

## Speed and Current Using Fuzzy Controllers of PMSM under Field-Weakening

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### Abstract:

The present study explores a field-weakening control strategy for Permanent Magnet Synchronous Motors (PMSMs) to enable high-speed operation beyond their nominal speed limits. The research introduces an innovative approach using Fuzzy Logic-based control to enhance speed and current sensitivity management. This methodology significantly improves the motor's dynamic performance, achieving rapid response and effectively counteracting load torque disturbances. A fuzzy controller is employed to regulate the rotational speed and the stator current component on the d-axis in external regulating loops, with reference values dynamically adjusted based on operating speed and conditions. Comparative simulations between the proposed Fuzzy-PI control system and the conventional PI controller reveal the superior performance of the fuzzy control strategy. Notably, when subjected to a load torque of 0.2 N·m at 0.4 seconds, the Fuzzy-PI controller minimized the effects of noise on speed regulation, as shown in the simulation results. Furthermore, under a higher load torque of 1 N·m at 1 second, the Fuzzy-PI controller demonstrated smoother transitions, reduced current vibrations, and enhanced stability in transient states. These results underline the controller's robustness, achieving faster response time, better stability, and more precise reference tracking. Such performance makes the proposed Fuzzy-PI control system a promising alternative for high-performance industrial applications requiring efficient and reliable motor operation at high speeds.

### Keywords:

Fuzzy logic; Field weakening; Permanent magnet synchronous motor (PMSM); PI control.

### Highlights:

- Control strategy of field weakening for Permanent Magnet Synchronous Motors (PMSMs).
- Logic control for better speed and current sensitivity management.
- A fuzzy controller is used to control the rotational speed and the stator current component.
- The Fuzzy-PI controller reduces the noise effects on the speed regulation.

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## 1. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have been widely used in many industrial applications due to their high efficiency, high power density, and precise speed control [1, 2]. However, PMSMs have a fundamental limitation in that they cannot operate beyond the base speed without the degradation of the motor performance [3]. This limitation is mainly due to the constant magnetic flux produced by the permanent magnets which cannot be dynamically modified [4-6]. In order to solve this problem, the field weakening control strategy has been developed and widely applied [7-9], such as the Fuzzy Sliding Mode Control [10], Rotor Field-Oriented Control (RFOC) and Stator Field-Oriented Control (SFOC) [11], Flux-weakening (FW) control technique [12], and PMSM Based on Online Model Parameter [13-15]. These control methods allow PMSMs to operate above the base speed by reducing the magnetic flux and extending the constant power region of the motor operating envelope [16]. Fuzzy logic control is one of the promising methods to control the field weakening which can provide improved dynamic performance and stability over traditional techniques such as PI controllers [17]. In this paper, a novel scheme for speed control of Induction Motor (IM) using fuzzy-logic control is proposed. The Fuzzy-Logic Controller (FLC) based on the indirect vector control is used in the outer loop and its performance is experimentally studied and compared with the conventional Proportional-Integral (PI) based drive. The results indicate that the FLC presents a better robustness and can be a good substitute of PI controller in high performance industrial drive applications. The structure of this paper is as follows: Section 2 presents the mathematical model of the PMSM system including the equations of voltage, current and torque. Section 3 describes the field weakening control strategy and its implementation. The design of the fuzzy control system is explained in Section 4. The performance of the fuzzy control system is compared with a conventional PI control system in Section 5. Finally, Section 6 concludes the paper and summarizes the main contributions. In this paper, we present a new fuzzy control system to improve dynamic performance and enhance stability over conventional methods, and establish an effective control strategy for permanent magnet synchronous motors (PMSMs) to break the limitation of maximum operating speed without affecting performance. The research will address proportional-integral (PI) controllers and will demonstrate means to mitigate the effects of vibrations on current and transient responses, and to enhance the stability of the system during load periods. Furthermore, the research will provide a

comprehensive framework to upgrade highly efficient industrial operations by advanced control technologies. For future work, an intelligent controller like Pelican Optimization Algorithm (POA), Neural Network Genetic Algorithm (NNGA), or Particle Swarm Optimization (PSO) algorithm [18-19]; using a precision scale, it can be used to evaluate the performance of the technologies presented.

## 2. MODEL OF THE SYSTEM

To ensure a clear path, a structured methodology was designed to achieve the objectives of this research. Initially, the system was dynamically analyzed, and mathematical models of the motor's behavior were developed in dq frame coordinates. Subsequently, the proposed control strategies were designed using fuzzy logic, and a closed-loop control system was developed based on the system's characteristics. The following work illustrates the systematic process employed:

- 1- System Analysis:
  - Study the electrical and mechanical behavior of the PMSM.
  - Formulate mathematical models to describe the relationships between voltage, current, and torque.
- 2- Design Control Strategies:
  - Design a Proportional-Integral (PI) controller.
  - Develop a fuzzy-logic control system to achieve stability and improve dynamic performance.
- 3- Modeling and Simulation:
  - Develop the dynamic model using MATLAB/Simulink.
  - Perform simulations to test different control strategies.
- 4- Analysis and Comparison:
  - Compare the dynamic performance of traditional PI controllers and fuzzy logic controllers.
  - Measure transient response, noise reduction, and system stability improvements.
- 5- Extracting Results:
  - Analyze the data obtained from simulations.
  - Evaluate performance and provide recommendations for practical applications.

