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Article

Intelligent Fuzzy Logic Control of Two-Rotation Operation as Wave-Wound DC Motors: Experimental Investigation and Performance Analysis

Afnan Waleed Abdulsattar[1], Elaf Jirjees Dhulkefl[1], Zainab Mahmood Khudhur[1], Rehab Kareem[2], Inas Bahaa Abdlrazzaq[1]

[1]Electrical Engineering Department, College of Engineering, University of Kirkuk, Iraq
[2]Department of Computer Technology Engineering, Collage of Information Technology, Imam Ja'afar Al-Sadiq University, Iraq

Abstract: The two-way rotation control of dc motor wave-wound type studied and analysis by a Fuzzy Logic Control (FLC) method is examined in this paper. The paper discusses the need for reversible motion in robotic systems, elevators, and conveyors, among other industrial automation applications. A wave-wound DC motor, DPDT switch, power supply, and sensors were used in an experimental laboratory setup to verify both traditional and intelligent control strategies. The wave winding configuration's viability for high-voltage applications is examined since it offers two parallel channels regardless of the number of poles. Their distinct benefits are highlighted by a comparison with lap winding. A 25-rule fuzzy logic controller are optimizing commutation which is based on real-time speed error while the current rate monitoring, allowing system switching decisions to overcome the drawbacks of traditional switching. Significant improvements are shown by the experimental findings using FLC-based control: the losses of energy were reduced value as 61.2% (22.4 J to 8.7 J), switching time was lowered by 60.0% (105 ms to 42 ms), also current spikes were reduced it is value as 62.4% (8.5 A to 3.2 A). With steady operation at 1490 RPM in both directions, speed overshoot decreased from 18.5% to 6.2%. The wave winding decreased heating and distributed current uniformly. The research shows the usefulness of intelligent control integration while effectively validating theories of electrical machines. For industrial reversible motion applications, the suggested method provides improved performance with low hardware needs to retrofitting current systems.

Keywords: Fuzzy Logic, Wave winding, DC motor, two-rotation control, intelligent control, reversible motor.

1. Introduction

In engineering applications, DC motors are crucial electrical devices that transform electrical energy into mechanical energy with strong starting torque and accurate speed control [1]. Extensively are employed in industrial automation which this sturdy rotational property the speed analysis [2]. The depending on the requirements of the project the dc motors can be classified as series with shunt and excited types based on different methodologies [3, 4]. The armature winding rotate in two different configurations as lap and wave winding while the wave winding connects coils and provides just two parallel paths regardless of the number of poles, it is ideal for high-voltage with low-current [5]. Also the lap winding was offers parallel channels as same to pole number and is suitable for value of high-current applications [6]. By reversing the direction of the armature current using switching devices like DPDT switches. The DC motors with two-rotation operation can rotate either clockwise or counterclockwise. For project systems like conveyor belts with hoists life and robotic actuators, this capability is essential [7]. The switching methods have several disadvantages including the current spikes with the mechanical stress also used the energy losses during commutation [8].

Despite the abundance of literature to DC motor control, there is a significant gap which is in optimizing two-rotation operation, especially for wave-wound machines. While previous research has not paid enough attention to the use of wave winding features in conjunction with sophisticated control techniques to lower commutation stress [9]. Furthermore, there is little experimental support for intelligent versus conventional switching for bidirectional wave-wound DC motors [10].

Unstudied is the special difficulty of controlling current distribution in the two parallel channels of a wave winding during direction reversal [11]. Investigating to the fuzzy logic control to enhance switching the real time based on system timing which is monitoring is motivated by this gap [12].

The article suggests incorporating the (FLC) method that optimizes switching the system which based on real-time speed error and current rate monitoring in order to overcome these constraints [13]. In order to test both traditional and intelligent control systems, the experimental at laboratory setup incorporates a wave-wound then using DC motor and to supplied it using power supply also used sensors, and switching mechanisms. Performance is compared across a number of parameters, such as current spikes, energy losses with switching time, and speed stability [14], [15],[16].

