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Deep-Learning-Based Control of Sensorless Drives for Robotics and Automation

Kasim M. Al-Aubidy [1]*, Izziyyah M. Alsudi [2], and Mohammed Abulaila [2]

[1] Mechatronics Engineering Deptartment, Tishik International University, Erbil, Iraq.
[2] Mechatronics Engineering Department, Al-Balqa Applied University, Jordan.

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**Email address:*
qasim.obaidi@tiu.edu.iq
**Corresponding Author*

Abstract: Permanent magnet synchronous machines (PMSMs) are essential components in automation and robotics systems due to their outstanding characteristics of small size, high efficiency and low maintenance requirements. Controlling these machines requires accurate detection of the rotor position to switch the electronic components in the inverter. The use of conventional and adaptive controllers, based on the mathematical model of the drive system, does not meet the design requirements in many robotics and automation applications because the controller parameters are affected by changes in the system dynamics. This paper deals with the design of a deep learning based controller that does not rely on a mathematical model of the drive system implemented by MATLAB/Simulink. In order to evaluate the performance of the proposed intelligent controller, the performance of the drive system was compared with other controllers, including PID traditional controllers such as PID and others based on the adaptive neuro-fuzzy inference system (ANFIS). The results of the comparison and analysis of controllers for sensorless drive systems were encouraging, as the deep learning-based controller outperformed both conventional and ANFIS-based controllers. These results indicate that the deep learning-based controller has no overshoot, with minimum rise and settling time compared to other controllers.

Keywords: *Drive Systems; Robotics and Automation; PID Controller; Artificial Intelligence; ANFIS-based Controller; Deep Learning-based Controller.*

1. Introduction

Permanent magnet synchronous motors (PMSMs) have several advantages that make them particularly important in robotics and automation applications. These motors are small, have a high power-to-weight ratio, high torque density, and are brushless, so they require low maintenance. Permanent magnet synchronous motors also provide smooth operation with higher efficiency and reliability than other motors [1,2], making them important in applications where accuracy, efficiency, and reliability are essential. On the other hand, controlling PMSMs remains a challenge, especially in detecting the rotor position, because the electronic switches in the inverter are controlled by the precise position of the rotor [3,4]. In this case, electronically commutated PMSMs will operate similarly to brushless DC motors, providing the additional benefit of not requiring periodic maintenance [5]. AC drive systems are nonlinear and multivariable, with complex dynamic behavior due to the coupling between the rotor and stator windings [2,4]. Therefore, controllers based on the mathematical model of the driving system cannot meet the requirements of robotics and automation applications where accuracy and stability are of utmost importance. With the rapid developments in computers and communications, researchers have been working on designing control algorithms using soft computing tools such as fuzzy logic and neural networks. Many studies have focused on employing artificial intelligence and its applications in designing intelligent controllers that can handle the dynamic behavior of PMSMs. Most of these studies have addressed the steady-state performance of the drive system, while others have prioritized the dynamic performance. While reviewing these studies, some of them focus on motor speed control [1,6], and others focus on position control [7,8] according to the application requirements.

PMSM machines are typically used in closed loop control systems, and in the case of a sensorless drive system, an accurate rotor position detection method is required to directly control the inverter power switches as well as to measure position and speed [2,3,4]. In most automation and robotics applications, a closed loop system is preferred to enhance system stability and achieve precise torque control over the required speed range [4,8,9].

Studies and research indicate that the performance of most conventional controllers does not meet the requirements in many applications in terms of accuracy, stability, and smooth operation. The main reason is that the design of controllers depends on the mathematical model of the driving system and thus requires continuous adjustment of its parameters [10,11,12]. Therefore, alternative control algorithms have been used, including direct torque control [13], adaptive control [14], slip mode control [8,14], and model reference control [15]. With the increasing interest in artificial intelligence and its applications, intelligent control systems have emerged that can provide fast dynamic responses. Controllers based on fuzzy logic [16] or neural networks [17] can be designed to control the speed or position of motors. Genetic algorithms have also been used as optimization tools to find the optimal values for controller parameters [18]. The use of soft-computing tools such as fuzzy logic and neural networks has significantly impacted the design of control algorithms that can learn and adapt to the dynamics of the drive system, improving performance. An adaptive network-based fuzzy inference system (ANFIS) can be used as a hybrid tool that combines the benefits of both fuzzy logic and neural networks, showing promising results in controlling PMSMs under various conditions [10,13,19]. Deep learning algorithms [20,21] can also be applied to control PMSMs due to their ability to model nonlinear systems and adapt to changes in motor behavior and environmental conditions, making them highly flexible in real-world applications.