The equations governing the dq-frame voltage are given in Eqs. (1) to (4) [3, 20]

$$v_d = R_s i_d + p \lambda_d - \omega_e \lambda_q \quad (1)$$

$$v_q = R_s i_q + p \lambda_q + \omega_e \lambda_d \quad (2)$$

$$\lambda_d = L_d i_d + \lambda_m \quad (3)$$

$$\lambda_q = L_q i_q \quad (4)$$

$v_d = d -$  axiz voltage,  $i_d = d -$  axiz operation current and  $\lambda_d = d -$  axiz operation linkage,  $L_d = d -$  axiz inductance,  $R_s =$  phase resistance,  $p =$

difference operator,  $\omega_e = \text{speed}$  and  $\lambda_m = \text{mutual magnetizing flu.}$

$$v_d = R_s i_d + L_d p i_d - \omega_e L_q i_q \quad (5)$$

$$v_q = R_s i_q + L_q p i_q - \omega_e (\lambda_m L_q i_q) \quad (6)$$

The torque is represented by:

$$T_e = \frac{3}{2} P (\lambda_d i_d - \lambda_q i_q) = \frac{3}{2} P \{ \lambda_m i_q + (L_d - L_q) i_q i_d \} \quad (7)$$

### 3. THE FIELD WEAKENING CONTROL STRATEGY

Within a range, as the voltage applied to the PMSM does not exceed its maximum limit, this voltage is adjusted by modifying the pulse width to control the rotation speed below the reference speed, since the machine can only supply a certain maximum voltage at its rated speed. The machine, in this case, operated in the field-weakening zone to provide a steady power region above base speed [20]. The creation of a synchronous motor is a type of PMSM that is typically regarded as a poor candidate for flux-weakening control due to its low inductance. As long as no current is provided in the stator, the PMSM exhibits a constant flux in the air gap, but any adjustment in the direct-axis stator current will affect the air-gap flux value [5, 21]. The machine's ability to draw a maximum current is capped, which automatically reduces the current on the q-axis and, as a result, lowers the load torque. The current and voltage are constrained in the real world.

$$i_q^2 + i_d^2 = i_s \leq I_s^2 \text{ max} \quad (8)$$

$$v_q^2 + v_d^2 = V_s^2 \leq V_s^2 \text{ max} \quad (9)$$

where  $I_s \text{ max}$  is the rated current, and  $V_s \text{ max}$  is the maximum voltage. For simplicity, the

voltage drop across the resistance is neglected in Eqs. (5) and (6):

$$v_d = -\omega_e L_q i_q \quad (10)$$

$$v_q = \omega_e L_d i_d + \omega_e \lambda_m \quad (11)$$

Substituting Eqs. (10) and (11) into Eq. (9) may be expressed as:

$$(L_q i_q)^2 + (L_d i_d + \lambda_m)^2 \leq \left( \frac{V_s \text{ max}}{\omega_e} \right)^2 \quad (12)$$

By rearranging Eq. (12) and Substituting Eq. (8), considering that ( $L_q = L_d$ ), the current  $i_d$  will be as follows:

$$V_{a,b,c} = \frac{\left( \frac{V_s \text{ max}}{\omega_{e-\text{base}}} \right)^2 - \lambda_m^2 - (L_q i_s)^2}{2L_d \lambda_m} \quad (13)$$

where  $\omega_{e-\text{base}}$  is the base value of speed if considering that  $\left( \frac{V_s \text{ max}}{\omega_{e-\text{base}}} \right)^2 = \lambda_m^2$  to get:

$$i_d^* = \frac{-(L_q i_s)^2}{2L_d \lambda_{m-\text{ref}}} \quad (14)$$

$\lambda_{m-\text{ref}}$  given by [22] :

$$\lambda_{m-\text{ref}} = \lambda_{m-\text{nominal}} \frac{\omega_{e-\text{base}}}{\omega_{e-\text{actual}}} \quad (15)$$

### 4. CONTROL SYSTEM DESIGN

#### 4.1. Using PI Controllers

Proportional-Integral (PI) and fuzzy-logic controllers are used to control the speed of a PMSM [22]. Figure 1 represents the control technique used in the PI controller design. Figure 2 represents the control technique used in the proposed controller. The current  $i_{sq}$  is determined by the speed regulator, provided that Eq. (8) is satisfied to keep the current within the permissible limits. The current  $i_{sd}$  is determined by the speed regulator with the necessity of achieving Eq. (14) for the current to remain within the permissible limits.