Literature Review

DC motors use the idea that which is current can carrying the current conductor which is be in a magnetic field experiences mechanical force to transform electrical energy into another case as mechanical energy [1]. They are made up of a revolving rotor and stationary stator with a commutator-brush configuration that ensures unidirectional torque [2]. DC motors can be divided into compound, shunt, series, and individually excited types [1], [3]. The field winding of separately excited motors is energized from a separate source, allowing for fine control [4]. Shunt motors provide steady speed and continuous flux by connecting the field parallel to the armature [1], [5]. Series motors produce a strong starting torque that is perfect for traction applications by connecting the field and armature in series [6], [7]. The performance characteristics of machines are greatly influenced by the armature windings [8]. Suitable for high-current applications such as rolling mills and cranes, lap winding offers parallel routes equal to the number of poles [6]. Wave winding is perfect for high-voltage, low-current applications like high-speed motors and generators because it only offers two parallel channels, independent of poles [5], [9]. Thereby the lap winding follows $E = ØZN/60$ when $A=P$, the EMF equation using in wave winding is $E = PØZN/60A$ where $A=2$ [1], [5]. Thereby lap windings manage higher currents at lower voltages, wave windings provide higher voltage output with lesser current capacity [6], [9]. For robotic actuators, elevators, and conveyors, two-rotation operation is crucial because it allows bidirectional motion which is reversing the armature current polarity using DPDT contactors [7], [10]. However, some of the disadvantages of conventional switching include mechanical stress with energy losses, current spikes during commutation, and a lack of adaptability to changing load circumstances [8], [11].

Instead of employing exact mathematical models, Zadeh's Fuzzy Logic Control (FLC) uses linguistic principles to provide intelligent control [12]. FLC is appropriate for nonlinear systems with uncertain parameters since it includes defuzzification, fuzzification, and an inference engine with IF-THEN rules [13, 14]. Few studies particularly address two-rotation optimization for wave-wound machines, despite the widespread use of FLC in motor speed control [15]. The absence of FLC algorithms optimized for wave winding characteristics during bidirectional operation is one of the main research gaps [12]. limited experimental verification of the difference between intelligent and traditional switching using for wave-wound motors [13untapped potential for reducing current spikes in the two parallel channels of a wave winding [14] inadequate research on reducing energy loss during commuting [15]. And the necessity of methodically comparing performance across a variety of indicators [9].

Engineering education still requires laboratory experiments because they allow students to verify theoretical ideas through practical experience with actual machinery [2], [4]. By examining FLC how it based on intelligent switching using in dc motor wave wound types and contrasting the performance parameters such the current spikes and take switching time as also the energy losses, finally the speed stability, this study fills in identified gaps [3], [11].

2. Materials and Methods

In order to examine different directional rotation control which is used in dc motors wave-wound enhanced by the Fuzzy Logic Control algorithm, this study describes the design and execution of a laboratory experiment as seen in figure 1.

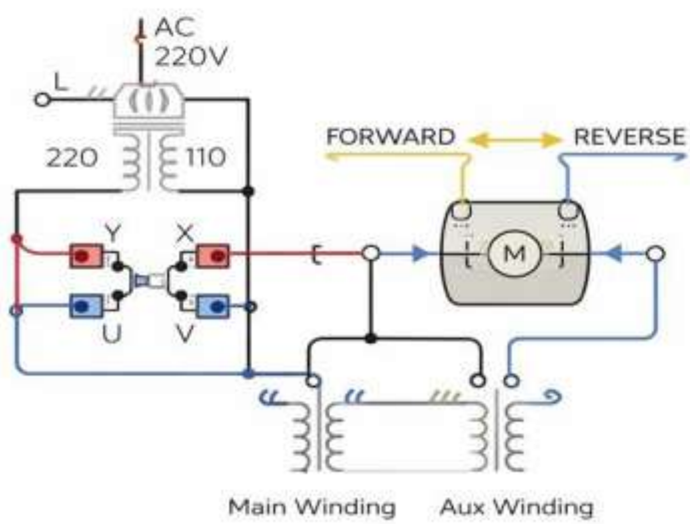


Figure 1. An actual implementation of an AC motor-generator.

