

Received Date: 9th November, 2025

Revision Date: 23rd December, 2025

Accepted Date: 21st January, 2026

Fuzzy Logic Controller Implementation for Induction Motor Soft Start

Bibek Dhakal^{1*}, Sagar Nayak², Sandip Rokaya³, Shashi Adhikari⁴

¹Dept of Electrical Engineering, Pulchowk Campus, TU, Nepal. E-mail : 077bel016.bibek@pcampus.edu.np

²Dept of Electrical Engineering, Pulchowk Campus, TU, Nepal. E-mail : 077bel036.sagar@pcampus.edu.np

³Dept of Electrical Engineering, Pulchowk Campus, TU, Nepal. E-mail :077bel037.sandip@pcampus.edu.np

⁴Dept of Electrical Engineering, Pulchowk Campus, TU, Nepal. E-mail :077bel041.shashi@pcampus.edu.np

Abstract — *Direct-on-line starting of three-phase induction motors causes high inrush current, voltage dips, and torque oscillations, reducing motor life and system stability. Conventional soft starters like auto-transformers and star-delta systems offer limited efficiency and control. This paper proposes a fuzzy logic controller (FLC)-based soft starter for induction motors driving fan-type loads to achieve smooth, adaptive, and energy-efficient operation. The system, modelled in MATLAB/Simulink with optimized membership functions and rule bases, uses weighted average defuzzification for real-time voltage control. Simulation results show that the FLC reduces peak starting current to about 41 A, compared to 80 A in direct-on-line and 54 A in PI-controlled methods. The fuzzy-based system provides smoother torque and speed response, reducing mechanical stress and improving performance. Thus, FLC-based soft starters offer an efficient, scalable, and intelligent solution for industrial applications such as HVAC systems, pumps, and conveyors, with potential for future hardware implementation.*

Keywords — *fuzzy logic controller, soft starter, MATLAB Simulink, fan-type load, intelligent control motor performance*

I. Introduction

Three-phase induction motors are very common in industrial and commercial systems due to their simplicity, robustness, and low maintenance requirements. However, when started directly on-line (DOL), these motors draw inrush currents up to six to eight times their rated value, causing voltage dips, high mechanical stress, and possible damage to motor windings. Traditional starting techniques such as star–delta, autotransformer, or resistor starters reduce the initial voltage but lack adaptive control and flexibility under varying load conditions.

Several studies have explored soft start mechanisms for induction motors, emphasizing the reduction of inrush current, torque shock, and harmonic distortion through

advanced control strategies. During start up, three-phase induction motors experience high current, leading to mechanical stress and potential coil damage [1]. N. Duah et al. (IRJET, 2022) compared DOL, Star-Delta, Autotransformer, and Soft Starting methods, concluding that soft starters are best suited for loads where torque increases with speed [13]. DOL starters often cause harmful voltage drops under weak AC supply conditions [2][9], while conventional methods, though improving startup characteristics, still exhibit lower efficiency and poor power factor under light loads [3][4][5]. Adjustable Frequency Drives (AFDs) offer precise speed control but are costly and demand higher insulation levels [6]. In contrast, thyristor-based soft starters have become more favourable for their cost-effectiveness, reliability, and compact design [7]. Abdelghany et.al. further modelled induction motor startup under fan-type loads, providing insights for efficient controller design [11]. Research findings consistently show that soft starters outperform DOL systems in minimizing current surges and mechanical stress during startup [10][13].

With recent advancements in intelligent control, fuzzy logic controllers (FLCs) have gained significant attention for nonlinear systems where precise mathematical modelling is challenging. Fuzzy logic provides adaptive, rule-based decision-making, allowing smooth control even under variable load and uncertain operating conditions [8]. Induction motors, particularly under full-load conditions, face issues with high inrush currents up to eight times the rated value resulting in voltage dips, thermal stress, and inefficiencies. The squirrel-cage motor's low starting torque per ampere, caused by heavy rotor current lag at standstill, further limits performance. In fan-type loads, where torque demand rises with the square of the speed, a fuzzy-logic-based soft-starting approach can limit the starting current to about three to four times the full-load current, enabling smooth acceleration, reduced mechanical stress, and improved system reliability.