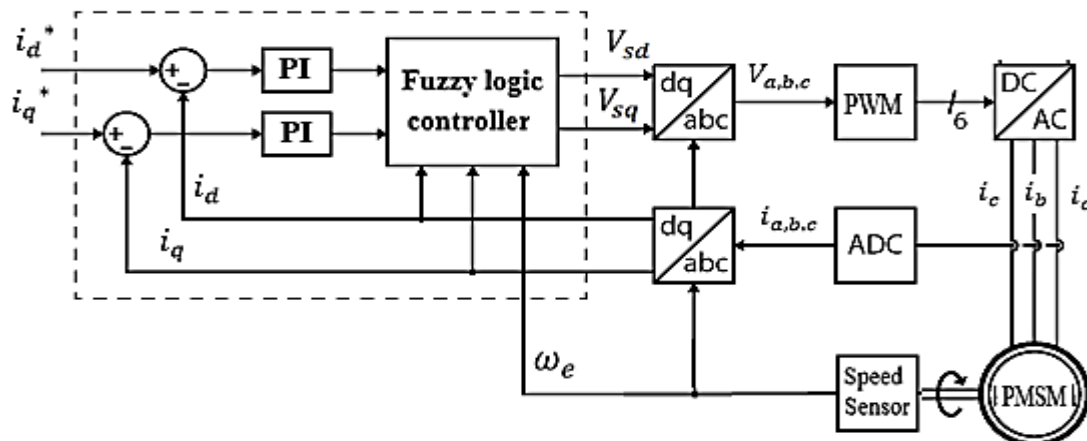
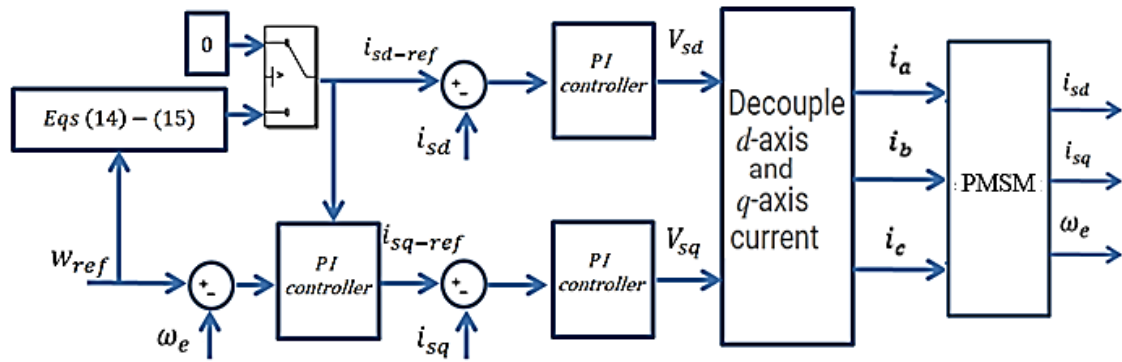


Fig. 1 The Control Technique Used in the Proposed Controller Design.

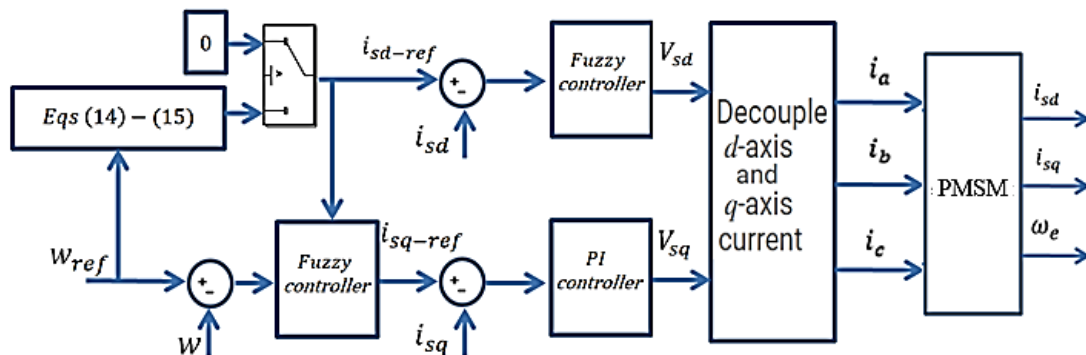


**Fig. 2** The Control Technique Used in the Proposed Controller.

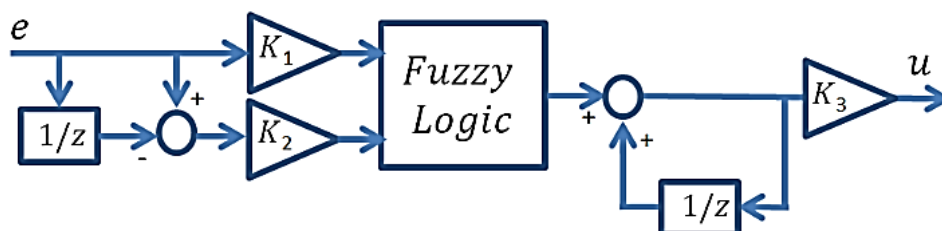
#### 4.2. Implementation of Fuzzy Logic Control

