Dynamic Analysis and Simulation of Field-Oriented Control for Permanent Magnet Synchronous Motors

MONZURUL ISLAM*, MD ABDUL HALIM**,KUTUB UDDIN HRIDOY***
*Mechanic, Weifang University,
Email: monzurul519@gmail.com
** Mechanotronics,Chongqing Jiaotong University
Email: halimmdabdul093@gmail.com)
***Mechanics, Jiangsu university of science and technology
Email: kutub.start@gmail.com

Abstract:
Permanent Magnet Synchronous Motors (PMSMs) are widely used in robotics, appliances, and hybrid electric vehicles due to their compact size, high efficiency, and superior dynamic performance. Field-Oriented Control (FOC) enables precise torque and speed regulation, enhancing motor operation. This study presents a mathematical model of a surface-mounted PMSM with multiple stator windings powered by rotor-mounted permanent magnets. A systematic simulation framework is developed using MATLAB/Simulink, incorporating realistic motor parameters, including resistance, inductance, and inertia, alongside control strategies such as proportional-integral (PI) controllers and space vector modulation (SVM). Dynamic analysis techniques, including transient response, frequency response, and stability assessment, are applied to evaluate motor behavior under various operating conditions. Simulation results demonstrate the effectiveness of FOC in achieving accurate speed control, fast torque response, and improved energy efficiency. These findings provide valuable insights for engineers and researchers to optimize PMSM control, contributing to the advancement of high-performance electric motor systems and future developments in motor control technology.

Keywords — **Field-oriented control, Permanent Magnet Synchronous Motors, MATLAB simulation, Dynamic analysis Control optimization**

I. INTRODUCTION

The development of effective and precise control systems for electric motors has been a longstanding focus in various industrial sectors. Field-Oriented Control (FOC) is a sophisticated strategy that significantly enhances the performance of Permanent Magnet Synchronous Motors (PMSMs) by accurately regulating both torque and speed, optimizing energy efficiency, and minimizing losses. This makes FOC highly suitable for applications such as electric vehicles, industrial automation, and renewable energy systems. PMSMs are extensively used in industrial applications, including robotics and hybrid electric vehicles, due to their superior performance, compact size, and wide-range controllability. With rising fuel costs and stringent environmental regulations, PMSMs have become the preferred choice for hybrid electric vehicles, enabling more efficient use of electrical energy. The key advantages of PMSMs include rapid acceleration and deceleration,
Precise torque control even at zero speed, smooth rotation, and minimal torque ripple at low speeds. , caused by the interaction between stator teeth and rotor magnets, which can hinder smooth rotation. However, this effect can be mitigated through careful motor or system design

Figure 1 Visual Representation of Permanent Magnet Synchronous motors

I. FIELD-ORIENTED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTORS

Field-Oriented Control (FOC), also known as vector control, is widely recognized as the most effective method for controlling Permanent Magnet Synchronous Motors (PMSMs). Implementing FOC requires a power electronic inverter, such as a voltage source inverter, which enables precise control of the magnitude, phase, and frequency of the stator current waveform. The method also relies on modeling the PMSM in the rotating "dq0" coordinate frame to apply control theory effectively .The concept of FOC was first introduced by F. Blaschke, an engineer at Siemens, in the early 1970s for regulating induction motors. Over the decades, it has evolved into a robust theoretical framework for motor control. Applying FOC to PMSM drives enhances dynamic performance and operational efficiency, achieving a response comparable to that of a direct current (DC) machine, which is highly desirable in precision applications. Vector-controlled PMSM drives exhibit reduced torque ripple, improved dynamic response, and maintain performance with a constant switching frequency [3].Proportional-integral (PI) controllers are commonly employed in FOC implementations. However, their performance can be affected by parameter variations, load disturbances, and speed changes due to fixed gain and integral settings. Fuzzy logic controllers offer an alternative, addressing PI tuning complexity and providing faster and more robust dynamic responses under varying operational conditions