The main contribution of this research is the design and evaluation of several control strategies that do not rely on the mathematical model of the driving system. Four controllers will be considered: fuzzy logic controller, neural network controller, ANFIS-based controller, and deep learning controller. The drive system's performance with these controllers will be compared with the traditional PID controller. The paper layout is as follows: Section 2 covers the basic components of the PMSM system. Section 3 deals with the modeling and simulation of the drive system. Section 4 deals with the design of five types of controllers. The results are discussed and analyzed in Section 5. While, section 6 summarizes the main conclusions.

2. PMSM Drive Systems

Permanent magnet synchronous motors are widely used in robotics and automation applications due to their compact size, efficiency, high performance, and low maintenance compared to other motors. The main components of a sensorless drive system, as shown in Fig. 1, include:

- Motor: A PMSM motor with permanent magnets embedded in the rotor.
- Inverter: A pulse width modulated (PWM) inverter that converts DC voltage to three-phase AC voltage to drive the PMSM. Signals from the rotor position sensor are used to switch power devices, such as MOSFETs, in the inverter.

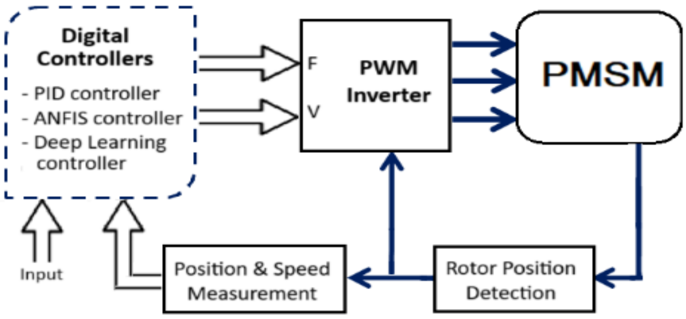

Figure 1: Elements of a sensorless drive system [22].

- Digital controller: Usually, computer algorithms are used to manage the operation of the PMSM by processing inputs from various sensors in real-time and generating control signals for the inverter.

- Rotor Position Detection: For sensorless drive systems, an accurate method of sensing the rotor position is required. Various methods have been used for rotor position detection, some are explicit sensors such as shaft encoders, others are implicit sensors such as search coils, Hall effect sensors. In robotics and automation applications, implicit rotor position sensors are often preferred.
- Position and Velocity Measurement: It is important to measure position and/or velocity in closed-loop control systems to achieve the desired stability and performance of the drive system.
- Sensors and Protections: Some motor control systems require additional sensors, such as current, temperature, or torque sensors, to ensure smooth motor operation and proper performance. Some applications also require the control system to be enhanced with overcurrent or overheating protection.

3. PMSM Modelling

A permanent magnet synchronous motor is a type of electric motors that uses permanent magnets in the rotor. These motors provide high torque density and high efficiency, making them ideal for robotics and automation applications. For DC brushless (or sensorless) drives, PMSMs use electronic commutation to switch the current in the stator windings depending on the rotor position detection. Table 1 lists the specification of the PM motor used in this paper.

