Analysis and simulation model of three phase Permanent Magnet Synchronous Motor Drive (PMSM)

Mohammed H. Ali[1], *Adam* Abdel Rahman Ramadan[1], *Duha* Mahmood Abass[2], *Mohammed* Hasan Ali[3,]*

[1]Central Technical University, Baqubah Technical Institute, Diyala, Iraq
[2]Diyala Governorate, Diyala, Iraq
[3]Department of Power and Electrical Machines Engineering, University of Diyala, Diyala, Iraq

Abstract. The Permanent Magnet Synchronous Motor (PMSM) has become a very dependable and efficient choice for a range of industrial and automotive applications in recent years. Because of their exceptional torque-to-weight ratio, great power density, and superior performance, PMSMs are the best choice for applications requiring precise control and high efficiency. An extensive review of PMSMs is given in this study, with particular attention to their design, control schemes, and applications. The research starts off with a thorough explanation of the PMSM construction, emphasizing the function of permanent magnets and where they are located in the rotor. Analysis of PMSMs' electrical and magnetic characteristics highlights the benefits they have over conventional induction motors, including reduced losses and increased efficiency. A thorough analysis of control techniques for PMSMs is conducted, with a focus on direct torque control (DTC) and field-oriented control (FOC). The robustness, dynamic reactivity, and implementation difficulty of these approaches are compared. Furthermore, sophisticated methods that combine artificial intelligence and model predictive control (MPC) are presented, demonstrating how they can improve PMSM performance in a range of operating scenarios. The integration of PMSMs in electric cars (EVs) is also covered in the study, with an emphasis on how these components improve driving enjoyment, lower emissions, and vehicle efficiency. Examined are industrial applications that highlight PMSMs' adaptability and versatility, including robotics, renewable energy systems, and aerospace. Moreover, issues with PMSM operation are discussed, including demagnetization, thermal control, and the effect of manufacturing tolerances on performance. The ongoing research and solutions aimed at reducing these problems are highlighted, highlighting PMSM technology's constant progress. To sum up, PMSMs are an essential technological accomplishment in the development of contemporary electromechanical systems. Because of their exceptional performance qualities and the continuous advancements in manufacturing

---

[*] Corresponding author: mohammed80ali@yandex.ru

and control methods, they will play a significant role in the development of efficient and sustainable motor drives in the future.

1 Introduction

An electric motor known as a permanent magnet synchronous motor (PMSM) generates a steady magnetic field by means of permanent magnets inserted into the steel rotor. Usually constructed of laminated steel, the stator is the stationary portion of the motor. It is coiled with coils of wire that transport alternating current (AC) to create a rotating magnetic field. The rotor rotates in synchronization with the stator field due to torque produced by the interaction between the rotor's permanent magnets and the stator's spinning magnetic field.

Key Components:

1. Rotor: Produces a steady magnetic field thanks to permanent magnets inside.
2. Stator: Powered by AC, this device is made of wire coils and laminated steel that rotate to produce a magnetic field.
3. Windings: The stator's coils, which rotate the magnetic field.
4. Shaft: Transfers rotor mechanical power to the load.

Operating Principle

The magnetic field interaction principle underlies the PMSM's operation. A revolving magnetic field is produced in the stator windings when AC is introduced. The rotor rotates in time with the stator field due to the interaction between this field and the magnetic field of the rotor magnets. The term "synchronous motor" refers to the fact that the rotor and stator fields are still synced.

Types of PMSMs:

1. Surface-Mounted PMSM: The rotor's surface is where the magnets are affixed.
2. Interior PMSM: The rotor contains integrated magnets.

Advantages of PMSMs

1. High Efficiency: PMSMs usually have high efficiencies because of the permanent magnets' continuous magnetic field.
2. High Power Density: Compared to induction motors, they are able to generate higher power per unit weight.
3. Outstanding Performance: PMSMs are the best choice for applications requiring accuracy because of their exceptional torque and speed control.
4. Low Maintenance: The need for maintenance is decreased when brushes are not there.

Applications

PMSMs are widely used in various applications, including:

1. Electric vehicles (EVs): Because of their excellent performance and efficiency.
2. Industrial drives: Used in robotics and machines for precision control.
3. Aerospace: In essential systems such as actuators.
4. Household appliances: To improve energy efficiency, consider air conditioners and washing machines.