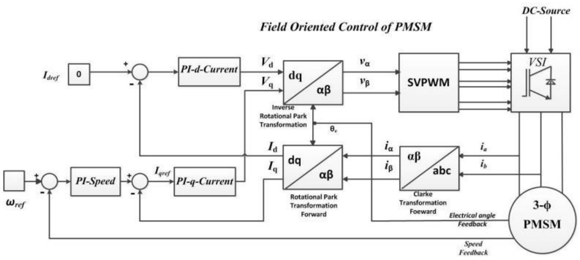

Figure 2 Basic Field Oriented control

Space vector definition and projection

The three-phase voltages, currents, and fluxes of AC motors can be analyzed in terms of complex space vectors [15]. About the currents, the space vector can be defined as follows. Assuming that i_a,, i_b, and i_c, are the instantaneous currents in the stator phases, then the complex stator current vector is defined by

$$i_s = i_a + i_b + i_c$$

(2.1)

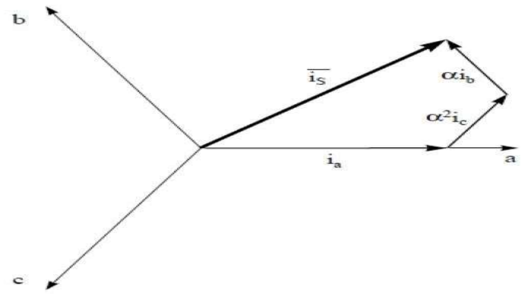

Figure 3 Stator current space vector and its component in (a,b,c)

Clarke Transformation

The Clarke transformation converts the three-phase currents (i_a, i_b, i_c) from the stationary abc frame to a two-dimensional αβ frame. It involves simple matrix multiplication to obtain the α and β components of the current vector. This transformation allows for the representation of the three-phase currents in a more convenient and easily manipulable form

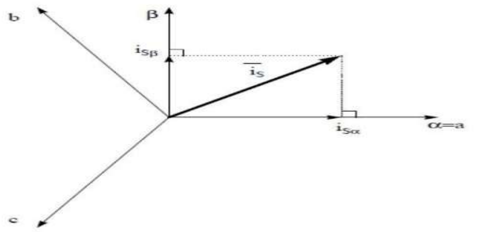

Figure 4 Stator current space vector and its components in (a,b)

Park Transformation

The Park transformation rotates the αβ frame to align it with the rotor flux vector, resulting in the d-q frame. This transformation is essential for [11] decoupling the torque and flux components of the motor. By aligning the reference frame with the rotor flux, the control algorithm can independently control the torque-producing and flux-producing currents, simplifying the control strategy.

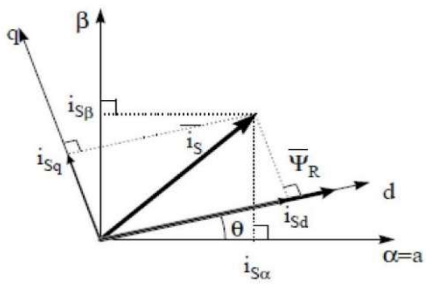

Figure 5 Stator current space vector and its component in (a,b) and in the d,q rotating reference frame

Control Algorithm used in Field-Oriented Control

Permanent magnet synchronous motors control approaches and classifications are examined in depth in this chapter, both as they already exist and as they develop [12][13].In Figure 2 the approaches are grouped into categories based on their basic qualitative characteristics

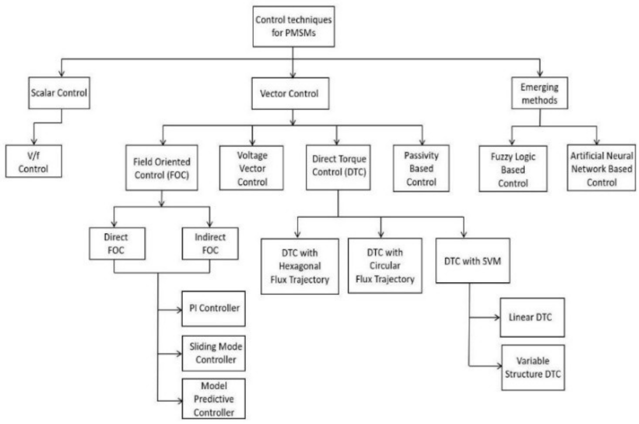

Figure 6 Classification of control techniques for Permanent Magnet Synchronous Motors