3.1 Mathematical Modelling of PMSM:

To simulate a sensorless drive system in MATLAB/SIMULINK, the first step is to create a mathematical model of the drive system. This model includes PMSM motor, power electronics for the inverter, rotor position detection, speed measurement, and control algorithms. Table 1 presents the main parameters of a 3.4 kW PMSM fed by a voltage source inverter. The electrical and mechanical parameters are incorporated into the drive system model using the following equations [17]:

(1) $$\frac{d}{dt} i_a = \frac{1}{3Ls}(2v_{ab} + v_{bc} - 3R_s i_a + \lambda p\omega_m(-2\varphi_a + \varphi_b + \varphi_c))$$

(2) $$\frac{d}{dt} i_b = \frac{1}{3Ls}(-v_{ab} + v_{bc} - 3R_s i_b + \lambda p\omega_m(\varphi_a - 2\varphi_b + \varphi_c))$$

(3) $$\frac{d}{dt} ic = -\left(\frac{d}{dt}ia + \frac{d}{dt}ib\right)$$

where; L is armature inductance, R is resistance of the stator windings, i_a, i_b, i_c are phase currents, φa, φb, φc are phase electromotive forces, v_{ab} and v_{bc} are phase to phase voltages, ω_m is angular velocity of the rotor, λ is amplitude of the flux induced by the permanent magnets of the rotor, P is number of pole pairs, and T_e is electromagnetic torque.

PMSM motors typically develop nonlinear torque, which can lead to vector control problems. The torque equation for synchronous rotation is:

(4) $$T_e = p\lambda(\varphi_a * i_a + \varphi_b * i_b + \varphi_c * i_c)$$

The mechanical system is represented by the following equations

(5) $$\frac{d}{dt}\omega_m = \frac{1}{J}(T_e - T_f - F\omega_m - T_m)$$

(6) $$\frac{d\theta}{dt} = \omega_m$$

where; J is armature inductance, F is combined viscous friction of rotor and load, θ is rotor angular position, T_m and T_f are shaft mechanical torque and shaft static friction torque.

Table 1: PMSM Specifications.

Stator phase inductance L_s (H)	0.0085
Stator phase resistance R_s (Ohm)	2.875
Flux linkage	0.175
Inertia J (kg.m^2)	0.0008
viscous damping F (N.m.s)	0.001
static friction T_f (N.m)	4

3.2 Drive system simulation:

A MATLAB/SIMULINK environment was used to implement the mathematical model of the PMSM motor system, using blocks representing the different components of the system. These blocks were linked together to form a complete simulation model, as shown in Fig. 2. This simulation model was then used to analyze the behavior of the PMSM motor system under three different control methods and different operating conditions. By evaluating the performance of the PMSM motor system with these three control algorithms, the main advantages of using deep learning models in the design and implementation of intelligent controllers will be identified.

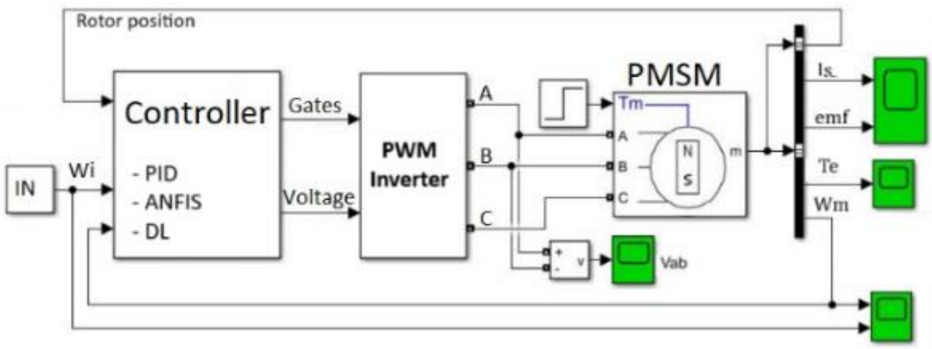

Figure 2: Simulation Model of a PMSM drive.

4. Motor Control

The choice of motor control methods in sensorless drive systems mainly depends on the performance requirements. Conventional and adaptive control methods for PMSMs are unable to meet these requirements due to their reliance on the mathematical model of the drive system and the need to constantly adjust the controller parameters. Updating controller parameters can be difficult, especially in real-time applications. With the rapid development of computer technology, it is now possible to use soft computing tools to design smart controllers that do not rely on the mathematical model of the drive system. This research aims to design a deep learning-based controller for motor speed control. The performance of the drive system with the deep learning-based controller will be compared to the performance of the system using other controllers, some of which are conventional such as PID and others employing soft computing tools such as ANFIS-based controller, under the same conditions.