Comparison with Other Motors

Induction Motors: PMSMs generally have higher efficiency and power density but are more expensive due to the cost of permanent magnets.

Brushless DC Motors (BLDC): Similar in many respects to PMSMs but typically used in applications requiring less power and precision.

2 Permanent Magnet Synchronous Motor Drives System: rotational description

The stator and rotor of a permanent magnet synchronous motor are shown in Figure 1's coordinate system.

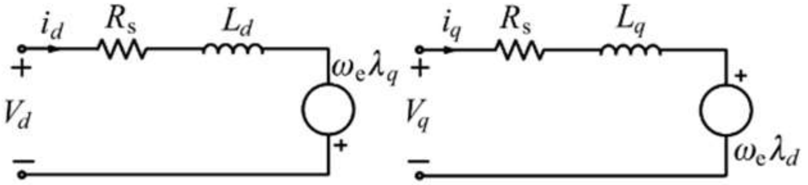

Fig. 1. Coordinate system of permanent magnet synchronous motor.

In order to simplify the mathematical description of a PMSM drive, a rigidly coupled coordinate system, denoted as d-q, is employed, with the d-axis aligned with the direction of the rotor's magnetic field.

In this instance, the electromagnetic and electromechanical processes in the PMSM drive are described by the operator of equations 1, 2, 3, 4, and 5.

$$U_d = R(T_d s + 1)i_d - \omega L_q i_q \quad (1)$$

$$U_q = R(T_q s + 1)i_q - \omega L_d i_d + \phi_0 \omega \quad (2)$$

$$M = p\frac{m}{2}(\psi_0 i_q + (L_d - L_q)i_d i_q) \quad (3)$$

$$s\omega_m = \frac{1}{J}(M - M_H) \quad (4)$$

$$s\theta_m = \omega_m , \omega = p\omega_m \quad (5)$$

3 PMSM drive's mechanical properties and regulation

The following equations represent the operating equation that characterizes electromagnetic processes in PMSM:

$$T_d = \frac{L_d}{R} \quad (6)$$

$$T_q = \frac{L_q}{R} \quad (7)$$

$$U_d + \omega L_q i_q = L_d \frac{di_d}{dt} + Ri_d \quad (8)$$

$$U_d = R(T_d s + 1)i_d - \omega L_q i_q \quad (9)$$

$$U_q - \omega L_q i_q - \phi_0 \omega = L_q \frac{di_q}{dt} + Ri_q \tag{10}$$

$$M = p\frac{m}{2}(\psi_0 i_q + (L_d - L_q)i_d i_q) \tag{11}$$

$$\frac{d\omega_m}{dt} = \frac{1}{J}(M - M_H) \tag{12}$$

4 PI controlers

A Proportional-Integral (PI) controller is a widely used feedback control mechanism in industrial control systems. It is a type of controller that combines two control actions: proportional control and integral control, to maintain a desired output level. PI controllers are employed to correct errors between a desired setpoint and the actual process variable by adjusting the control inputs.

Components

1. **Proportional Control (P)**: This component produces an output that is proportional to the current error value. The proportional term provides immediate correction based on the magnitude of the error.

2. Integral Control (I): This part generates an output proportionate to the total of all previous faults. The cumulative offset that may result from using only proportional control is addressed by the integral term.Mathematical Representation

The control action of a PI controller can be mathematically expressed as:

$u(t)=Kpe(t)+Ki\int 0te(\tau)d\tau u(t)=Kpe(t)+Ki\int 0te(\tau)d\tau$

where:

- $u(t)u(t)$ is the control output.
- $e(t)e(t)$ is the error at time tt, defined as the difference between the set point and the process variable.
- $KpKp$ is the proportional gain.
- $KiKi$ is the integral gain.

Working Principle

1. By taking into account both the current error and the accumulation of previous errors, the PI controller modifies the control input to minimize the error over time:
2. **Proportional Action**: Adjusts the control output proportionally to the current error, providing a quick response to changes.

3. Integral Action: Removes steady-state error and enhances long-term accuracy by modifying the control output in response to the cumulative error over time.