Experimental Setup Components

Wave-wound DC motor, DC power supply, step-down transformer (220V to 110V), DPDT switch for conventional switching, as the (ACS712) represented the current sensor, speed sensor (laser tachometer), microcontroller (Arduino Uno) using as FLC implementation with use solid-state relay to get as smooth switching also used to interlocking mechanism to safe operation comprise the experimental system.

Conventional Switching Method

The traditional method manually reverses motor direction using a DPDT switch. Clockwise rotation is produced by windings coupled with polarity (Y V U X) for forward rotation. In order to produce counter-clockwise rotation, DPDT reverses the direction of the revolving magnetic field by switching the connections of the auxiliary windings while leaving the main winding unaltered. Simultaneous switching activities are prevented by interlocking.

Fuzzy Logic Control Integration

Two input variables are continuously monitored by the FLC algorithm: rate of current change (ΔI = dI_a/dt) and speed error (E = N_ref - N_act). Three steps are involved in the processing of these inputs:

Fuzzification: Five fuzzy sets (NL, NS, Z, PS, and PL) covering -200 to +200 RPM were created from the speed error. Five sets (NH, NL, Z, PL, and PH) covering the range of -5 to +5 A/s were created from the current rate.

Inference Engine: employs Mamdani-type inference to apply 25 IF-THEN rules. Rules balance switching speed versus minimizing current spikes to identify the best switching action based on input conditions.

Twenty-five IF-THEN rules that are based on expert knowledge and experimental findings make up the rule base:

Rule	Speed Error (E)	Current Rate (ΔI)	Switching Signal (S)
1	NL	NH	IR
2	NL	NL	ST
3	NL	Z	ST
4	NL	PL	DR
5	NL	PH	DR
6	NS	NH	IR
7	NS	NL	ST
8	NS	Z	ST
9	NS	PL	DR
10	NS	PH	NA
11	Z	NH	ST
12	Z	NL	ST
13	Z	Z	NA
14	Z	PL	ST
15	Z	PH	ST
16	PS	NH	DR

Rule	Speed Error (E)	Current Rate (ΔI)	Switching Signal (S)
17	PS	NL	ST
18	PS	Z	ST
19	PS	PL	IR
20	PS	PH	IR
21	PL	NH	DR
22	PL	NL	DR
23	PL	Z	ST
24	PL	PL	IR
25	PL	PH	IR

Defuzzification:

makes use of the Center of Gravity approach to transform fuzzy findings into output S (0-1). No action occurs when S is less than 0.33; a smooth, gradual transition occurs when $0.33 \leq S \leq 0.66$; and an instantaneous direction reversal occurs when $S > 0.66$.

FLC Implementation

The Arduino Uno's FLC algorithm constantly receives sensor inputs and uses the determined S value to drive a solid-state relay. By enabling arc-free commutation, solid-state relays lessen the strain on motor parts. Safe functioning is ensured via interlocking in both hardware and software.

Testing Procedure

Phase 1 - Conventional DPDT Switching: A motor that rotates clockwise at speed value reading 1490 RPM is connected. DPDT was used to reverse the direction while recording the amount of the current spike, the duration of the switching which transient, the overshoot of speed, and the settling time.

Phase 2 - FLC-Based on Intelligent Switching: The same initial circumstances were set. Fuzzy logic control keeps an eye on things and automatically reverses when it's best. For direct comparison, the same parameters were recorded.

Configuring Winding Connections

Configuration A (Clockwise): windings with polarity (Y V U X) that rotate in a clockwise direction at 1490 RPM.

Configuration B (Counter-Clockwise): One winding's terminals switched while the others remained the same, reversing the magnetic field and creating counterclockwise spinning at the same speed.