4.1 Conventional PID Control

PMSM control methods typically include PID control, direct torque control, Field-oriented control, and slip mode control. These controllers are straightforward and suitable for applications where high performance is not critical. In robotics and automation applications, flexibility, accuracy, stability, and smooth operation are essential. Therefore, such controllers need a mechanism to adjust their parameters efficiently based on the mathematical model of the PMSM. For example, PID controllers are widely used in industrial control systems due to their simplicity and effectiveness in regulating processes. However, such a controller requires constant parameter updates when used to control a drive system. The general PID control equation is [23]:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{7}$$

$\boldsymbol{K_p}$: Proportional coefficient, $\boldsymbol{K_i}$: Integral coefficient, $\boldsymbol{K_d}$: Derivative coefficient.

Several methods are available for updating PID parameters, including trial and error, system response tests, and exploratory techniques such as the Ziegler-Nichols method to determine initial PID parameters. This method tunes PID parameters to enhance response and stability. Effective implementation of this tuning method requires careful interpretation of step response data, which necessitates a mathematical model of the motor.

4.2 AI-Based Controllers:

PMSMs exhibit non-linear characteristics, and soft-computing tools can effectively model and control these nonlinearities, providing smoother and more accurate control compared to conventional linear controllers. Intelligent controllers exhibit robustness against changes in system plant parameters compared to conventional controllers and offer superior noise rejection capabilities. As modern control strategies become more sophisticated, adaptive controllers remain highly competitive in high-performance drive applications. Therefore, employing an AI-based controller can effectively deliver accurate and faster solutions while handling complex nonlinear characteristics. AI-based control systems can effectively manage the non-linear characteristics of permanent magnet motors, enabling them to achieve the desired performance.

4.2.1 ANFIS-Based Controller Design:

Adaptive neuro-fuzzy inference system is a powerful hybrid intelligent system that combines the adaptability of neural networks with the interpretability of fuzzy logic. ANFIS-based controllers can adapt to varying operating conditions and system dynamics of PMSMs, making it suitable for applications where the motor operates under different loads and speeds. The most important issue in using ANFIS for PMSM drive is its ability to learn from data, enabling it to improve its control performance over time without requiring extensive manual tuning. In fact, using ANFIS-based controllers in PMSMs allows for robust and adaptive control, capable of handling the complexities and nonlinearities inherent in such systems, thereby enhancing overall performance and efficiency. Figure 3 shows the layout of the implemented ANFIS-based controller for the PMSM drive. It employs fuzzy logic rules, given in Table 2, to map input variables to an output. Each input variable corresponds to fuzzy sets, and their combinations create a rule base. Through training, the network optimizes these rules, improving the system's ability to handle complex, nonlinear control tasks.

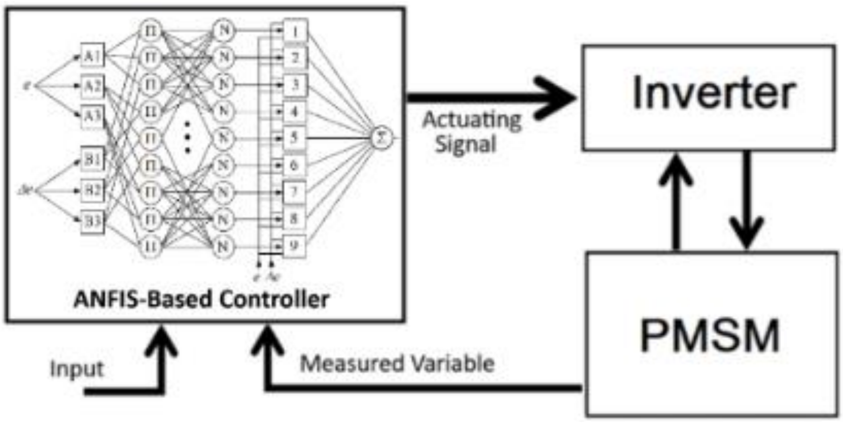

Figure 3: ANFIS-based controller of PMSM drive.