Fuzzy logic control's fundamental idea is to use human experience to build a controller for a process whose input-output relationship is defined by a set of fuzzy rules. The design approach of the Fuzzy Logic Controller (FLC) does not require comprehensive system model knowledge, as it is based on data gathered from skilled operators' incorrect, heuristic understanding [22, 23]. Fuzzy logic controllers are developed instead of proportional-integral controllers for the outer regulation loops (the  $i_{sd}$  regulation loop and the speed regulation loop). Whereas  $K_i$  and  $i=1:3$  are empirical constants. The output of the fuzzy controller ( $u$ ) is  $V_{sd}$  for the  $i_{sd}$  regulation loop and  $i_{sq}$  for the speed regulation loop, as shown in Figs. 3 and 4. The main role of separation blocks is to separate current components. Separation blocks are used to separate the direct-axis ( $i_d$ ) and quadrature-axis ( $i_q$ ) currents in the synchronous reference frame, which is necessary to independently control magnetic

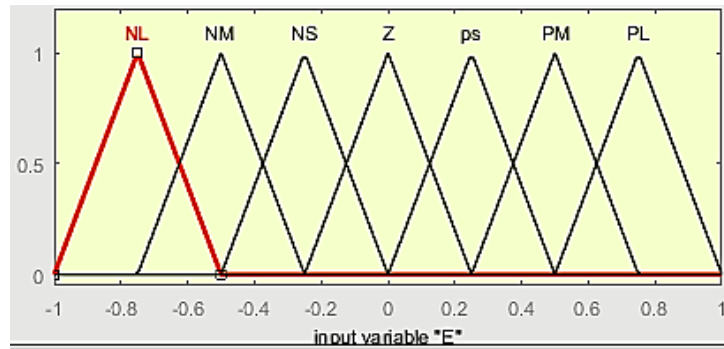
flux and torque and to compensate for mutual coupling effects. In PMSMs, there are mutual coupling effects between the  $d$ - and  $q$ -axis currents due to motor inductances and the reverse electromotive force, which are compensated by the separation blocks. It ensures that changes in one axis do not affect the other, thereby improving control precision and stability, as well as overall control performance. By separating the current components, these blocks help achieve better dynamic performance, such as faster response times and greater stability, improving the controller performance and stability, especially when the motor operates under variable load conditions. The membership functions for the Sugino method's errors  $E$  and  $CE$  used to create the fuzzy controller are shown in Figs. 5 and 6, respectively. The membership of the output  $CU$  is shown in Fig. 7. The value of membership functions for the output signal ( $CU$ ) is  $NL=-1.00$ ,  $NM=-0.66$ ,  $NS=-0.33$ ,  $Z=0.00$ ,  $PS=0.33$ ,  $PM=0.66$ , and  $PL=1.00$ . The rule base is shown in Table 1.



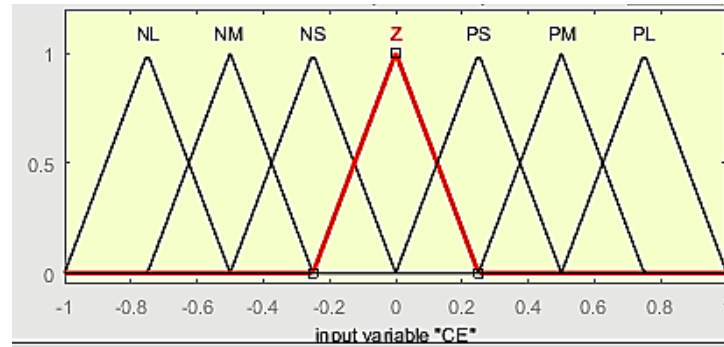
**Fig. 3** The Block Diagram of a Closed-Loop Control System Using Fuzzy Controllers.



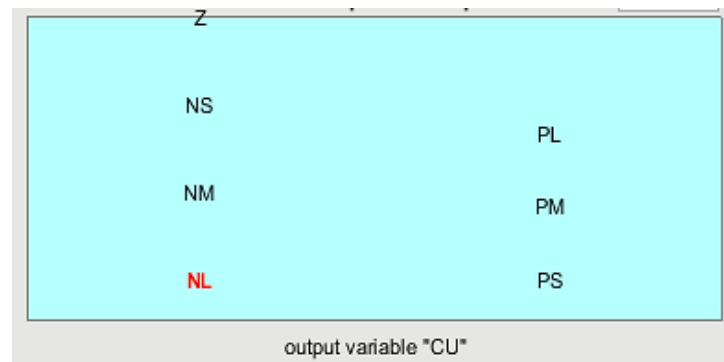
**Fig. 4** The Structure of the Fuzzy Logic Controller.