Tuning a PI Controller

In order to attain the desired performance, a PI controller must be tuned by choosing the proper values for the integral gain (Ki) and proportional gain (Kp). The goal of tuning is to achieve a balance between low overshoot, stability, and responsiveness. Typical tuning techniques include of:

1. **Ziegler-Nichols Method**: A heuristic method based on closed-loop response.
2. **Cohen-Coon Method**: A method based on the process reaction curve.

Advantages of PI Controllers

1. **Simple Implementation**: PI controllers are straightforward to implement and understand.

2. **Improved Steady-State Performance**: The integral term ensures the elimination of steady-state error.
3. **Good for Slow Processes**: Effective for processes where the dynamics are relatively slow and the system can tolerate some overshoot.

Applications

PI controllers are used in various industrial applications, such as:

1. **Temperature Control**: Maintaining desired temperature levels in furnaces, ovens, and HVAC systems.
2. **Speed Control**: Regulating the speed of motors and conveyors.
3. **Process Control**: Managing flow rates, pressure, and other process variables in chemical plants and refineries.

Comparison with Other Controllers

- **Proportional-Derivative (PD) Controller**: Includes a derivative term to predict future errors, offering better control for systems with rapid changes.
- **Proportional-Integral-Derivative (PID) Controller**: Combines proportional, integral, and derivative control actions, providing comprehensive control for complex systems.

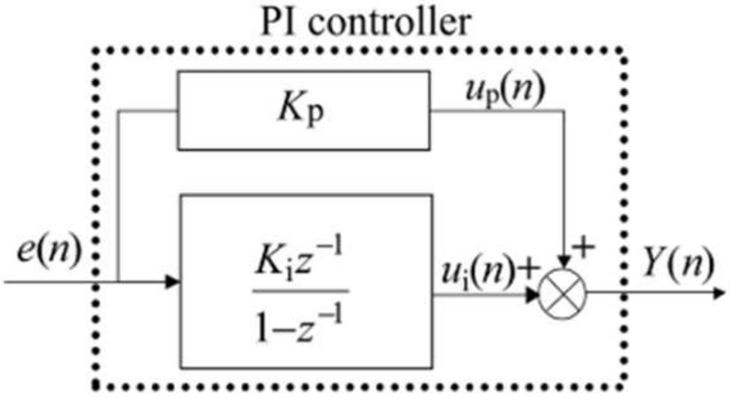

Fig. 2. Block diagram of PI-controller.

5 Technique for direct torque control

Direct torque control (DTC) has been shown by Takahashi and Toshihiko Noguchi for the past 25 years. Three-phase AC motor drives' torque and stator flux are controlled using this technique, which also controls the motor's speed. The DTC can be produced by computing the flux and torque of an electric motor with only measurable stator parameters, like the stator voltage and stator current of the AC motor drive. In traditional direct torque control, two hysteresis comparators are used: one for estimating torque error and the other for calculating stator flux error. The scheme diagram for the DTC method is constructed as shown in Figure (3).

The fundamental working principle of DTC is based on a voltage source inverter with eight stator voltage vectors, six of which are not zero vector states and the other two of which are zero vector states. This allows the inverter to maintain the stator flux and electromagnetic torque within the necessary value of a hysteresis band. The voltage space vector reference is found in the switching table. The DTC controller takes two signals as inputs: one for produced torque and one for stator flux. It uses these signals to compare the references value with the feedback signal and determine the torque and flux error. The stator flux error hysteresis comparator has two standard levels: zero and one.

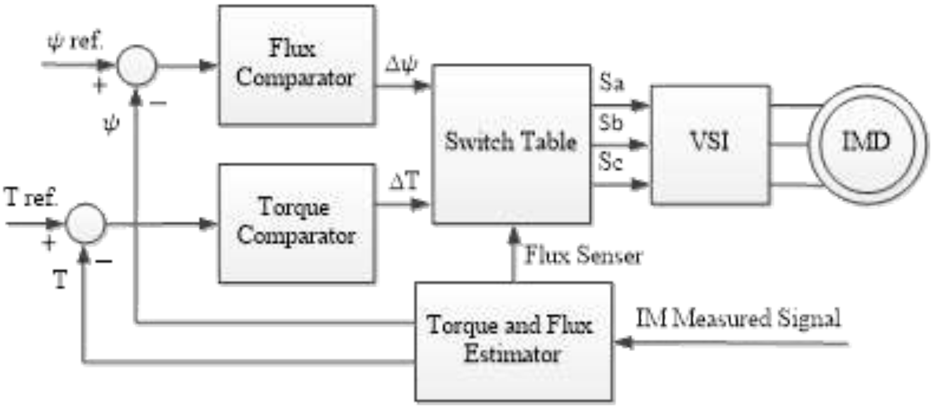

Fig. 3. DTC control technique block diagram.