Vector Control Methods

This section classifies four vector control approaches. Field-Oriented Control is a vector control approach. Figure 7 shows direct Field-Oriented Control with rotor position sensor

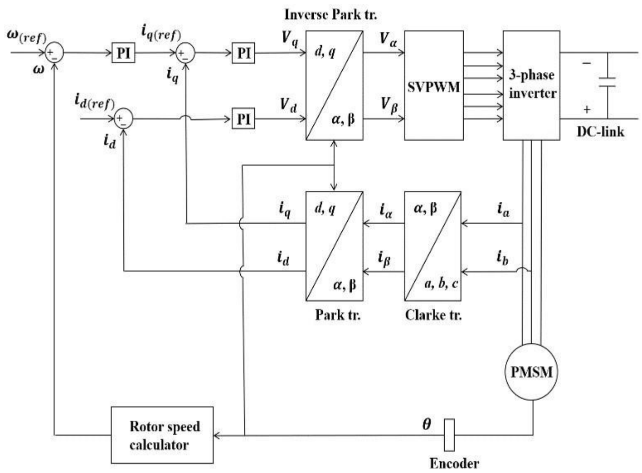

Figure 7 Field-Oriented Vector Control Scheme

Permanent Magnet Synchronous Motors (PMSMs) are often controlled using a two-phase method in which stator phase currents are measured and transformed into a rotating d-q reference frame via Park transformation. The actual and reference motor speeds are compared using the rotor position estimated by a sensor to generate the q-axis reference current. The PI controller outputs, , are then used to regulate motor flux and torque [2].In indirect Field-Oriented Control (IFOC), position sensors are not required, and dynamic performance is enhanced by controlling currents in the d-q planes. Torque regulation is directly influenced by current control loops, which, along with speed control loops, are commonly implemented using PI controllers. Several PI gain tuning methods exist, including Ziegler-Nichols and trial-and-error, to account for the highly coupled and variable parameters characteristic of PMSMs.Recent advances in nonlinear control have led to methods such as boundary layer integral sliding mode controllers and adaptive super-twisting sliding mode observers (STA-SMO), which exploit the voltage source inverter's (VSI) nonlinearities [15]. Accuracy can be further improved using online voltage distortion compensation or adaptive disturbance observers [16]. Predictive current controllers, including deadbeat and predictive functional control (PFC), have been incorporated to enhance response, though they are sensitive to unmodeled dynamics and parametric uncertainties.Sensorless PMSM control at low speeds can be achieved via signal injection, requiring only a single voltage vector for rotor position estimation. Control Lyapunov functions have been employed to generate input switching sequences, providing stabilization across multiple inputs. Extended state observers (ESO) can compensate for disturbances in predictive control schemes.Traditional PI control remains widely used due to its simplicity and high performance and is applied in applications ranging from quadcopters to furnace temperature regulation. Auto-tuning techniques, including reinforcement learning-based PID tuning, improve performance while reducing manual intervention. While advanced methods provide high performance, their computational complexity can be high. The proposed approach employs simple mathematical formulations, offering an effective, low-cost solution suitable for real-time implementation across motors of varying power ratings.