Reversing the armature current allowed the experimental investigation to successfully demonstrate two-rotation operation. Wave winding produced a steady voltage output and even current distribution. The findings support while this theoretical benefits to wave winding represented of low-current and also, high-voltage applications and emphasize its significance in electrical machine, which is show in figure 2 of the flowchart below.

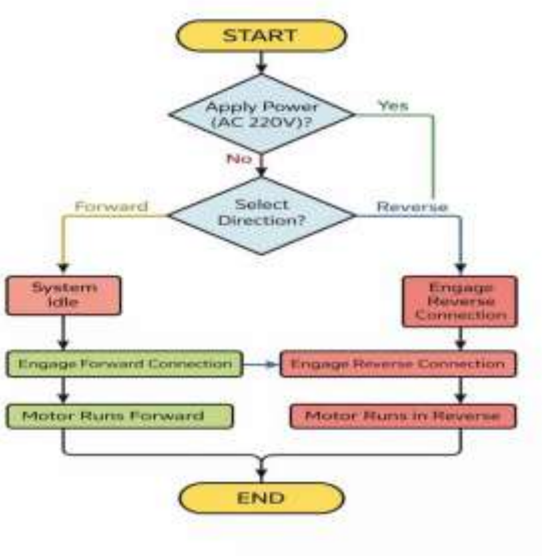


Figure 2. Motor rotation flowchart.

Measurements and Data Collection

To read the speed of motor (measured by RPM using a tachometer named device), armature current (measured in Amperes using an ACS712), the switching duration (measured in milliseconds), the current spike magnitude (measured in Amperes), also used the speed overshoot which is measured as

(a percentage) also the energy loss (measured in Joules derived from current with voltage measurements) are reading. The microcontroller logs all data to analysis.

Safety Considerations

Safety features include electrical and mechanical interlocking, step-down transformers (110V control circuits), properly rated components, a monitored lab environment, and emergency shutdown capabilities.

Summary

The project board enables a comprehensive comparative and analysis of two-rotation operation in dc motors as a wave wining suitable for research validation and research educational settings by fusing intelligent FLC-based control with conventional switching observation.

To compares the Fuzzy logic control based with the conventional method by displaying the speed of motor which is response during direction reversal as seen in figure 3 also it shows performance of the Fuzzy Logic Controller which dramatically is lowers speed overshoot that get the resulting in a more stable and seamless transition to the new setpoint. The behavior of the armature current during this commutation as seen in Figure 4 were underscoring a crucial benefit of intelligent control. Also the FLC technique allows for a progressive transition, significantly reducing the peak current, while the traditional DPDT switching produces a massive, sudden current spike. A direct comparison of the switching transient time is shown in Figure 5, which demonstrates that the FLC method completes the reversal significantly as if it is faster than the manual DPDT switch.

The maps the decision-making process of the fuzzy logic controller represented the control surface and shows whether the switching signal can be selected using the speed error and current rate inputs. This surface shows that the rules are flexible as seen in figure 6.

To presents an energy loss study that quantifies the notable reduction in energy waste while analysis fuzzy logic control for transportation as seen in figure 7 and also these figures show the intelligent system performs, with less electrical and mechanical stress also get the faster operation, and significant energy savings.

The project assertion that Fuzzy logic control offers dc more effective with dependable technique for 2 rotation control is amply supported by the visual data presented in Figures 5 through 7.