* Corresponding Author

II. Therefore, this paper focuses on the design and simulation of a fuzzy logic controller (FLC)-based soft starter for a three-phase induction motor operating with fan-type load characteristics. The primary goal is to reduce starting current and torque oscillations while ensuring smooth acceleration, enhanced efficiency, and overall system stability, supporting potential applications in HVAC systems, industrial ventilation, cooling towers, and centrifugal pumps.

III. Methodology

2.1 System Overview

The system under study consists of a three-phase 5.4 HP (4 kW) squirrel cage induction motor with a rated voltage of 400 V, 50 Hz, and 8.25 A rated (RMS) current. The model simulates motor dynamics under DOL, PI, and FLC-based starting techniques to compare performance parameters such as current, torque, and speed.

The motor drives a fan-type load, characterized by torque proportional to the square of speed ($T_L \propto \omega^2$). The simulation setup includes, The system consists of a three-phase voltage source supplying power to an SCR-based converter for voltage control, integrated with a control logic unit—either a Proportional-Integral (PI) or Fuzzy Logic Controller (FLC)—to regulate the startup process. Additionally, measurement blocks are included to monitor motor parameters such as current, torque, and speed for performance evaluation and feedback control.

2.2 Fuzzy Logic Controller Design

A fuzzy logic controller (FLC) for soft starting of an induction motor enhances performance and reliability through adaptive, real-time control. It features a *self-tuning algorithm* that continuously adjusts parameters based on the deviation and rate of deviation of the motor's starting current. Key components include:

1. **Self-Tuning:** Automatically modifies fuzzy rules and membership functions in real time to minimize inrush current and mechanical stress.
- Quantitative and Scale Factor Tuning:** Adjusts input/output scaling and numerical parameters for accurate response to current deviations.
- Constant Current Control:** Maintains current within a safe range during startup, ensuring smooth acceleration and reduced thermal and mechanical stress.
- Fuzzy Inference Process:** Involves *fuzzification* (converting inputs to fuzzy values), *rule evaluation* (applying fuzzy

rules), and *defuzzification* (producing real-world control signals).

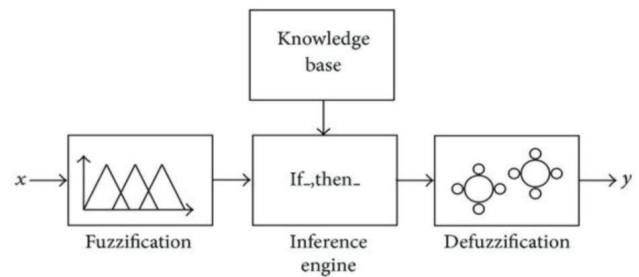


Fig 1: Fuzzy logic control mechanism

The fuzzy logic controller (FLC) was designed with one input and one output variable:

- Input: Error in stator current (difference between actual and reference current)
 - Output: Control signal to adjust the converter's firing angle
- The fuzzy system consists of three stages:

1. **Fuzzification:** Converts the crisp input error into fuzzy linguistic variables (e.g., *Low*, *Medium*, *High*).
2. **Inference Mechanism:** Applies a rule base to determine the control action using the Sugeno method.
3. **Defuzzification:** Converts fuzzy output back into a crisp value using the *weighted average (WA)* method:

$$x^* = \frac{\sum \mu(x_i) x_i}{\sum \mu(x_i)} \quad 1$$

2.3 Simulation Model

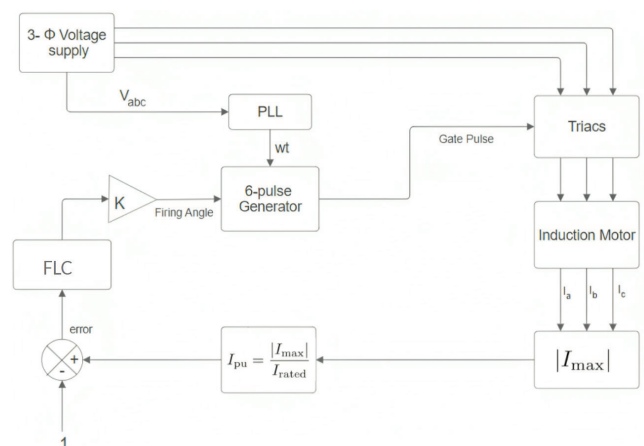


Fig 2: Block Diagram

The input and output membership functions of the fuzzy logic controller (FLC) are simulated for a fan-type load using the Sugeno model as shown in below figure.

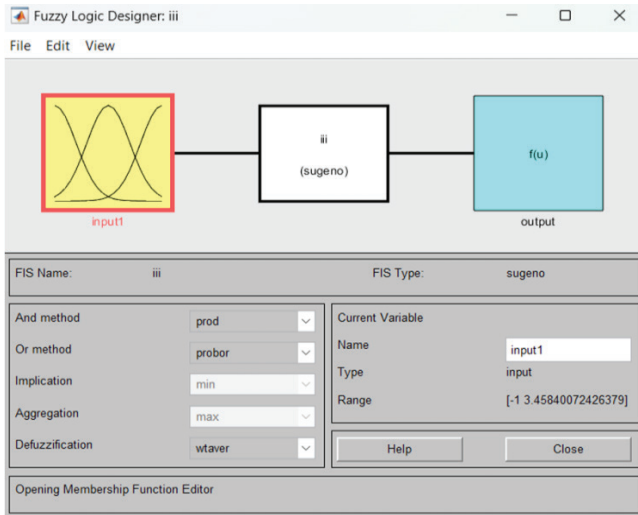


Figure 3: Sugeno FIS structure with input setup in MATLAB.

2.4 Membership Function Design

The input variable (current error) was divided into four triangular membership functions (MFs) ranging from -1.3-1.3-1.3 to 3.4583.4583.458 pu. The output variable (firing angle adjustment) was divided into four constant membership functions.

Table 1

Input Membership Functions

MF	Range	Type
in1mf1	[-2.518, -1.027, -0.1096]	Triangular
in1mf2	[-0.5662, 0.5974, 1.569]	Triangular
in1mf3	[-0.0242, 2.189, 3.528]	Triangular
in1mf4	[1.992, 3.595, 5.07]	Triangular

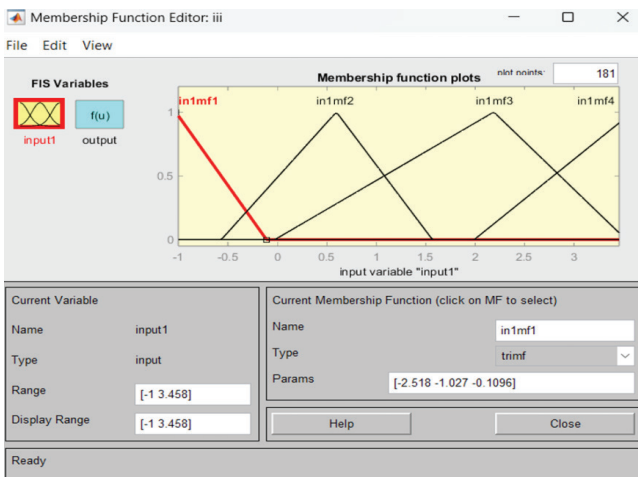


Figure 4: Input membership function: in 1mf1

Table 2

Output Membership Functions

MF	Value (pu)	Type
out1mf1	0.6724	Constant
out1mf2	0.0647	Constant
out1mf3	0.5513	Constant
out1mf4	0.999	Constant

