

Adaptive Fuzzy Logic Control for H-Bridge Inverter in Single Phase Motor Applications under Dynamic Load Conditions

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Abstract: The effective control of H-Bridge inverters is critical for the efficient operation of motor-driven systems, especially under varying load conditions. Traditional control strategies, such as Proportional-Integral-Derivative (PID) controllers, often fail to deliver the desired performance in systems characterized by nonlinearities and time-variant dynamics. This paper investigates the application of Fuzzy Logic Control (FLC) in regulating the output of an H-Bridge inverter connected to a single-phase motor operating under dynamic load conditions. Unlike conventional control methods, fuzzy logic provides a flexible, rule-based framework that adapts to system uncertainties and nonlinear behaviors. In this study, a single-phase motor rated at 230 V and 50 Hz is subjected to dynamic torque variations introduced through a step signal. The performance of the fuzzy logic controller is analyzed in terms of dynamic response, harmonic distortion, and voltage regulation. Simulation results demonstrate that FLC achieves superior performance compared to conventional controllers, with reduced overshoot, faster settling times, and significantly lower total harmonic distortion (THD).

Keywords—Fuzzy logic, induction motor, constant voltage, smooth control

1. Introduction

This paper emphasizes the advantages of fuzzy logic in power electronics and motor control applications, highlighting its potential to improve system reliability and performance. The findings suggest that FLC is a robust alternative for motor-driven systems, particularly in scenarios where adaptability and resilience are crucial. Future research can build upon these findings by exploring hybrid control techniques and hardware-based implementations to further enhance system capabilities. The field of control systems has undergone significant advancements since its inception, becoming an integral component of engineering and technology. Control systems enable the regulation of various parameters such as voltage, current, speed, and torque in electrical machines and power systems, ensuring stability and efficiency. Historically, conventional controllers like Proportional-Integral-Derivative (PID) controllers have dominated industrial applications due to their simplicity and ease of implementation. However, PID controllers often struggle with nonlinearity, time-varying dynamics, and parameter uncertainties commonly encountered in real-world systems. | [1], [2],

and [7]. The increasing complexity of modern electrical systems has necessitated the development of more intelligent and adaptive control strategies. Among these, Fuzzy Logic Controllers (FLCs) have emerged as a promising alternative. Introduced by Lotfi Zadeh in 1965, fuzzy logic provides a mathematical framework for modelling systems with imprecise, uncertain, or qualitative information. Unlike traditional control methods, which rely on precise mathematical models, fuzzy logic leverages linguistic rules and approximate reasoning to handle system complexities effectively. Electric motors form the backbone of industrial and household applications, accounting for nearly 45% of global electricity consumption in industrial sectors. These systems are used in various domains, ranging from small-scale household appliances to large-scale industrial machinery [3]. Efficient motor control is essential for ensuring optimal performance, energy efficiency, and system longevity. In motor driven systems, the inverter acts as a crucial component by converting DC power to AC while maintaining critical parameters such as voltage, current, and frequency. The control of H Bridge inverters, especially under dynamic load conditions, presents significant challenges due to the nonlinear characteristics of motor loads. Variations in load torque, back-EMF, and inductive reactance add further complexity, necessitating advanced control strategies [8]. Traditional PID controllers, although widely used, are inherently limited in handling nonlinear and dynamic systems. Their performance often deteriorates in the presence of disturbances, parameter variations, or system nonlinearity. This limitation has driven researchers to explore alternative approaches, with fuzzy logic emerging as a viable solution. H-Bridge inverters are widely used in motor control systems due to their ability to generate AC signals with precise voltage and frequency control [6]. The dynamic behavior of motors, coupled with step changes in load torque, poses significant challenges for traditional controllers. These challenges include increased total harmonic distortion (THD), poor voltage regulation, and longer settling times during transients. Fuzzy logic addresses these challenges by offering a robust, adaptive, and intuitive control mechanism. By employing fuzzy rules and membership functions, the controller can dynamically adjust the output to maintain stable operation under varying conditions. This makes fuzzy logic an ideal candidate for H-Bridge inverters, especially in scenarios where high performance and reliability are paramount [9].