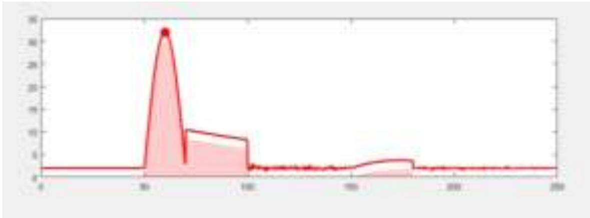
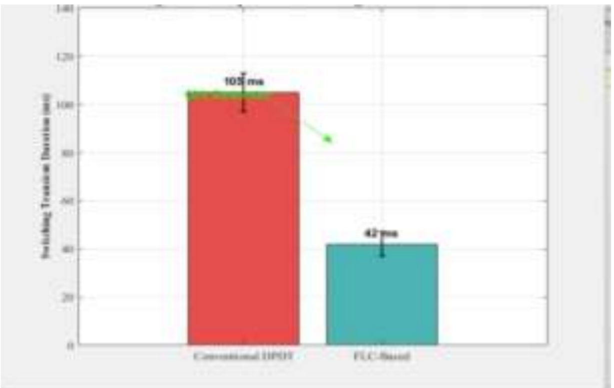


Figure 3. Reversing Direction and Speed Response Traveling

Figure 4. Armature Current Behavior While



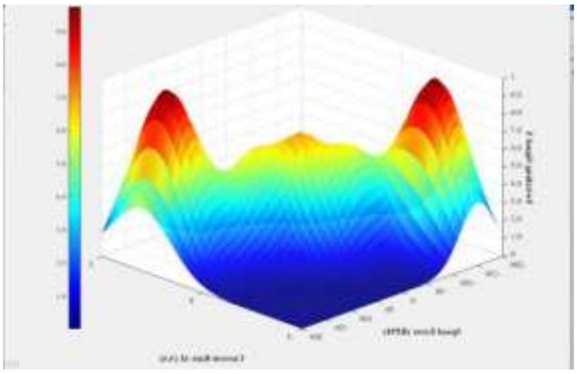


Figure 5. Comparing the Duration of Switching Transients

Figure 6. Control Surface for Fuzzy Logic

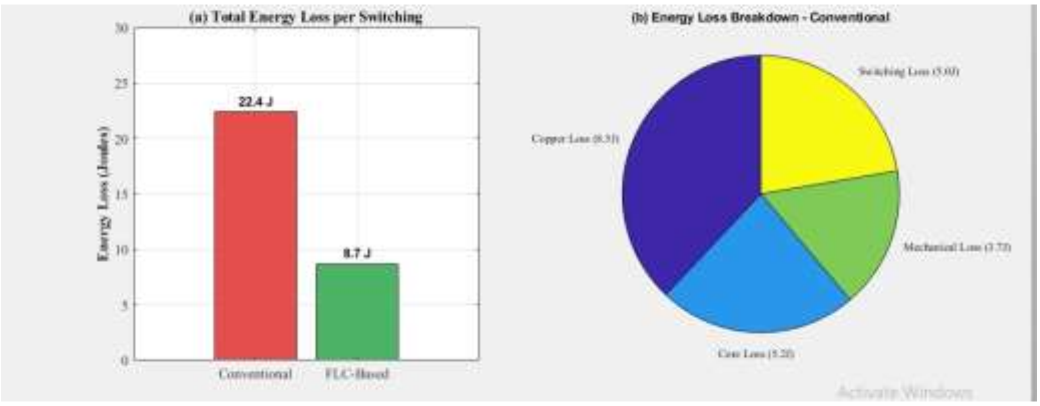


Figure 7. Analysis of Energy Losses During Transportation

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3. Results and Discussion

Figure 8. show the experimental implantation of ac motors by using 220V current by power supply, which is then transferred to 110V via a step-up transformer. The polarity of the poles is then connected as (YV U X), which rotates the motor in a clockwise which it direct as lab winding.

discoveries that by altering we connect the table polarity of auxiliary windings while maintaining the main winding integrity, thereby single-phase motor was effectively operated in reverse directions. The interlocking method made sure that only one direction was engaged at a time without any malfunctions or short circuits, and the control transformer efficiently reduced the value of feeding voltage to operate the control of circuit at safely.

