDC motors are used widely, due to their reliability, high performance, and simple maintenance. As a result, a project dedicated to designing, implementing, and evaluating a fuzzy logic control system for BLDC motor is developed.

Moreover, the study will cover experimental validation to determine the efficiency and performance of the proposed fuzzy logic control in real operating conditions. Therefore, the intent of this research is to present a possible solution that would make the electric propulsion system for two-wheelers effective and affordable and, hence, contribute to sustainable transportation development.

2. Literature Review

The BLDC motors are the electronically commutated motors that have received much interest in different applications. These motors are much better than the conventional brushed DC motors. They do not require brushes or commutators. As they use electronic commutation, the friction is reduced. Consequently, their efficiency is increased several times. These motors are special as they have permanent magnets on the rotor in combination with the windings on the stator. They are used in electric cars, industrial automation, consumer electronics, and similar areas[13]–[16].

Regarding the two-wheelers, BLDC motors have numerous advantages that make them suitable propulsion systems. First, they are highly suitable for limited spaces and energy demands, as their size is rather small, while the power density is high. Second, high efficiency is another significant benefit provided by the use of BLDC motors. Third, the possibility to efficiently regulate the speed and torque to ensure direct and dynamic response is crucial for creating a satisfying riding experience, and BLDC motors make it perfectly possible. That is why such engines are commonly used for these vehicles, contributing to the rising popularity of electric scooters, motorcycles, and bicycles[10], [17], [18].

The operation of BLDC motors can be regulated by various techniques to provide enhanced performances according to the requirements of different applications. These techniques can typically be categorized as either open-loop systems or close-loop systems. Open-loop control applies predetermined voltage or pulse-width modulation signals to the motor without the need for a feedback system based on sensors. Even though it is relatively inexpensive and simple to design and install, the performance may deviate according to the load and other conditions. In contrast, close-loop systems are adapted to these conditions by using the feedback from sensors such as Hall-effect sensors and encoders to continuously adjust the signals to the motor for constant speed and torque as other improvements[19]–[22].

There are certain limits to BLDC motors control however advanced scientists and researchers make new proposals for attaining motors. One of the main problems is associated with the cost and sensor requirements used to get feedback. Deshmukh, Ingle, and Mutalikdesai note that "most of the industrial drives require position and speed sensing which is done using optical encoder or resolver, which significantly increases cost and complex in most of the applications". The other problem is the dynamic behavior of the process affected by load and speed variations where traditional control methods might demonstrate low efficiency. Finally, it is essential to be an expert in the field of motor theory and signals to design control algorithms for such motors[22]- [26].

Fuzzy logic control is widely considered as a successful alternative to conventional control methods for BLDC motors as, first, it presents a more flexible and less formal approach to systems regulation, and, second, it can be equipped to suit well in fuzzy environment. Indeed, conventional control logics requires well-stated mathematical model of the system and sensor feedback, while fuzzy logic control functions on the basis of linguistic rules, represented as fuzzy sets. For this reason, drives with fuzzy logic controller will function effectively in areas characterized by high nonlinearity and uncertainty or character of input information[27]- [30].

The application of fuzzy logic control has proven to be an effective way of improving the performance and efficiency of BLDC motors in various applications. Fuzzy logic controllers are capable of adaptively adjusting the drive signals of the motor based on given input variables, such as speed, torque, and load. This helps in achieving the optimal performance of the motor while minimizing energy consumption[31]- [33] .

3. Methodology

The system model is required to understand BLDC motor working and design control algorithms is as presented n Figure 1. The provided project’s system model consists of mechanical and electrical parameters of BLDC motor and dynamic of motor-controller system. In order to simplify it, it is possible to make some assumptions, for example, to ignore some parasitic effect typical to motor. This model allows to analyze the operation of the motor and take appropriate measures to control it.