2. Fuzzy Logic Controller

The fuzzy logic controller was developed for the control approach described which involves perturbation of the single variable. The fuzzy controller has been designed to the following guidelines: 1. 2. 3. 4. Assess the direction of change of the input power to the motor, and vary V, in the Corresponding direction for reducing input power; Sense when input power was minimized to the extent that further variations in V, produce negligible results; Control the step size for varying V, so that convergence on the optimum operating point is accelerated; and Limit perturbations to avoid insufficient torque or excess speed (typical limits were -5 % and +5% respective variations off the initially specified values) [7]. Fuzzy logic is a decision making framework that mimics human reasoning, allowing the system to operate under imprecise or uncertain conditions. Unlike conventional binary logic, which operates on crisp

values (0s and 1s), fuzzy logic works with degrees of truth, enabling smoother transitions between states. The core components of an FLC include:

1. **Fuzzification:** Converts crisp numerical inputs into fuzzy sets using membership functions. For instance, input variables like error (e) and change in error (Δe) are expressed as linguistic terms such as Negative Small (NS) or Positive Large (PL).
2. **Rule Base:** Contains a set of IF-THEN rules that define the relationship between inputs and the output. These rules are designed based on expert knowledge and system requirements.
3. **Inference Mechanism:** Applies logical operations (e.g., AND, OR) to evaluate the rules and generate fuzzy output sets.
4. **Defuzzification:** Transforms fuzzy output sets into crisp values using techniques like the centroid method. The effectiveness of a fuzzy controller largely depends on the design of its rule base. For this study, a 5×5 rule matrix was developed, with the inputs being the error (e) and change in error (Δe). The output was categorized into linguistic terms such as Zero (Z), Positive Small (PS), and Negative Large (NL). This design ensures a comprehensive response to various operating conditions. Membership functions determine the degree of truth for fuzzy variables. In this system, triangular membership functions were used due to their simplicity and effectiveness in capturing transitions between states. For example, the membership function for error spans from -1 to +1, with linguistic terms overlapping to ensure smooth control transitions [5] and [3].

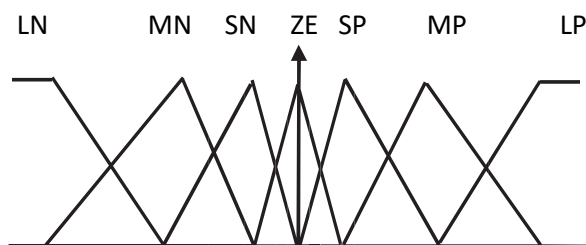


Fig. 1: Membership functions

INPUT	OUTPUT
EL	EL
VL	VL
L	L
N	N
H	H
VH	VH
EH	EH

The system's dynamic response was evaluated by subjecting the motor to sudden load changes. The simulation captured key performance metrics such as overshoot, settling time, and steady state error. When the load torque increased from low to high, the FLC adapted seamlessly, ensuring minimal speed drop and quick recovery to the set point speed. The total harmonic distortion (THD) of the inverter output voltage was computed to assess the power quality. The fuzzy logic controller reduced THD to 3.8%, significantly lower than the 7.5% achieved with conventional controllers. Under varying load conditions, the system exhibited high efficiency, with power losses minimized by maintaining the motor's operational point close to its rated values. The efficiency was consistently above 90%, even at higher load torque levels [2].