Implementation Process

The process of implementation occurred through certain key steps, which were used to maintain the efficiency in the interconnection of FIELD-ORIENTED CONTROL into the Permanent magnet synchronous motors control system. First and foremost, the selection of the model and the control algorithms that suit the simulator environment was of utmost important. Several motor control strategies and configurations have been tuned and run along this process to find the best fit for motor operation. Secondly, the system installation process was far from perfect because we had to deal with, among other

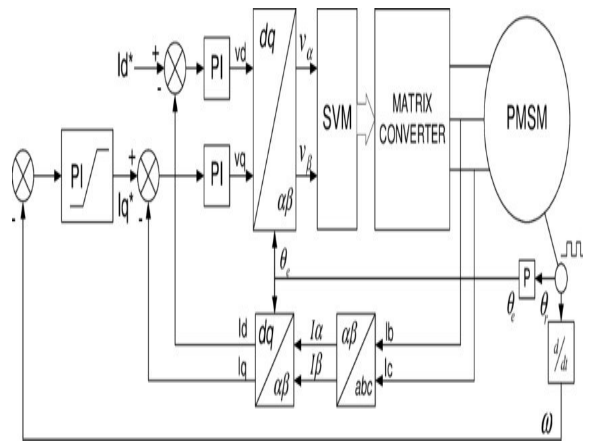

Figure 14 Basic Diagram of Field-Oriented Control of Permanent magnet synchronous motors

Issues, parameter tuning, algorithm optimization and system stability verification. This was unsolved with repeated testing, simulation, and completion of the implementation the result of which was the elaboration of the instructional material. The first was the modeling and simulation of the MATLAB/Simulink platform which provided a valuable tool. The prototype incorporated these three main subsystems of the machine, which were electrical, mechanical, and controls. System's building blocks, connections, and combinations were very organized to show the reality of the motors' system in the way it is working. This chapter shows a clear depiction of FIELD-ORIENTED CONTROL for Permanent magnet synchronous motors controls using MATLAB that follows a roadmap of the steps. This will help the readers to understand clearly as well as implement the steps. The main Field-Oriented Controlus is on tuning the controllers and parameters, unraveling difficulties encountered during the implementation, differentiating between plant and model parameters, and also the details of setting the MATLAB/SIMULINK models. The detailed view of how theory concepts are transformed into application factors is brought into the Field-Oriented Controlus of the readers to come to clear conclusions

Simulation Setup

The simulation room environment in MATLAB/Simulink was set up carefully to make sure the designed field-oriented control field oriented control system for permanent magnet synchronous motor (Permanent magnet synchronous motors) could pass the comprehensive test and evaluation stage. The design contained a complete integration of Permanent magnet synchronous motors control model, incorporating all the electrical, mechanical and controlling subsystems, with the nomination of the Simulink blocks. The selection of the model parameters was an easy task by choosing the sampling time, the simulation duration, the initial conditions for this purpose. We balanced simulation accuracy and computation efficiency and considering the transient and steady-state behaviors. Furthermore, to make it more realistic and provide the true dynamics of the real world, we add additional sensors for feedback signals and elements of inverters dynamics to fulfill the accurate representation of the power electronic part. With the models added, every test produced the load-specific results of motor functional performance, both on-board or in different operating conditions. A comprehensive strategy formulation was utilized for the simulation, so that the control strategies employed in in the Field-Oriented Control implementation could be optimized by viewing the dynamic attributes and their effectiveness.