Table 2: ANFIS Fuzzy rules.

Error (e)

Change of Error (ce)

	NB	NM	NS	ZO	PS	PM	PB
NB	ZO	PS	PM	PB	PB	PB	PB
NM	NS	ZO	PS	PM	PB	PB	PB
NS	NM	NS	ZO	PS	PM	PB	PB
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NB	NB	NM	NS	ZO	PS	PM
PM	NB	NB	NB	NM	NS	ZO	PS
PB	NB	NB	NB	NB	NM	NS	ZO

The ANFIS-based controller utilizes a five-layer neural network to implement the fuzzy rule-based controller, as illustrated in Fig. 4. This system enables the fuzzy controller to use the neural network to optimize the membership functions of all fuzzy sets. The input layer consists of two nodes to execute the AND operator for the fuzzy rules. The input membership layer comprises 49 nodes, which handle the “IF” part of the fuzzy rules. The rule layer, also containing 49 nodes, normalizes the membership functions. The output membership layer includes a single node that implements the “THEN” part of the fuzzy rules. Finally, the output layer features the controller output node.

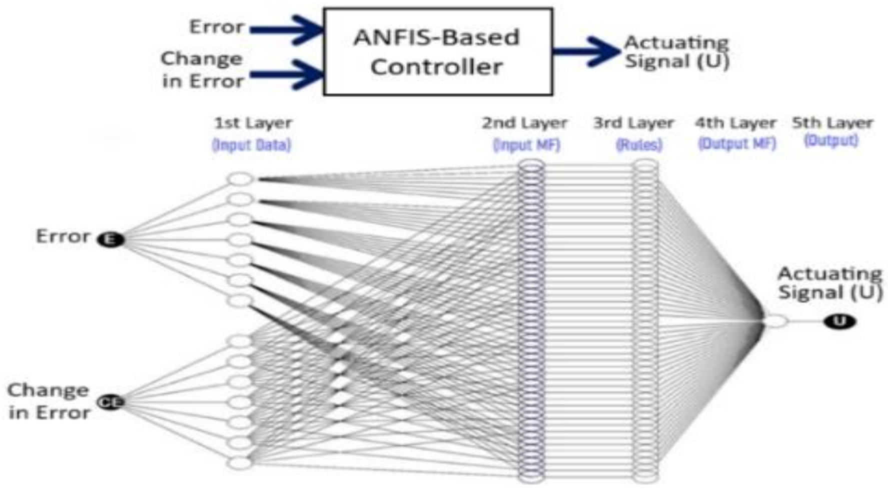

Figure 4: Layout of the ANFIS-based controller.

Data on the performance of the drive system with the fuzzy controller were collected and divided into three sets: 60% for training, 20% for testing, and 20% for validation. The weights and input/output membership functions were adjusted using a hybrid method that combines backpropagation and least squares estimation, applied to both the training and testing datasets. Figure 5 illustrates the training data for the ANFIS-based controller, showing that a small number of epochs was sufficient to achieve the required performance.

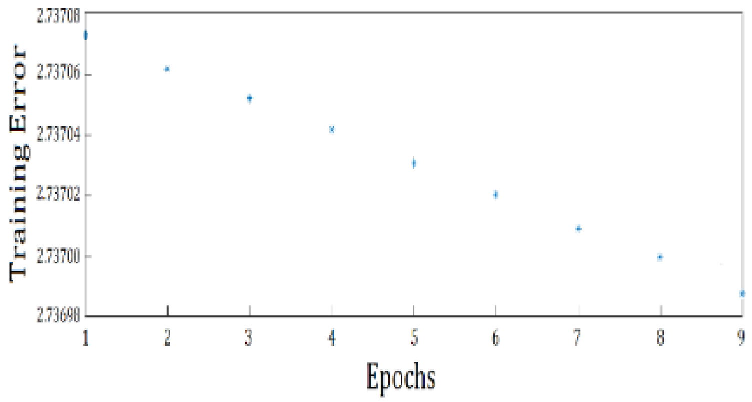

Figure 5: Plot of training data.