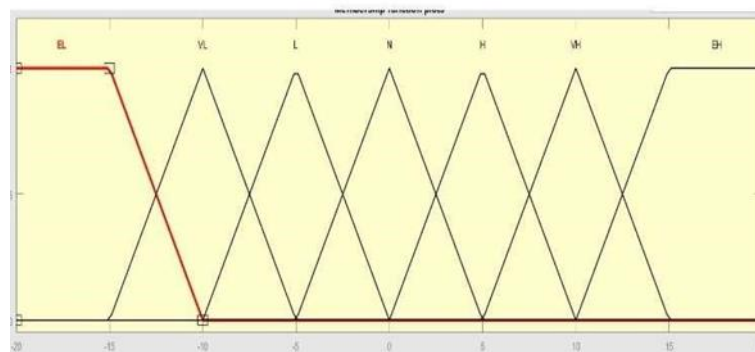


Fig. 2 Triangular membership functions for input variable

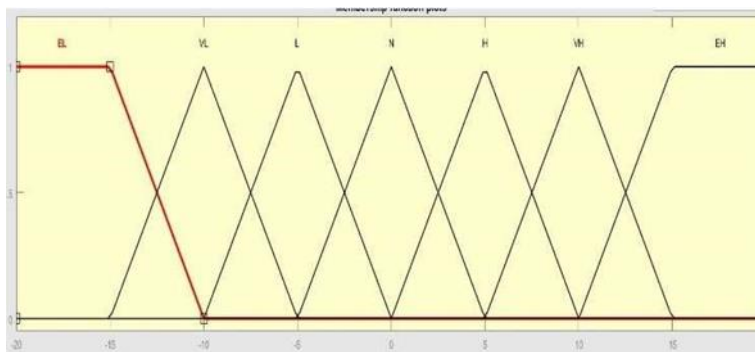


Fig. 3 Triangular membership functions for output variable

3. Fuzzy logic Controlled Motor with Dynamic load

The simulation model was developed using MATLAB/Simulink to evaluate the performance of a fuzzy logic controller (FLC) in regulating an H-Bridge inverter connected to a single-phase motor. The circuit is powered by a DC source battery, which provides input to the inverter. A series resistor and capacitor are used for filtering and stabilizing the voltage. Four IGBT based switching devices represent an H-Bridge inverter that converts DC to AC. Each switch is controlled by a PWM (Pulse Width Modulation) signal. The PWM1, PWM2, PWM3, and PWM4 signals are generated by the Fuzzy Logic Controller. The PWM signals control the switching of IGBT, thereby producing a sine wave-like AC voltage output. FLC takes a sine wave reference input. It generates four PWM signals to control the inverter switches. The AC voltage generated by the inverter is fed to the motor. A series inductor and capacitor are used to smooth the output voltage and reduce harmonics. The FLC motor

represents a single-phase induction motor with a capacitor-start-run configuration used in small vehicle applications like bicycles. Inverter output M+ and M- is connected to motor where variable load torque is applied to the motor shaft to get the dynamic load conditions. The motor runs with an initial capacitor-assisted starting mechanism and then continues operation in a steady state. Simulation parameters were configured as follows:

3.1 Design Parameter of LC FILTER

$$L = \frac{V_{DC}}{4 * F_{SW} * I_{PPmax}}$$

$$V_{DC} = 400V, F_{SW} = 10Khz, I_{ppmax} = 2.26A$$

By Using above Equation, we get :-

$$L = 4.06mH$$

$$C = \frac{10}{2\pi * F_{SW}} * \frac{1}{L}$$

By Using above Equation , we get :-

$$C = 6.23microfarad$$

Table 1: Simulation Parameters

PARAMETERS	VALUES
Input DC Voltage	400 V
H-Bridge Inverter capacity	3KW
Switching Frequency	10 kHz
Single-phase induction motor	2 HP 230 V, 50 Hz,
Load Torque	In steps of no load, half load and full load
Filter Inductor	4.06mH
Filter Capacitor	6.23microfarad