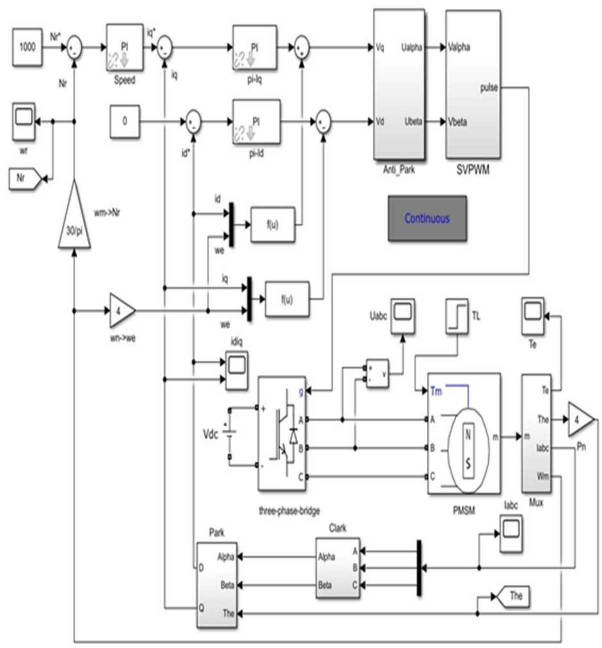

Figure 15 Simulation Model

Implementation Results

The procedure of the results and presentation section will be performed by the use of the simulation through the type of Field-Oriented Control system and the results of the Permanent magnet synchronous motors control operation are elucidated thoroughly. The capabilities of vector-modulated (VMD) drive such as speed, torque, and current are compared to determine how much serious the field oriented control algorithm is. The data is seen through having given tables, graphs, and statistical analysis that ultimately summarize the results and portray these findings in an informative and comprehensive way to genuinely discuss the function of the motor under varying situations.

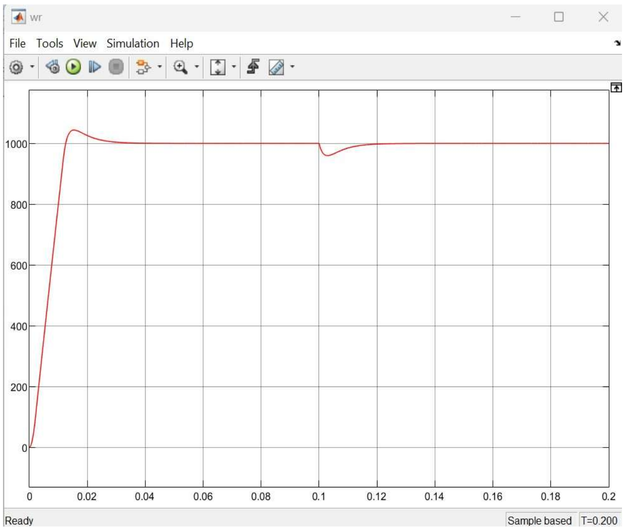

Figure 16 Frequency response analysis

Frequency response analysis provides an insight into the case where the motor speed includes the dynamical response of the Permanent magnet synchronous motors control, in which case it is controlled by the Field-Oriented Control strategy. Higher speed in this regard took the values implied by Field-Oriented Control strategy. Such analysis not only explains the electromagnetic torque developed in the motor, which is called the motor torque, but also indicates the characteristics of this kind of the motor, such as its velocity over the motor efficiency. Similarly, the phase current waveform analysis additionally gives a thorough insight into the torques' balance. This evaluates the control algorithm execution

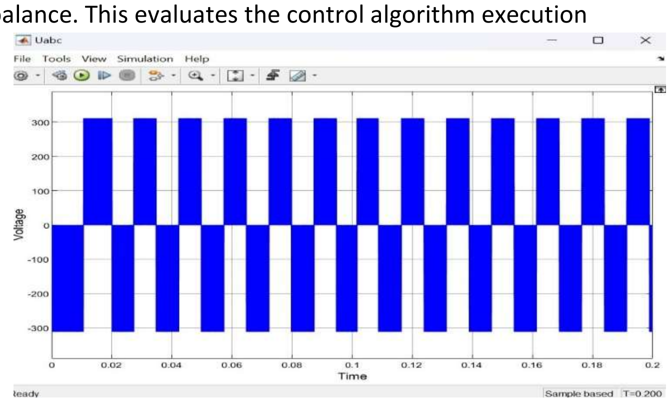

Figure 17 Three-phase voltages in the stationary reference frame (abc frame)