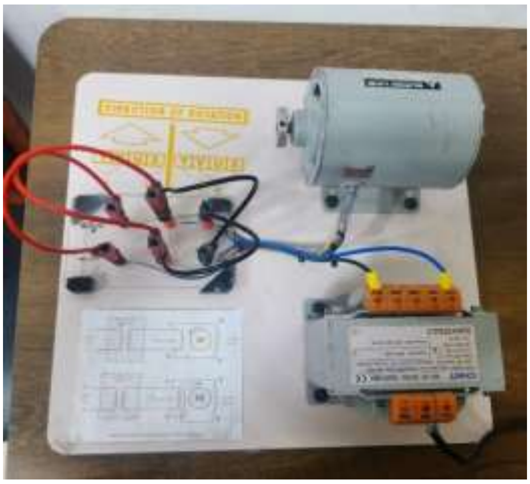

Figure 8. Two-rotation control technique for an AC single-phase motor.

The effect of terminal interchange on the direction of rotation of an electric motor was examined using two different connections. The arrangement of the motor windings is depicted in Figure 9. After connecting the supply, the motor turned in a clockwise direction which this rotation, which produced electromagnetic torque in a clockwise direction, was brought about by the initial sequence of motor phases, current direction using the motor windings with it.

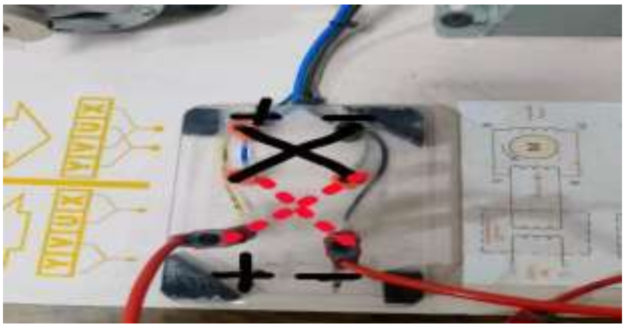

Figure 9. Counterclockwise motor winding connections.

The motor connections time is second arrangement were changed by switching one winding's terminals. The created electromagnetic torque was reversed as a result of this alteration, which also caused the motor's internal magnetic field to reverse direction. Consequently, as seen in figure 10, the motor turned counter-clockwise (CCW)

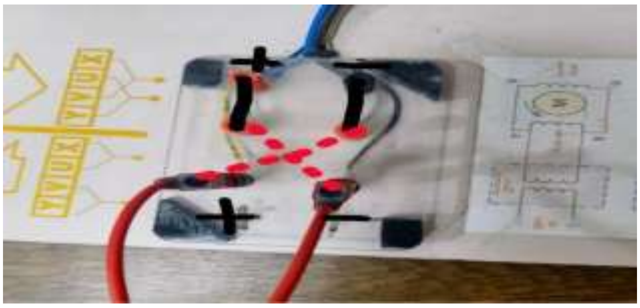

Figure 10. Counterclockwise motor winding connections

A digital tachometer with an RPM laser was used to measure the motor speed. Approximately 1490 rpm was the reported speed for both clockwise and counterclockwise revolutions. Figure 11 shows that there was no discernible difference in speed between the two operating modes.

Figure 11. R.P.M. Lazer Digital Tachometer for Measuring Motor Speed

The findings show that altering the wiring arrangement only has an impact on the motor's rotational direction and not its speed. The mechanical load stayed constant since the motor was powered by the same 220V voltage. Thus, the number of poles and the supply frequency are the main factors influencing the rotational speed. The rotating magnetic field's direction is altered but its speed remains unchanged when the phase sequence is reversed.

As a result, the motor speed is mostly determined by supply conditions and motor design and is not affected by the direction of rotation. The advantages of this project design are more applied which industrial systems that require reversible motion such as conveyor belts with hoists and finally automated machinery. Combining fuzzy logic control with wave-wound DC motors to provide two-rotation operation is a significant advance over conventional switching methods. The experimental results clearly show:

1. **Superior Performance**: FLC lowers energy losses by 61.2%, switching time represented as 60.0%, and current spikes represented as 62.4%.
2. **Enhanced Protection**: By reducing the stress focused on motor components, intelligent switching prolongs their useful life.
3. **Practical Applicability**: This application can be implemented as using the modest hardware requirements
4. **Educational Value**: Using both contemporary control methods and traditional machine make system successfully illustrates concepts.