**Fig. 5** The Membership Functions of the Error (E).



**Fig. 6** The Membership Functions of the Error (CE).



**Fig. 7** Membership Functions of the Output (CU).

**Table 1** Rule-Based for Speed Fuzzy PI Controller.

CE/E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

## 5. SIMULATION AND RESULTS

First, the plant model for the permanent magnet synchronous motor was developed with the following parameter values shown in Table 2.

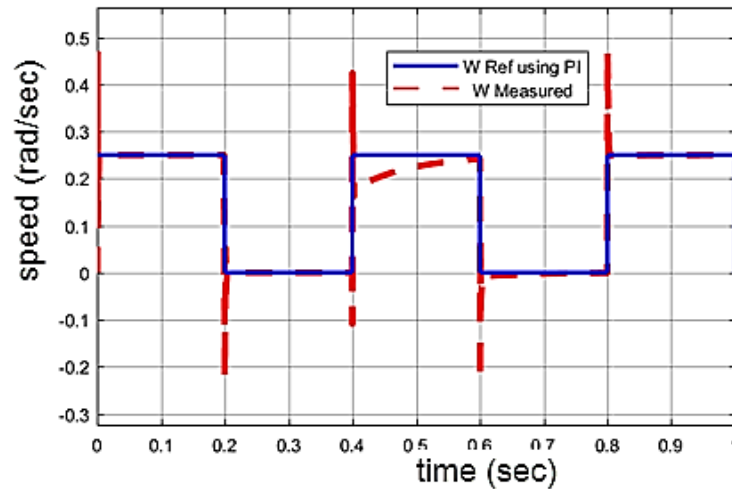
**Table 2** Motor Parameter.

Parameter	Value	Unit
J	0.00033	kg.m <sup>2</sup>
F	0.0003	N.m.s/rad
Rs	1.02	Ohm
Lsd=Lsq=Ls	0.0037	H
$\lambda_m$	0.0558	Wb
speed	1256	rpm
$\omega_{e-base}$	132.29	rad/s
$I_{s,max}$	4.1	A
$V_{s,max}$	70	V
Rated power	400	W

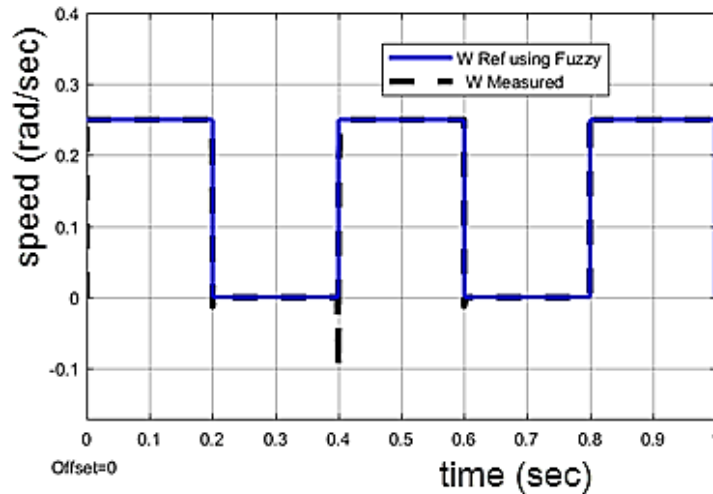
The reference speed is set to half the base speed during the period from 0 to 1 second. Then it doubles the base speed after 1 second. Load torque is applied at 0.4 seconds, equaling 0.2 N.m, to allow the system to recognize the primary effect of the load on the controllers used [24]. The simulation of the tested system and operating conditions has been modeled and simulated in MATLAB/Simulink. The results have been illustrated and discussed in the following sections. The response of the PI Controller is shown in Fig. 8. The 0.2 N.M. load was applied to the system at 0.4 seconds. The response of the Fuzzy-PI is shown in Fig. 9. The 0.2 N.M. load was applied to the system at 0.4

seconds. Figures 8 and 9 show that the noise affects the system with a PI controller, while the fuzzy controller eliminates its effect. Figure 10 shows the system response for  $i_{sd}$  current regulation using a PI controller, with noise