4.2.2 Deep Learning-Based Controller:

Using a deep learning (DL) model to control a sensorless drive system involves several steps. The model can learn complex patterns and make predictions based on collected data. Figure 6 illustrates the general scheme of the deep learning-controller model, which includes:

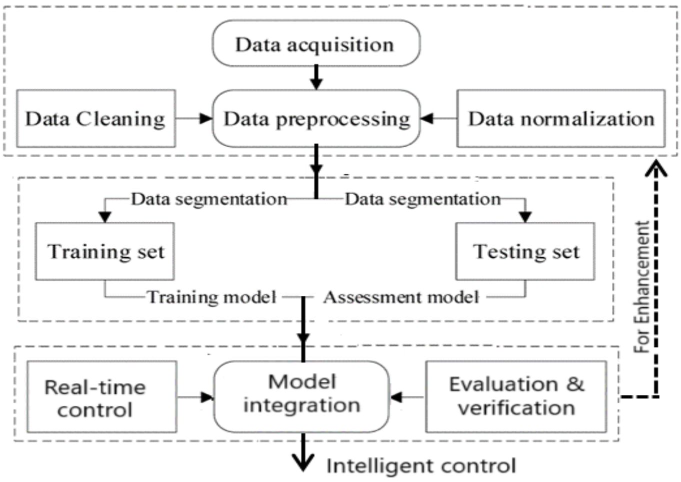

Figure 6: Layout of a deep learning model.

- Collect a large amount of data related to the control of the drive system. This data is then preprocessed and divided into 60% for training, 20% for testing, and 20% for validation sets.
- Identify features relevant to the drive system that affect motor performance. Then, generate input/output pairs related to the controller operation.
- Choose the Long Short-Term Memory (LSTM) as the deep-learning model.
- Train the model by feeding it input-output pairs and optimizing it using loss functions and backpropagation.
- Integrate the trained deep learning model into the drive system to predict the required control actions based on real-time input data.
- Monitor the drive system's performance to ensure that the controller meets performance standards.
- Evaluate the performance of the deep learning-based controller against other control methods.

5. Results and Discussion

The characteristics of PMSMs have greatly contributed to making them the best choice, especially in applications that require high accuracy, stability and smooth operation, such as automation and robotics systems. Despite these features, PMSMs suffer from major control challenges due to the need for accurate rotor position detection. In sensorless drive systems, rotor position signals are used to control the operation of the inverter's power devices. The selection of a suitable controller for PMSM depends on the required performance specifications. This paper focuses on the use of a deep learning model to develop an intelligent controller for managing the motor's speed. The design of such a controller is based on the data collected from the real-time operation of the PMSM, as well as the methods used to process these data for training and validating the model. The performance of the drive system using the deep learning-based controller is compared with that of an ANFIS-based controller and a conventional PID controller with carefully selected parameters. The deep learning-based controller shows the best performance, with a fast response, no overshoot and fast steady-state achievement, as shown in Fig. 7. The ANFIS-based controller and the PID controller also show good responses, but with slightly higher overshoot.