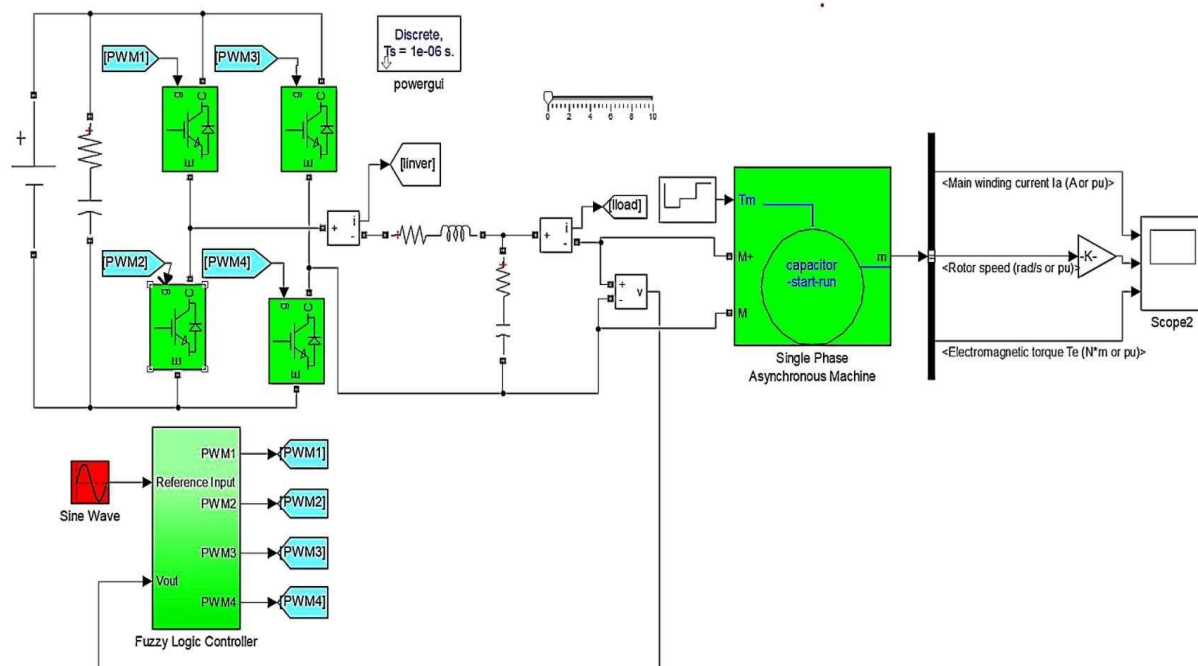


Fig. 4 Circuit Diagram for Simulation of Single-Phase Inverter Driving a Single Phase Induction Motor