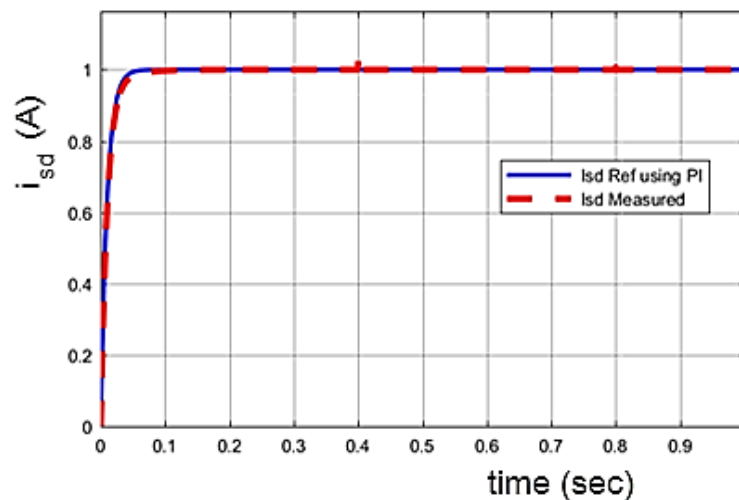
added at 0.4 seconds with a value of 0.2 N.M. Figure 11 shows the system response for the  $i_{sd}$  current regulation using a fuzzy control system, with noise added 0.4 seconds with a value of 0.2 N.M.



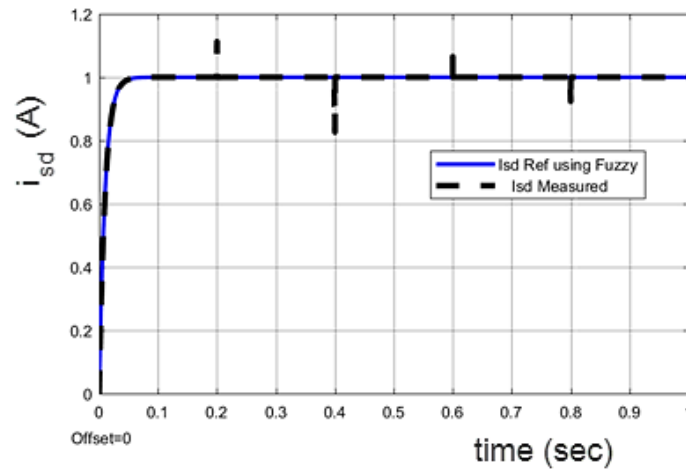
**Fig. 8** System Response for Speed Regulation Using a PI Controller.



**Fig. 9** System Response for Speed Regulation Using Fuzzy-PI Controller.



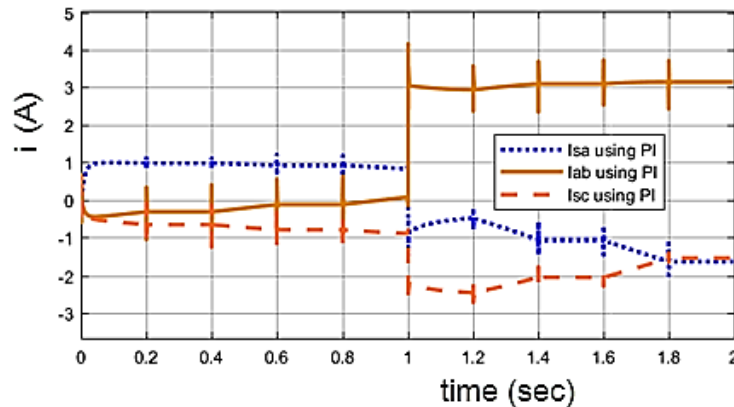
**Fig. 10** System Response for  $i_{sd}$  Regulation Using PI Controllers.



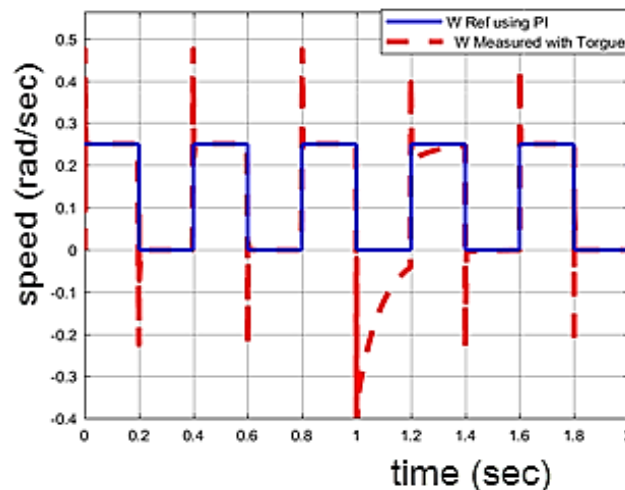
**Fig. 11** System Response for  $i_{sd}$  Regulation Using Fuzzy-PI Controllers.