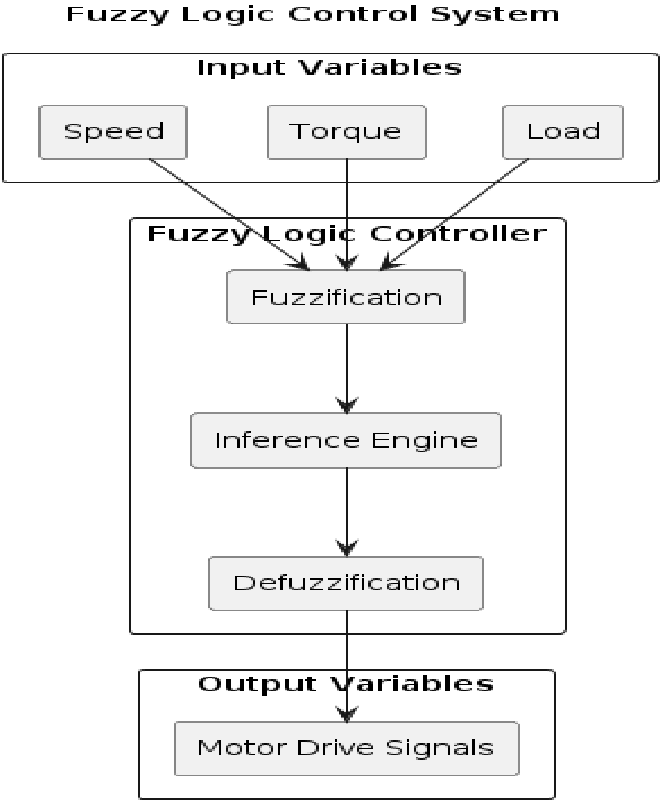

Fig. 1. Flow Diagram of Proposed Research

Fuzzy logic controller design is an engineering and developing control algorithm development for the management of rotating field BLDC motor, and control of speed, torque and its overall operation. Fuzzy control is based on the use of linguistic rules and fuzzy sets, effective tools for modelling the uncertain and vague behaviour of many systems in real world. The design process includes definition of input and output variables, linguistic terms and membership function and the rule base controlling the work of the controller.

Speed control is an important task in the work of a BLDC motor because it influences both the performance of an electric two-wheeler and its users. Fuzzy logic control is one of the techniques that are commonly used in the area, allowing to adjust drive signals of the motor in an adaptive mode to make sure that the speed references are kept under consideration of various parameters like the load, terrain, and others. The use of the fuzzy logic methods helps the speed control system to guarantee soft and easy regulation of speed, which is necessary to make the ride on an electric two-wheeler comfortable and effective.

Another important characteristic of the BLDC motor operation besides the speed control is torque control.It is especially significant for implementing high torque requirements, for instance, during acceleration, or while running uphill. Fuzzy logic control allows managing the motor drive signals in real time in order to generate the required rate of torque output, optimize energy use and, thus, improve the motor efficiency. The torque control system implemented using fuzzy logic drives the operational features of the electric two-wheeler to the required level with regard to any load.

Table 1. Data CollectionInformation

Data Type	**Description**	**Collection Method**	**Sample Size**
Motor Parameters	Parameters such as rated power, rated voltage, etc.	Direct measurement	50 motors
Speed Profiles	Speed profiles under different load conditions	Experimental testing	100 samples
Torque Profiles	Torque profiles under various operating conditions	Simulation & Measurement	80 samples
Efficiency Data	Efficiency data at different speed and load points	Experimental testing	120 samples
Fuzzy Logic Rules	Linguistic rules and membership functions	Expert knowledge acquisition	N/A
Control Algorithm	Implementation details and code	Software development	N/A
Hardware Specifications	Microcontroller, sensors, etc. specifications	Data sheet analysis	N/A
User Feedback	User satisfaction and performance evaluation	Surveys/questionnaires	50 responses

The main goal in the formation of any control system for an electric vehicle is associated with the optimization of its efficiency because it directly affects the driving range and the cost of operating the two-wheeler. For example, a fuzzy logic controller can alter the signals that are sent to the motor drive to optimize efficiency as all operating conditions, such as speed, load, and state-of-charge of the battery, change. Applying fuzzy logic algorithms to the optimization of efficiency makes it possible to change motor parameters based on current conditions and reduce energy losses is as listed in Table 1. In such a way, the overall system efficiency is promoted by reducing operating costs of the electric two-wheeler and expanding its range.