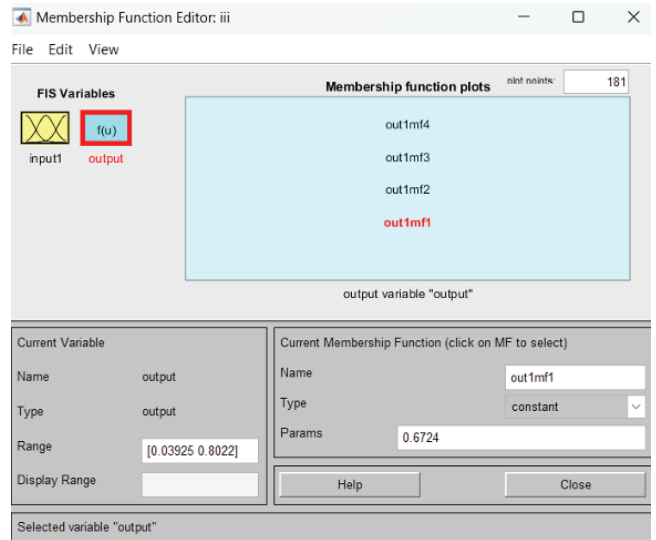


Figure 5: Output membership function: out1mf1

2.5 Fuzzy Rule Base

The rule base defines the mapping between input and output membership functions as follows:

1. IF (Error is in1mf1) THEN (Output is out1mf1)
2. IF (Error is in1mf2) THEN (Output is out1mf2)
3. IF (Error is in1mf3) THEN (Output is out1mf3)
4. IF (Error is in1mf4) THEN (Output is out1mf4)

This structure ensures adaptive voltage control: when current exceeds the rated value, the controller increases the firing angle to reduce voltage; when current decreases, voltage gradually increases, ensuring smooth acceleration.

The simulation was executed under identical conditions for DOL, PI, and FLC-based control to enable direct performance comparison.

IV. Results and Discussion

A. Direct Online Starting Method

Direct-On-Line (DOL) method is the simplest and most generic method to start three-phase induction motors. For this process, the motor is directly connected with the supply

voltage using a switch or a starter. During the starting, the motor has an enormous starting current since there exists no back electromotive force (EMF) at that time. This inrush current is generally 5 to 7 times the full-load current of the motor. In a plot of current vs. time, we have a large spike at the start which steadily reduces as the motor picks up speed and back EMF increases. Ultimately, the current approaches the rated value over time.

The details we obtained are:

- Steady State Current: 11.67 A
- Peak Current: 80 A

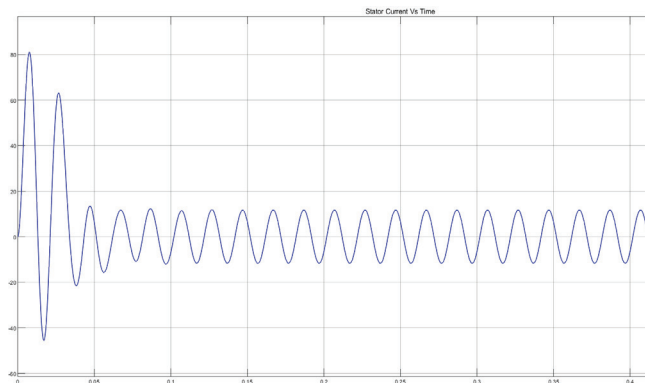


Fig. 6. Correct detection of vegetation fault and normal insulator condition

This shows the starting current response of the induction motor during Direct-On-Line (DOL) starting. From the figure, we observed that the starting current shoots up to around 80 A initially, which is approximately 7 times the rated current (11.67 A). After a few seconds, the current gradually settles down to the steady-state value. This large inrush current can cause electrical and mechanical stresses on the motor and supply system.