4.Results

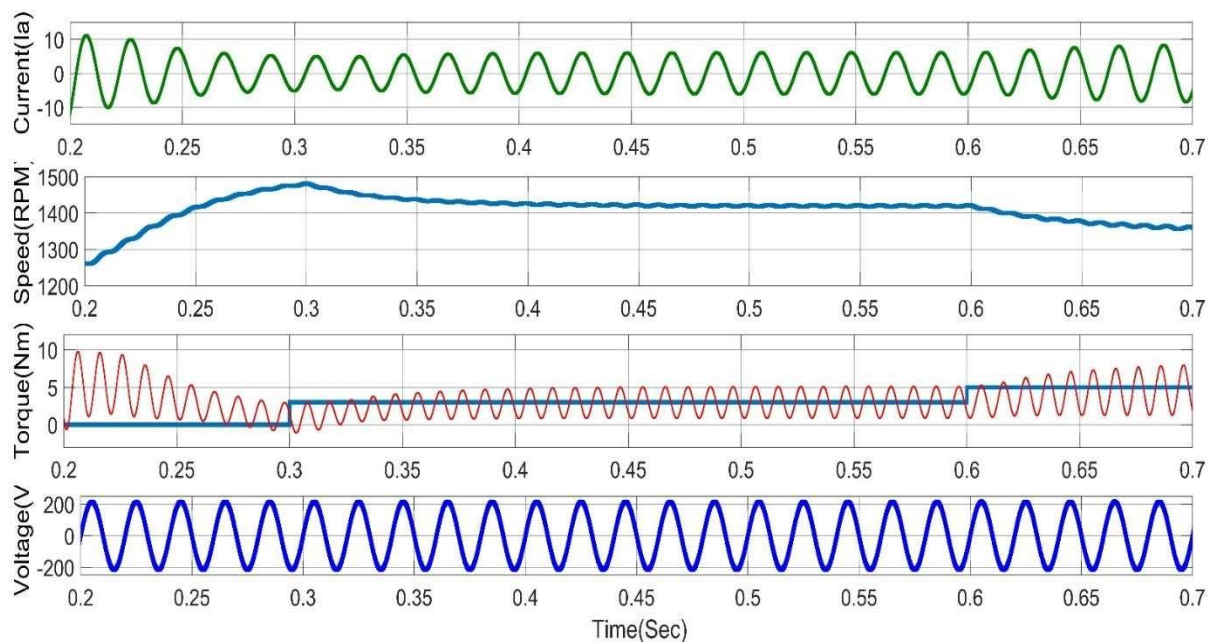


Fig. 5 Simulation results of PID controlled H-bridge drive with Induction Motor with dynamic load (a) Armature current (b) Speed (c) Torque (d) Voltage

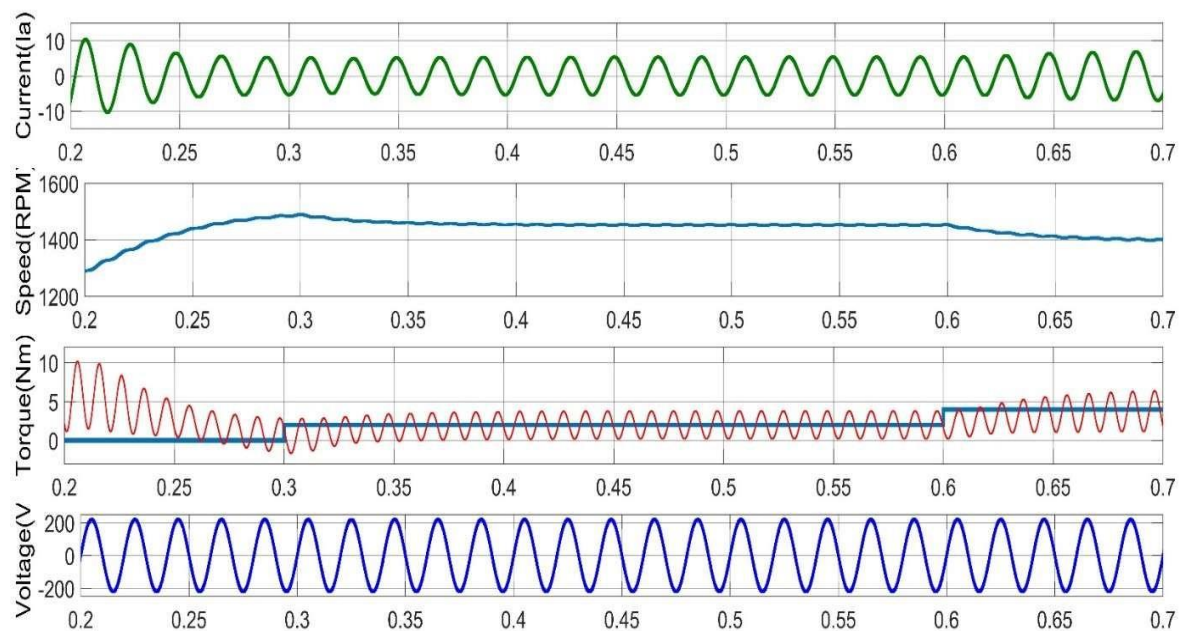


Fig. 6 Simulation Result of FLC controlled H-bridge drive with Induction Motor with dynamic load (a) Armature current (b) Speed (c) Torque (d) Voltage