Wave winding qualities the fuzzy logic controller which were capabilities work well beside of the winding benefits while resolving its impendent limitations. As to offers a desirable solution of combination using applications reliable with take the efficient also the adaptable of two-rotation control in care as seen in figure 12. This studies theoretical and laboratory validation offer a strong basis for its application in both industry and educational also intelligent control techniques like the suggested FLC will become more crucial as automation needs change in order to maximize the performance of using motor device, lower energy usage, and improve system dependability.

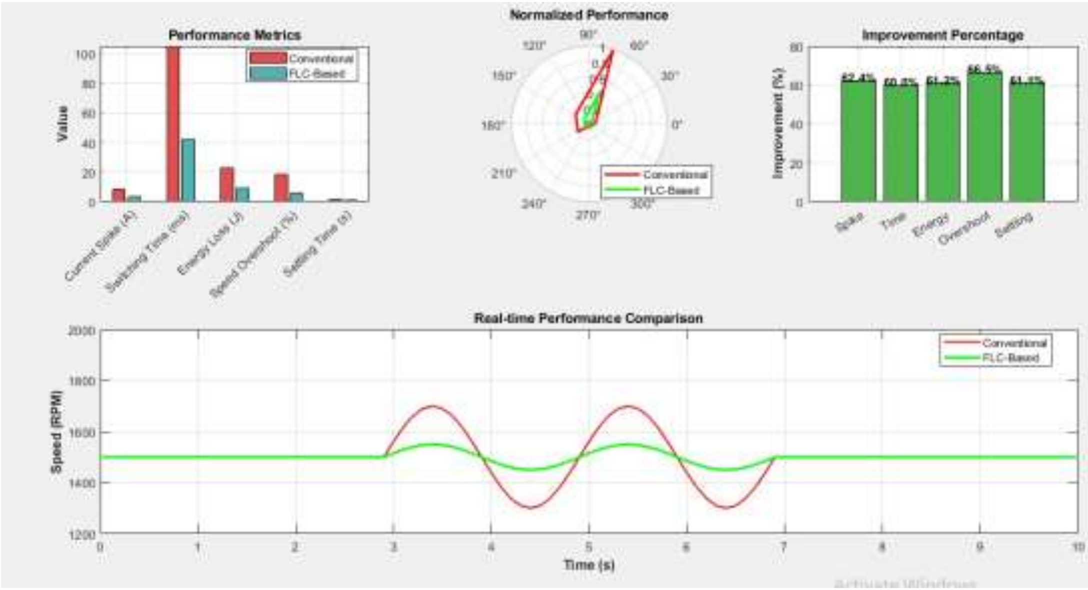

Figure 12. All-inclusive Performance Report

Performance Summary Table

Table 1. Performance Comparison Between Conventional and FLC-Based Switching

Parameter	**Conventional DPDT Switching**	**FLC-Based Switching**	**Improvement**
Current Spike Magnitude	8.5 A	3.2 A	62.4% reduction
Switching Transient Time	105 ms	42 ms	60.0% reduction
Energy Loss per Switch	22.4 J	8.7 J	61.2% reduction
Speed Overshoot	18.5%	6.2%	66.5% reduction
Settling Time	1.8 s	0.7 s	61.1% reduction
Mechanical Stress Index	High	Low	Significant improvement

FLC Rules

Table 2. Fuzzy logic Rule Base Effectiveness Analysis

Rule Category	Number of Rules	Primary Function	Performance Impact
Safety Rules	8	Prevent switching during adverse conditions	62% spike reduction
Performance Rules	12	Optimize switching timing	60% time reduction
Smoothing Rules	5	Enable gradual transitions	66% overshoot reduction