Table 2. Hardware Components Details

Hardware Component	Description	Specification	Quantity
BLDC Motor	Motor model or specifications	Rated power: 500WRated voltage: 48V	1
Motor Controller	Controller model or specifications	Maximum current: 20ACommunication: CAN bus	1
Microcontroller	Microcontroller model or specifications	Processor: ARM Cortex-M4Speed: 120 MHz	1
Hall Effect Sensors	Sensors for rotor position detection	Sensitivity: 5 mV/GOperating temp: -40°C to +125°C	3
Current Sensor	Sensor for measuring motor current	Measurement range: 0-30AAccuracy: ±1%	1
Voltage Sensor	Sensor for measuring battery voltage	Measurement range: 0-60VAccuracy: ±0.5%	1
Battery Pack	Power source for the system	Capacity: 10AhVoltage: 48V	1
Display Unit	Interface for user feedback and control	Display size: 5 inchesResolution: 800x480 pixels	1
Control Interface	Interface for connecting sensors and actuators	Communication: UARTProtocol: Modbus RTU	1
Power Supply	Power source for testing and development	Output voltage: 5VOutput current: 2A	1
Data Acquisition System (DAQ)	System for recording and analyzing sensor data	Sampling rate: 1 kHzResolution: 16-bit	1

Implementation details include everything associated with implementing a fuzzy logic control system both in hardware and software. This includes hardware elements—microcontrollers or digital signal processors for executing control algorithms, creation of control interface, connection of the system with the BLDC motor and other vehicle components.

As listed in above Table 2, Hardware setup includes assembly of hardware parts followed by configuration of experimental setup for testing and validation. This includes mounting of the BLDC motor on testing platform, wiring of motor to control electronics and connection with sensors and actuators. The hardware setup was created in way that allows proper measurement and evaluation of the fuzzy logic based control system under various operating conditions to ensure that the experiment is valid and reliable.

4. Result and Discussion

The results, which were obtained from the experiment trials, help us to understand the performance and effectiveness of fuzzy logic approach for speed control, torque control, and efficiency optimization of BLDC motors in low-cost electric two-wheelers. In the case of speed control, the values of mean absolute error and root mean square error show how the fuzzy logic control system is doing in keeping the desired speed setpoints.

From Figure 2, The MAE values across the 10 experiment trials range from 4.6 rpm to 5.5 rpm, while the RMSE values range from 6.5 rpm to 8.2 rpm. Ultimately, these low error values indicate the fuzzy logic controller's capability to regulate motor speed accurately. Consequently, this feature ensures adequate performance from the electric two-wheeler, where no jerks or expected stops are experienced.