Figures 10 and 11 show that the fuzzy control system exhibits better dynamic performance than the conventional PI control system. The rotational speed negatively increases when a load torque is applied to the motor. It is also associated with changes in the stator current on the q-axis, where increasing the current on the q-axis will increase the flux. Therefore, the  $i_{sd}$  current needs to be increased negatively to keep the flux low and allow the motor to rotate at high speeds. As mentioned, the flow must remain low in value (below the nominal value)

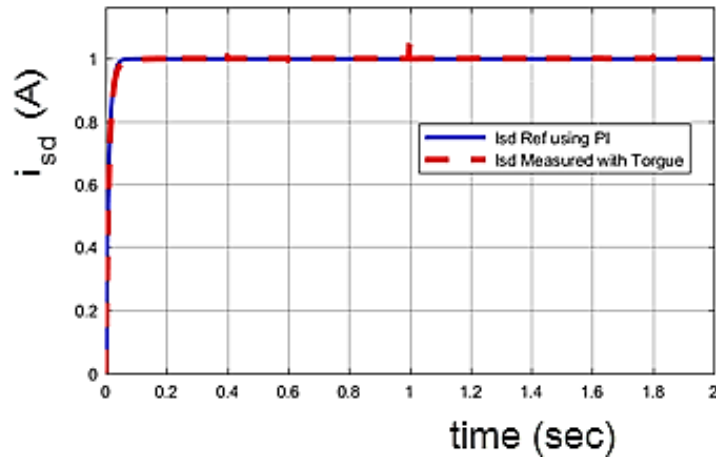
to rotate at high speeds when the flux is at its nominal value, given that the motor rotates at a value less than the base speed, where the  $i_{sd}$  current is equal to zero. Figure 12 shows the changes in magnetic flux during the simulation period, including the effect of the current, with the load increasing to 1 N.M. at 1 second. Figure 13 shows the changes in motor response due to load torque with a PI controller. Figure 14 shows the effect of load torque on the motor  $i_{sd}$  using a PI controller.



**Fig. 12** The Current when the Load Torque is Added During Operation Using the Fuzzy-PI Controller.



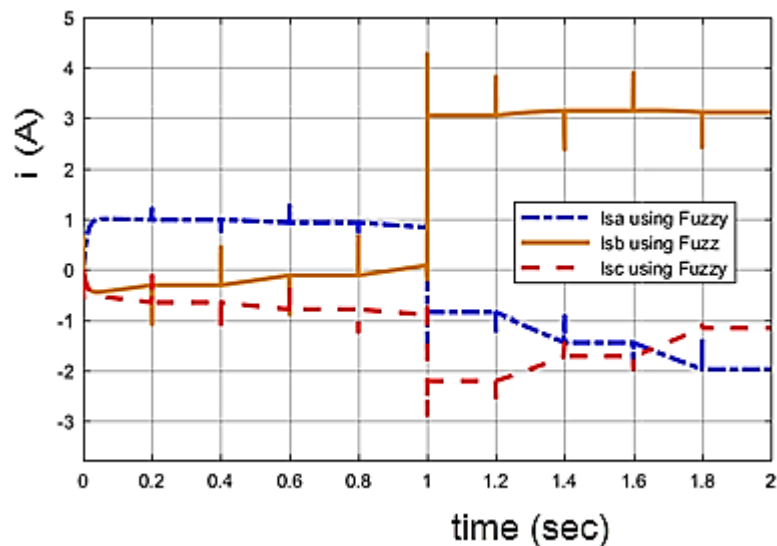
**Fig. 13** The PMSM Response when the Load Torque is Added During Operation Using a PI Controller.



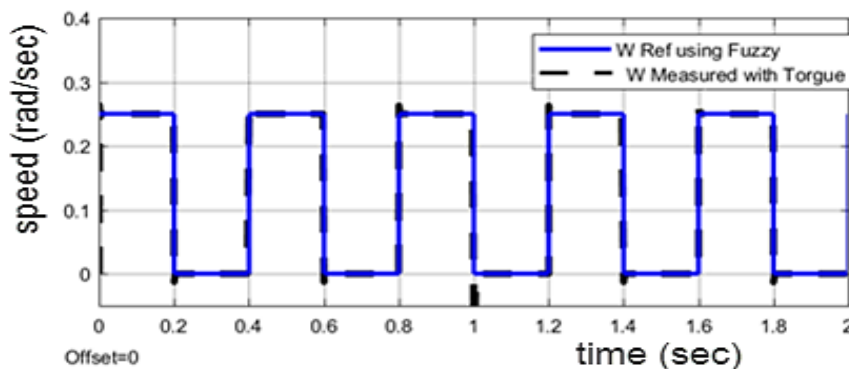
**Fig. 14** The Current  $i_{sd}$  when the Load Torque is Added During Operation Using a PI Controller.