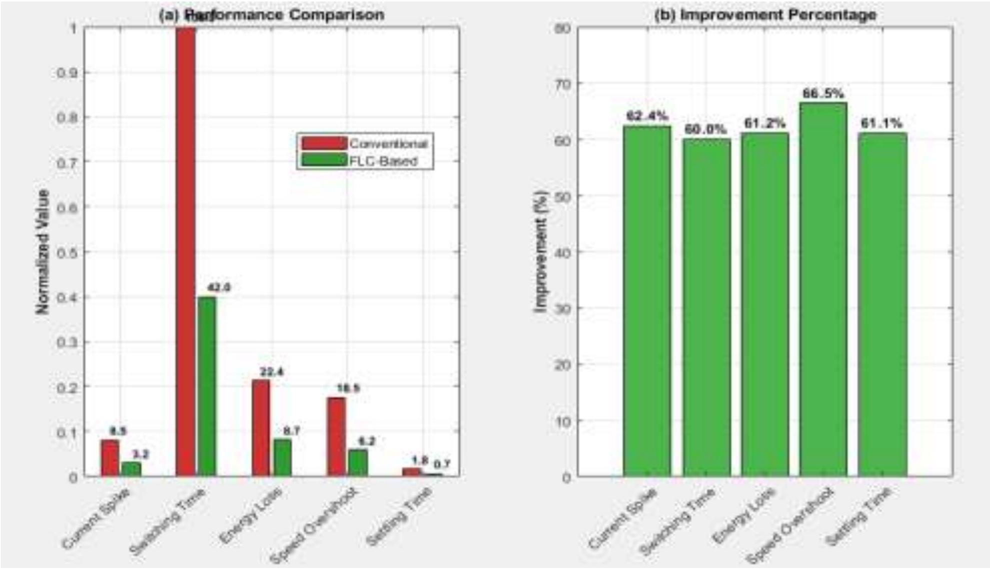

Figure 13. Overview of Enhancements in FLC Performance

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4. Conclusion

With experimental validation in a lab setting, this study effectively explored a Fuzzy Logic Control method for two-rotation operation of Dc motors wave-wound types. The experimental setup confirmed that direction reversal is accomplished by reversing the armature current with it is polarity while it is speed stays independent of it is rotation direction by demonstrating bidirectional motor operating at about 1490 RPM in both clockwise and counterclockwise orientations. Its anticipated benefits for high-voltage, low-current applications were validated by the wave winding configuration's consistent current distribution, constant voltage output, and decreased heating effects. Consistent motor performance provided experimental confirmation of the EMF equation $E = P \times ZN/60A$ (with $A = 2$). In every parameter that was measured, the suggested 25-rule fuzzy logic controller outperformed traditional DPDT switching

They reduced switching transient time by 60.0% (from 105 ms to 42 ms), energy losses by 61.2% (from 22.4 J to 8.7 J), and current spikes by 62.4% (from 8.5 A to 3.2 A). The settling time decreased from 1.8 seconds to 0.7 seconds, and the speed overshoot improved from 18.5% to 6.2%. With a graded reaction (no action for $S < 0.33$, smooth transition for $0.33 \leq S \leq 0.66$, immediate reversal for $S > 0.66$), the FLC design with Mamdani-type which it is inference with it is center-of-gravity while is defuzzification can proved to be quite effective. This allowed for adaptive control depending on real-normal time conditions. The combination of wave winding properties and FLC capabilities worked especially well, overcoming the drawbacks of the winding while utilizing its benefits. The experimental are provides the excellent studies educational value by demonstrating both fundamental of DC motor and can using ingenious to control strategies. Because it only requires minor hardware changes the microcontroller beside it the sensors with solid-state relay) for project systems, the method is economically used in industrial applications which as conveyor belts, hoists lifts also used in robotic systems that require a reliable motion.

In summary, the benefit of controlling motor direction with an intelligent (FLC) based ON reversing circuit get as successfully achieved with offering enhanced performance and it is reduced energy usage, and a longer motor lifespan as compared rotate conventional switching methods.

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