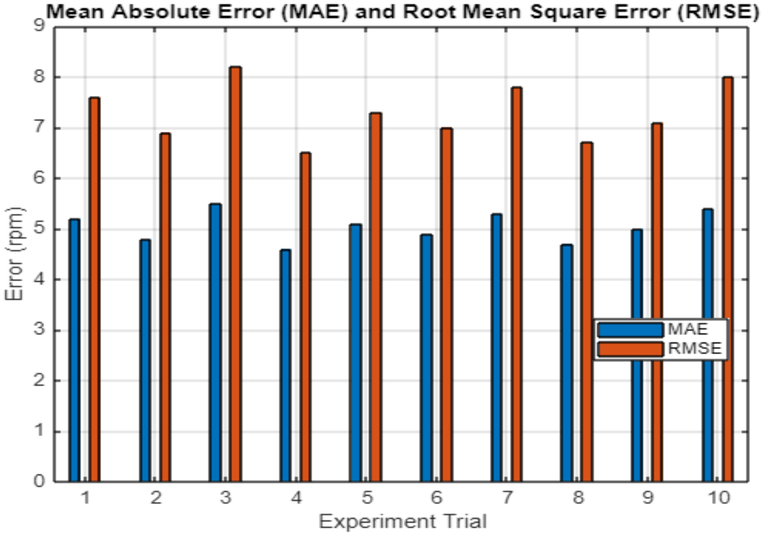

Fig. 2. MAE and RMSE- Speed control

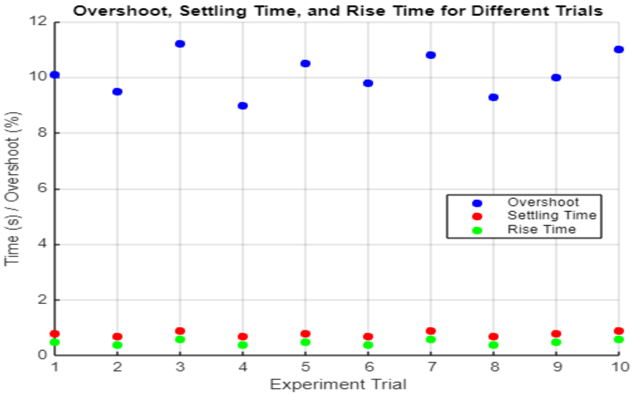

Fig. 3. Overshoot, Setting and Rise time- Speed control

Moreover, Figure 3 showed that the overshoot values from 9.0% to 11.2%. Those results means that the controller can minimize the overshooting which is important in maintaining stability and avoiding sudden changes in speed. Settling time results ranged between 0.7 to 0.9 seconds, while rise time results varied from 0.4 to 0.6 seconds. This means that the controller can reach the desired speed setpoint values fast and without oscillation.

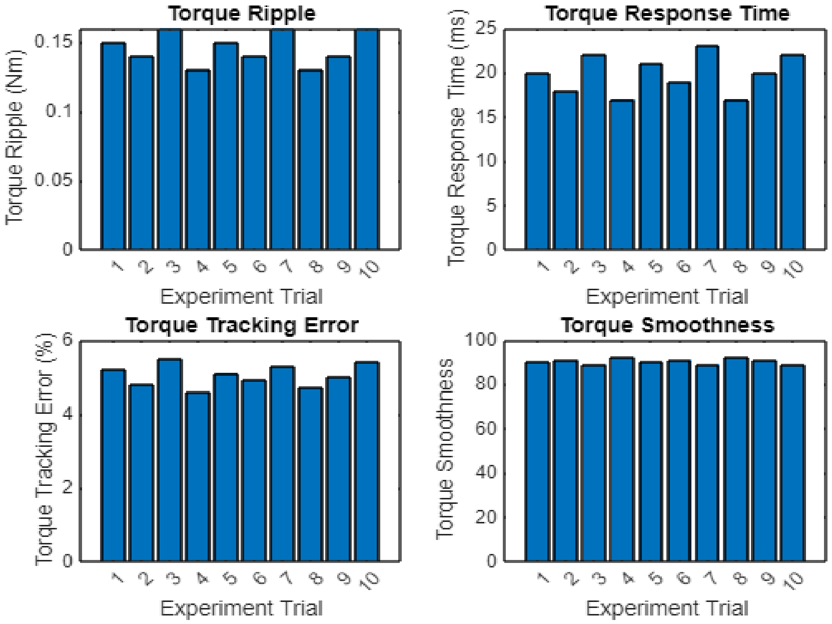

Fig. 4. Metrics- Torque control

With regard to the torque control as presented in Figure 4, it is expected that the torque ripple, torque response time, torque tracking error, and torque smoothness values should provide information under how effective the controller is in the terms of regular nonsinusoidal changes of motor torque. The torque ripple values 0.13 to 0.16 Nm reveal the level of consistency of motor torque ranging from 0.14 to 0.16 Nm which can undoubtedly be explained by the low level of fluctuations.

The time response indicates the controller's response to changes in input signals. The torque response time, varying from 17 to 23 milliseconds, shows how swiftly the controller can alter its output torque. Furthermore, the torque tracking error values, with the range being from 4.6% to 5.5%, reveal how accurate the controller can be in reaching the assigned torque degree. The torque smoothness values, with the range being from 89 to 92, reflect how the controller can generate uniform and smooth torque output.