6 Discation and result

This paper presents the modeling and simulation of a mathematical model of a PMSM using a rotational coordinate frame and a rotor position sensor. The study examines the motor specifications, including speed, torque, and current, as well as the regulation characteristic under various conditions, based on equations 1 through 12.

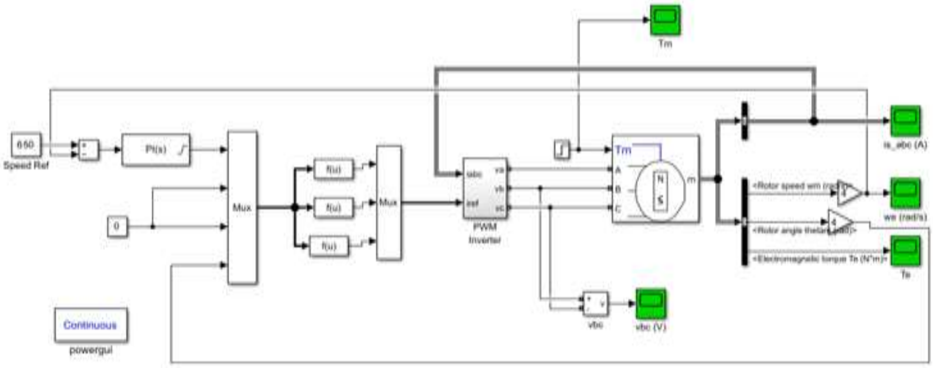

Fig. 4. PMSM drive modeling in a rotating coordinate system.

Table 1. Input data.

R	2.875	Ω
Ld , Lq	0.03	H
Φ_0	0.175	
J	0.0013	$Kg.m^2$
P	8	

Table 2. Regulation Characteristic of PMSM.

uq	**ωm**	
	MH=5	**MH=0**
0,00	-1,80	0,00
5,00	2,00	3,20
10,00	5,20	6,90
15,00	8,50	10,20
20,00	12,00	14,00
25,00	15,20	17,00
30,00	19,00	20,50
35,00	22,00	24,00
40,00	25,00	27,50
45,00	29,00	30,50

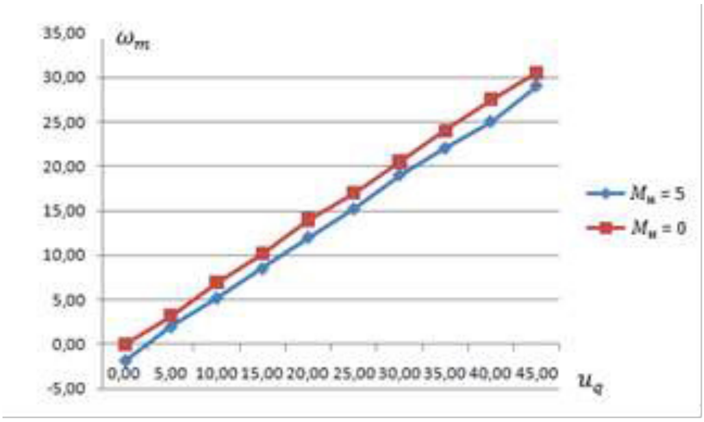

Fig. 5. Vq and ωm's relationship.

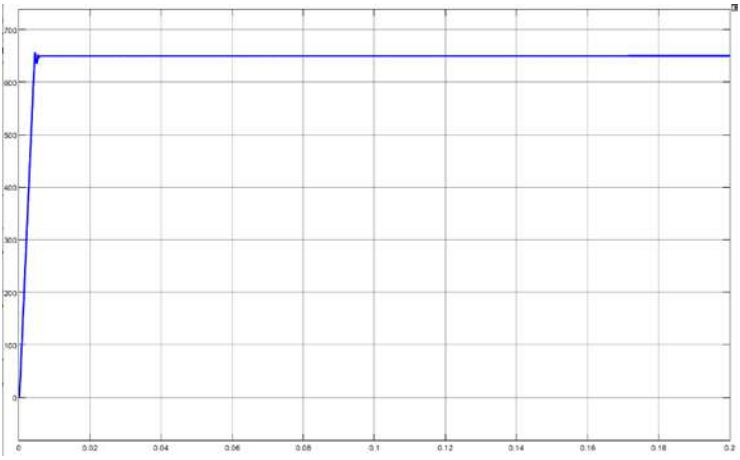

Fig. 6. The relation between speed with time.