By adding a Fuzzy-PI controller to the PMSM, the effect was eliminated, as shown in Fig. 15. From the simulation, the current effect, with increasing load to 1 N.M. at time 1 second, is low compared to the classical PI controller. Figure

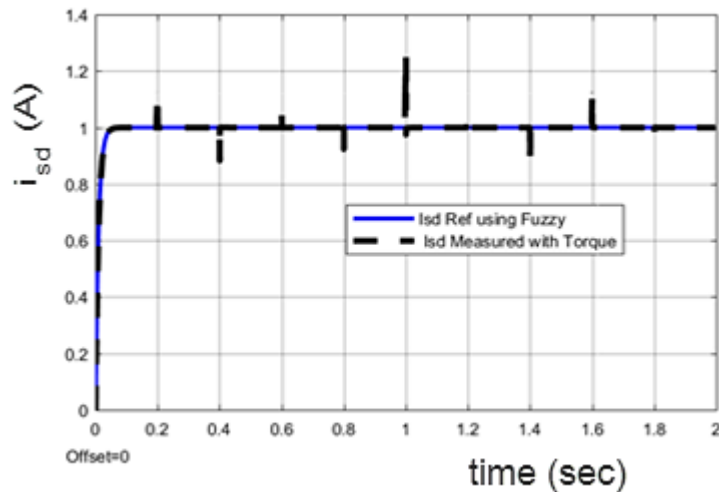
16 shows the PMSM speed response when the load torque is added during operation using a Fuzzy-PI controller. Figure 17 shows the current  $i_{sd}$  when the load torque is added during operation using the Fuzzy-PI controller.



**Fig. 15** The Current when the Load Torque is Added During Operation Using a Fuzzy-PI.



**Fig. 16** PMSM Speed Response when the Load Torque is Added During Operation Using a Fuzzy-PI Controller.



**Fig. 17** The Current  $i_{sd}$  when the Load Torque is Added During Operation Using the Fuzzy-PI.

As shown in Fig. 7, the fuzzy control system achieves faster response and greater engine stability. Moreover, Figures 16 and 17 show that the Fuzzy-PI control system maintains smooth torque changes and reduces vibrations during transient states.

### 5.1. Field Attenuation Results

The field-attenuation results highlight the performance of a fuzzy logic-based control strategy for PMSMs, with main results including improved dynamic performance: the fuzzy logic controller exhibits superior performance compared to conventional fuzzy logic controllers, providing faster response times and better stability under load disturbances, and lower noise. However, the fuzzy logic controller effectively reduces the effects of noise on speed regulation and provides smoother transitions under load changes, such as when a load torque of 0.2 Nm is applied at 0.4 s. In addition to enhanced stability at high loads, under higher load torque, e.g., 1 N.m at 1 s, the fuzzy logic controller exhibits lower current oscillations and greater stability during transient states, making it suitable for high-performance industrial applications. The study focuses on the use of the Fuzzy-Pi console to improve the performance of simultaneous permanent-magnet (PMSM) engines under field-weakening conditions. The research shows a clear superiority of the blurry control unit compared to the PI, especially in improving dynamic performance, reducing noise, and increasing stability during loading periods. The Fuzzy-PI console showed faster response and more stable organization than the traditional control, when the pregnancy torque of 0.2 Nm was applied at 0.4 seconds. The negative effects of a higher torque (1 Newton meter at 1 second) on the current and the speed were less clear when using the fog control unit. The different methods for PMSM control have been discussed in the previous studies. For example, the study in 2023 encompassed

advanced control techniques and hybrid strategies for PMSM drives. It can improve energy efficiency and extend applications to electric vehicles and renewable energy systems [7]. Previous work has investigated field-weakening control based on fuzzy logic to suppress voltage fluctuations and enhance the stability of the system in high speed operations [4]. Compared to other studies, this research work focuses on improving the dynamic performance and providing a faster response for a permanent magnet synchronous motor under varying load conditions using a Fuzzy-PI control strategy.

### 6. CONCLUSIONS

A fuzzy control system model was established for rotational speed control. The external control loops with the d-axis stator current component have demonstrated better dynamic performance than a conventional PI control system. The proposed technique using Fuzzy controller has given a faster response, improved reference tracking and better handling of applied load torque. Furthermore, a field-weakening approach was incorporated with the fuzzy control strategy to enable the operation of the PMSM at speeds higher than the base speed, while ensuring the stability and efficiency of the system. This method successfully extended the constant power region of motor operation envelop. Moreover, the fuzzy control system had better dynamic performance, such as less overshoot, shorter settling time and better disturbance rejection, compared with the PI control system. These improvements strongly enhanced the overall PMSM drive performance and reliability. The results of this study indicate that the combination of field-weakening control and fuzzy logic control is an effective method to improve the high-speed operation of PMSMs. This control strategy is particularly advantageous for applications with wide speed ranges, high torque density and accurate speed regulation such as electric vehicles, industrial automation and aerospace systems.

## CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

**Layth Fadhil Abbas:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luma A. Almajeed:** Methodology, Investigation. **Nihad M. Ameen:** Methodology. **Riemann Essa Ahmed:** Writing – review & editing, Investigation. **Arkan Ahmed Hussein:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Yushaizad Yusof:** Supervision, Writing – review & editing. **Muhammad Ammirul Atiqi Mohd Zainuri:** Methodology, Validation.

## DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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