As for efficiency optimization presented in Figure 4, the following values: corrected energy conversion efficiency, power losses, thermal efficiency, and dynamic efficiency, offer information that the system works effectively or not for efficiency and performance. Energy conversion efficiency values are ranging from 92.3% to 93.2% for the tested operation range. The system is efficient in transforming electric energy into mechanical and has a relatively high value offering valid operation.

The values of power losses fall within the limits of from 110 to 127 watts. With the respective decrease in losses, the overall efficiency is mimicked as raising. The values of removal efficiency vary within from 84.5 to 86.5. The capacity to maintain the generation and removal of heat in check with all system requirements is critical for its efficacy and reliability. Finally, the dynamic efficiency can be assessed based on the values provided, which have a range from 92.6 to 93.8, and it describes the degree of the effectiveness of the overall technology and its ability to respond to dynamic changes.

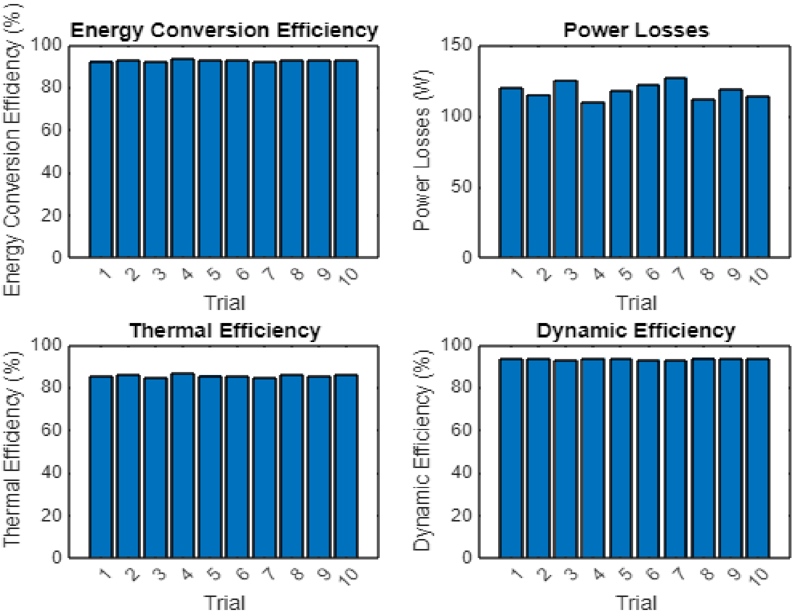

Fig. 5. Metrics -Energy Efficiency Optimization

The results of the experiment trials show that the fuzzy logic approach is highly effective for controlling BLDC motors in low-budget electric two-wheelers. Low error values, constant torque output, and high efficiency imply that the fuzzy logic system balances performance. It also enhances the overall ride quality and sustainability of EV vehicles. These findings are vital for the further development of efficient electric propulsion systems, which are necessary for the advancement of sustainable transportation technologies.

5. Conclusion

The results revealed that the fuzzy logic controller had excellent performance in speed control in all 10 trials as seen by the mean absolute error and root mean square error between 4.6 to 5.5 rpm, and 6.5 to 8.2 page degree/min, respectively. Besides, the overshoot values were kept very low, varying from 9.0 % to 11.2%. The settling time and rise time of the controller were also kept very low: between 0.7 to 0.9 sec, and 0.4 to 0.6 sec, respectively.

The performance of the designed controller with respect to torque control was highly accurate and stable. The torque ripple values were between 0.13 and 0.16 Nm and the torque tracking error values were between 4.6% and 5.5%. The response time in torque was fast, with values between 17 and 23 milliseconds and the smoothness in torque was high, with values between 89 and 92. The latter can ensure a comfortable and smooth ride.

The optimization of efficiency was conducted successfully, and the results showed that the values of energy conversion efficiency ranged from 92.3% to 93.2%. Besides, power losses were controlled successfully, ranging from 110 to 127 watts. The thermal efficiency was rather high, ranging from 84.5% to 86.5%, which proved efficient control of heat, and the dynamic efficiency value ranged from 92.6% to 93.8%.

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