B. Starting Method Using PI

Secondly, we focused on the starting behavior of an induction motor using a Proportional Integral (PI) controller. A PI controller works by minimizing the error between a desired setpoint and the actual output through proportional and integral actions. During startup, it regulates the applied stator voltage to gradually accelerate the motor, minimizing the harsh electrical and mechanical stresses typically associated with direct starting methods. In this project, the PI controller successfully limited the initial inrush current profile during startup. Compared to traditional Direct-On-Line (DOL) starting, the PI controller ensured a controlled and optimized motor acceleration, improving system reliability and reducing mechanical wear. The graphs we

obtained through the Matlab simulation during PI Controller Method are shown below:

The details we obtained are:

- Steady State Current: 11.67 A
- Peak Current: 54 A

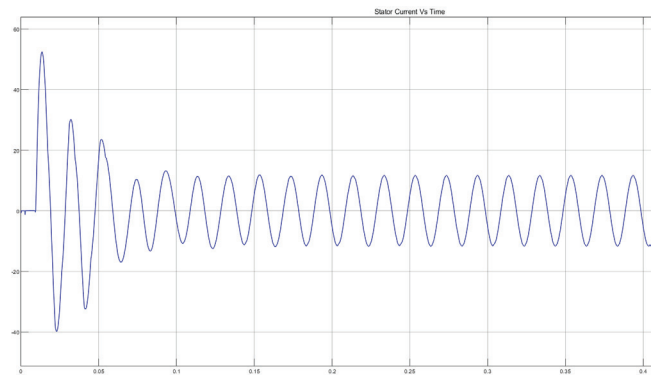


Fig. 7. Training and validation losses

From the plot, we observed that the starting current initially rose to a peak value of approximately 54 A, which is significantly lower than the 80 A for Direct-On-Line (DOL) starting. The values $P=0.67$ and $I=0.0055$ are used in the PI controller to achieve a starting current of 54 A. As compared to DOL, where the rise in current occurs very quickly and imposes excessive stress on the motor and electrical equipment, the PI controller limits the inrush current very well, and the start up is very smooth and safe. After the initial peak has passed, the PI-controlled motor current damps out and settles to the steady-state value of approximately 11.67 A. This operation depicts how the PI controller not only aids in lowering the peak start up current but also aids in achieving the smoother and faster current settling compared to the DOL process where current takes a greater period of stabilizing

C. Starting Method Using Fuzzy Logic Control

Thirdly, Fuzzy Logic Control (FLC) was utilized to optimize the starting performance of an induction motor. The voltage applied across the stator windings is adjusted gradually. We implemented the Sugeno fuzzy method, and we designed four triangular membership functions for the input variables and four constant membership functions for the output. This design allowed for simple yet highly effective decision-making during the startup phase to ensure adaptive control of the stator voltage and minimizing inrush current. MATLAB simulations were carried out to validate the system's performance, and the results demonstrated the superior ability of the fuzzy controller to manage starting

conditions smoothly and efficiently. The simulation results clearly demonstrate its effectiveness in minimizing inrush current and achieving a smooth acceleration profile. As observed from the graphs generated in MATLAB, the peak starting current reached approximately 41 A, which is less than the four times the rated full-load current. The graphs we obtained through the Matlab simulation during Fuzzy Logic Controller (FLC) Method are shown below:

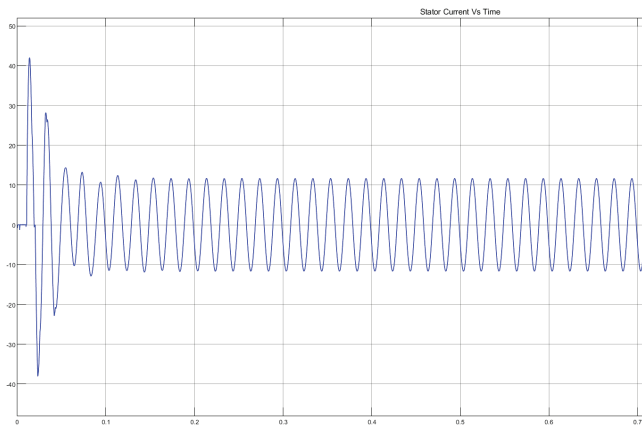


Fig. 8. Training and validation losses

The peak starting current characteristic of an induction motor is significant when it comes to protecting the motor and maintaining network stability. In Figure 4.4, the PI controller was able to reduce the peak starting current to about 54 A, which was already a significant improvement over the 80 A observed during DOL starting. However, there are more visible damped oscillations prior to stabilization to steady state. Though the PI controller significantly improved current control during DOL starting, residual oscillations and slower stabilization were still drawbacks. The Fuzzy Logic Controller (FLC) solved these problems by not just reducing the peak starting current even further to 41 A but also by giving a faster and more smooth transition to steady-state, minimizing electrical stresses and enhancing the reliability of the startup procedure.

V. Conclusions

Our project developed a fuzzy logic-based soft starter for induction motors, reducing inrush current and mechanical stress during startup. Experimental and simulation results showed that the DOL starter had a high inrush current of 80A, the PI controller-based soft starter reduced it to 54A, and our fuzzy logic controller further minimized it to 41A, improving motor performance with smoother speed and torque characteristics. Unlike DOL, auto transformers, or star-delta methods, our approach provides adaptive control without detailed motor parameters, lowering harmonic

distortion and improving power quality without costly filters. It is cost-effective and ideal for HVAC, pumps, conveyors, and fan-type loads. We are optimizing the system to further reduce the starting current to 40A for better efficiency. While load-related limitations exist, this method enhances smart motor control and industrial automation.

References

- [1] P. Oli, "Transmission Line Survey in Nepal," *Proceedings of the FIG Working Week 2023: Protecting Our World, Conquering New Frontiers*, Orlando, Florida, USA, May 28–June 1, 2023
- [2] "MyRepublica," "Nepal's transmission lines doubled to 6,507 circuit km in eight years," *MyRepublica*, Nov. 21, 2024.
- [3] eSmart Systems, "All You Need to Know About Power Line Inspections with the Use of Drones."
- [4] D. C. Nguyen, L. N. Tam, D. H. Phan, C. Nguyen, D. N. Duy, and Q. N. Xuan, "Using drone and AI application for power transmission line inspection and maintenance: a case study in Vietnam," in *Lecture notes in networks and systems*, 2023, pp. 684–698. doi: 10.1007/978-3-031-37717-4_44.
- [5] H. Huang et al., "TLI-YOLOV5: a lightweight object detection framework for transmission line inspection by unmanned aerial vehicle," *Electronics*, vol. 12, no. 15, p. 3340, Aug. 2023.
- [6] C. Chen, G. Yuan, H. Zhou, and Y. Ma, "Improved YOLOv5s model for key components detection of power transmission lines," *Mathematical Biosciences & Engineering*, vol. 20, no. 5, pp. 7738–7760, Jan. 2023.
- [7] J. Redmon, S. Divvala, R. Girshick, and A. Farhadi, "You Only Look Once: Unified, Real-Time Object Detection," *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, Las Vegas, NV, USA, 2016, pp. 779–788, doi: 10.1109/CVPR.2016.91.
- [8] J. Breckling, Ed., *The Analysis of Directional Time Series: Applications to Wind Speed and Direction*, ser. Lecture Notes in Statistics. Berlin, Germany: Springer, 1989, vol. 61.
- [8] S. J. Pan and Q. Yang, "A Survey on Transfer Learning," *IEEE Transactions on Knowledge and Data Engineering*, vol. 22, no. 10, pp. 1345–1359, Oct. 2010, doi: 10.1109/TKDE.2009.191.
- [9] Goodfellow, Y. Bengio, and A. Courville, *Deep Learning*. Cambridge, MA, USA: MIT Press, 2016.