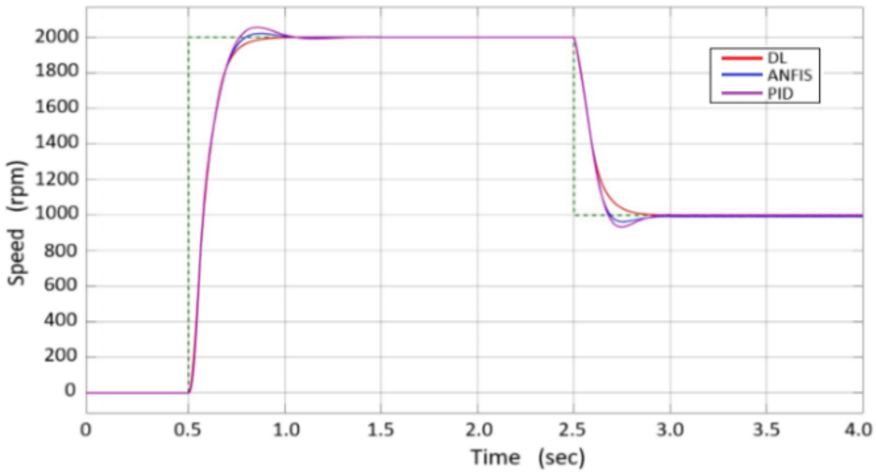

Figure 7: Speed response without disturbances.

The three controllers were also tested for disturbances in the steady state region, as illustrated in Fig. 8. The deep learning-based controller shows superior ability to handle disturbances and changes in motor dynamics compared to the other controllers. It maintains excellent performance with minimal (if any) fluctuations, whereas the ANFIS-based controller shows small fluctuations. In contrast, the PID controller exhibits larger fluctuations under disturbances and dynamic changes in the drive system.

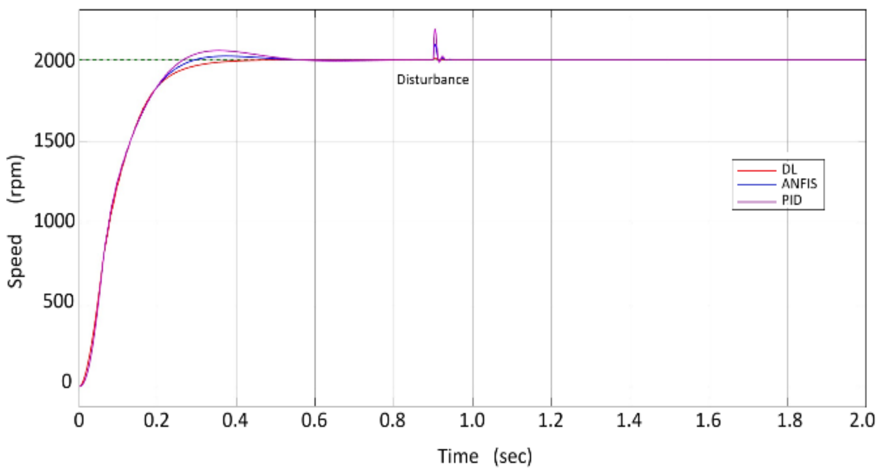

Figure 8: Speed response of a PMSM with disturbances.

The comparison results in Table 3 indicate that the deep learning-based controller outperforms the other controllers, achieving fast stabilization without overshoot and superior disturbance rejection. This makes deep learning-based controllers the most efficient among those compared. This efficiency is attributed to the ability of deep learning and ANFIS controllers to automatically update their parameters in response to dynamic changes and external disturbances, without requiring the motor's mathematical model.

Table 3: Comparative Analysis.

Controller	Peak time (s)	Rise time (s)	Settling time (s)	Overshoot %
Deep learning	-	0.1875	0.423	0
ANFIS	0.375	0.18882	0.505	1.21
PID	0.351	0.18884	0.525	2.85

6. Conclusion

There is a clear increase in the use of permanent magnet synchronous motors in automation and robotics applications due to their high efficiency, compact size, and low maintenance requirements. In most of these applications, an implicit rotor position detector is employed to switch the inverter power electronic components, resulting in a sensorless drive system. Controllers based on mathematical models of the driving system may not achieve the required performance, therefore, this paper focused on the design and evaluation of AI-based control algorithms. Such controllers can effectively handle dynamic system changes and external disturbances, ensuring smooth and stable operation. The performance of a sensorless driving system using a deep learning-based controller was analyzed and compared with that of a conventional PID controller and an ANFIS-based controller. The analysis demonstrates that deep learning-based control algorithms can adapt to changes in motor behavior and working environment. They are also flexible in achieving optimal performance in terms of no overshoot and rapid stability with minimal settling time. Unlike conventional controllers, intelligent controllers can learn and update their parameters independently, without the need for a mathematical model of the drive system.

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