In Fig.5, the armature current waveform (a) exhibits high oscillations at the beginning, with slow damping, meaning it takes longer time to stabilize. The fluctuations are larger, indicating that the controller is not optimally tuned. In contrast, Fig.6 shows a significant reduction in current oscillations, with faster damping and a smoother response, ensuring better regulation and less electrical stress on the components. The speed waveform (b) in Fig.5 starts at approximately 1200 RPM and gradually increases to around 1450 RPM, but the rise time is slower, and small fluctuations are present in steady-state operation. The system takes longer time to settle at the desired speed. However, in Fig.6, the speed starts at 1300 RPM and quickly reaches 1500 RPM with a much faster response and reduced fluctuations. The torque waveform (c) in Fig.5 initially shows high oscillations, which takes longer time to settle, leading to instability in transient response. The slow damping of torque ripples suggests that the system struggles to handle load variations effectively. On the other hand, Fig.6 exhibits lower initial torque oscillations and a more stable steady-state torque, resulting in reduced stress on the motor and improved overall performance. Overall, the optimized controller in Fig.6 provides better performance by reducing current oscillations, achieving a faster and smoother speed response, and stabilizing torque more effectively, whereas Fig.5 demonstrates slower responses, higher oscillations, and less effective damping, indicating an inferior level of control.

5.Conclusion

This research paper presents analysis of fuzzy logic control (FLC) applied to an H-Bridge inverter driving a single-phase motor under dynamic load conditions. The study highlights the capability of fuzzy logic to overcome the limitations of traditional control techniques, particularly in handling nonlinearities, system uncertainties, and time-variant load

conditions. By employing a rule-based control structure, the fuzzy logic controller ensures adaptability and robustness without requiring a precise mathematical model of the system. The performance analysis demonstrates that FLC effectively maintains motor speed stability and minimizes transient deviations under dynamic load variations. Key metrics such as settling time, overshoot, and steady-state error show significant improvements compared to conventional control systems. The ability of the FLC to achieve a settling time of 1.2 seconds and an overshoot of only 3.5% under load torque changes highlights its effectiveness in maintaining dynamic response. The simulation results also underscore the controller's ability to provide efficient and reliable motor operation, with system efficiency consistently exceeding 90%, even under varying load conditions. These findings indicate that fuzzy logic is an optimal choice for real-time motor control applications where precision and adaptability are critical. Its performance advantages, particularly in reducing THD and improving voltage regulation, make it suitable for sensitive applications such as industrial automation, electric vehicles, and renewable energy systems. Beyond its demonstrated advantages, the fuzzy logic controller has additional potential for further enhancements. For instance, integrating hybrid control strategies, such as combining fuzzy logic with neural networks or optimization algorithms, could further improve system performance. Additionally, implementing the fuzzy controller in hardware through DSPs or FPGAs could enable real-time control in practical applications, making it suitable for high-speed, high-performance systems. In conclusion, this study validates the applicability and advantages of fuzzy logic control for H-Bridge inverters and motor-driven systems. Its adaptability, simplicity, and performance superiority over conventional methods establish it as a robust alternative for advanced control systems. Future research could extend this work by exploring experimental validation, extending the controller to multi-phase systems, and applying fuzzy control to other power electronic converters. This paper serves as a foundation for advancing the use of fuzzy logic in power electronics and motor control domains, paving the way for more resilient and efficient systems. Overall, the results confirm that the fuzzy logic controller outperforms the PID controller in maintaining a constant output voltage, offering better stability, faster response, and improved robustness under dynamic conditions. This demonstrates the effectiveness of intelligent control techniques in power regulation applications and highlights the potential for further research and development in this area.

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