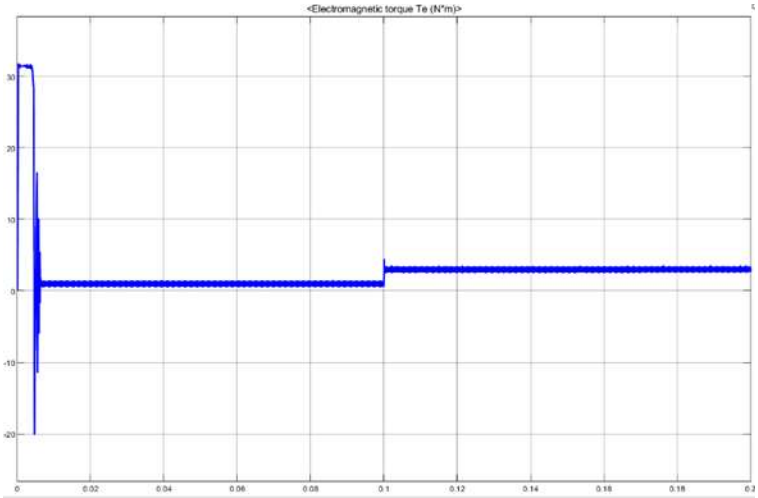

Fig. 7. Electromagnetic torque with time.

7 Conclusion

PMSMs are a cornerstone of modern electric motor applications, blending efficiency, performance, and reliability. As technology advances and the demand for energy-efficient solutions grows, the role of PMSMs is expected to expand further, driving innovations in various industries. Understanding their operation, benefits, and applications is crucial for engineers and technologists looking to leverage their full potential in designing advanced motor-driven systems.

References

1. H. Ahn et al., Journal of Electrical Engineering & Technology **15**, 1177-1187 (2020)
2. X. Liu et al., IEEE Transactions on Industrial Electronics **63(6)**, 3533-3545 (2016)
3. F. Mohd Zaihidee, M. Saad, M. Marizan, Energies **12(9)**, 1669 (2019)
4. H.-T. Moon, H.-S. Kim, M.-J. Youn, IEEE Transactions on Power Electronics **18(1)**, 464-472 (2003)
5. H. Kim, J. Son, J. Lee, IEEE transactions on Industrial Electronics **58(9)**, 4069-4077 (2010)
6. X. Zhang et al., IEEE transactions on power electronics **28(3)**, 1358-1365 (2012)
7. V. M. Bida, D. V. Samokhvalov, F. Sh Al-Mahturi, “PMSM vector control techniques—A survey”, in *IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)* (2018)
8. S. Li, M. Zhou, X. Yu, IEEE Transactions on Industrial Informatics **9(4)**, 1879-1891 (2012)
9. Q. Wang, S. Wang, C. Chen, IEEJ Transactions on electrical and electronic engineering **14(10)**, 1543-1552 (2019)
10. T. Boileau et al., IEEE transactions on industry applications **47(4)**, 1944-1957 (2011)
11. V. Bobek, Freescale Semiconductor **7(8)**, 13 (2013)

12. Z. Mynar, L. Vesely, P. Vaclavek, IEEE Transactions on Industrial Electronics **63(8)**, 5156-5166 (2016)
13. J.-X. Xu et al., IEEE Transactions on industrial electronics **51(3)**, 526-536 (2004)
14. B. Nahid-Mobarakeh, F. Meibody-Tabar, F.-M. Sargos, IEEE Transactions on Industry Applications **40(2)**, 457-471 (2004)
15. K. Jezernik, J. Korelič, R. Horvat, IEEE Transactions on Power Electronics **28(7)**, 3549-3556 (2012)