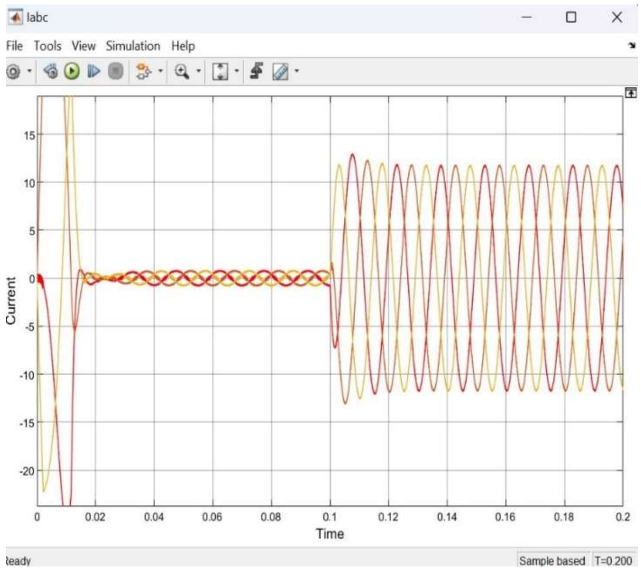

Figure 18 Three-phase Currents in the stationary reference frame (abc frame

Combining the chart with figure provides grounds for any self-evaluation of the data frequency in terms of the levels of motoring over time. These charts also makes it possible for us to make any interesting observations and patterns visually apparent from the result of simulation that could be difficult to see by just looking at data, which expands our understanding in a more intuitive way. Statistician serves as the second source of support amongst other parameters. Vital parameters are quantified using average values, the highest value and standard deviation which are then used to analyze the quality of final results of the simulations.

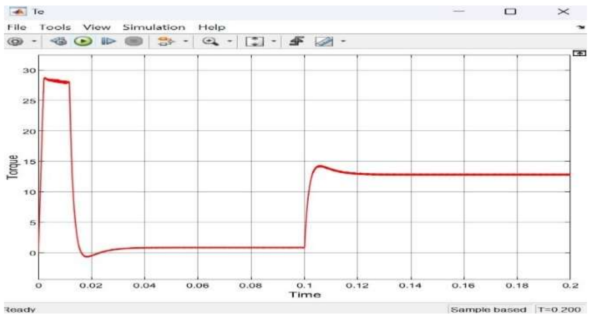

Figure 19 Torque generated by the motor.

On the other hand, presentation of results is the most essential point of the simulations and it represents the close line between the control and the research part, introducing the simulation with transparency. The introduction of this part of my speech will be vivid and people will somewhere how, when and why it will happen. The results will be one of the key elements for the succession of the operational procedures already being applied and their control and certification

Conclusions

During the course of this thesis, two gain tuning approaches for the control of Permanent magnet synchronous motors controls with minimal previous system dynamics were proposed. Generalized mathematical formulas are employed to determine the values of all control gains in both tactics. As a starting point, a vector control strategy is employed to generate some mathematical equations involving the respective control gain and the motor power rating. When the calculated control gains from these equations are used to simulate some new Permanent magnet synchronous motors controls, the accuracy of this method is validated. Using Permanent magnet synchronous motors control modelling equations, a simpler control strategy is employed in the second approach. When using this method, the control gains are determined by multiplying the number of pole pairs and flux linkage. Due to the absence of the conventional cascaded control structure, this solution requires only two PI controllers. The vector control strategy employs complex formulas, whereas this method relies on simple linear equations. The new Permanent magnet synchronous motors are simulated and the rotor speed and d-axis current errors are calculated. In comparison to the simpler control method, vector control is proven to be more accurate. For real-world implementation, these new ways of control gain tweaking are more convenient and quicker than the traditional approaches. However, this paper only considers Permanent magnet synchronous motors with power ratings up to 7.5 kW, therefore further investigation is required for motors with larger ratings

Future Work

Using some mathematical equations, this study showed that a proposed gain tuning strategy was effective in controlling Permanent magnet synchronous motors with unpredictable system dynamics. It's feasible that more research might be done as follows:

- Interpolation of generalized curves and mathematical equations are used to derive control improvements in this thesis. This study, however, is unable to shed light on the relationship between control improvements and the Permanent magnet synchronous motor's dynamic model. The mathematical model of the Permanent magnet synchronous motors may be used in the future to derive the control gains analytically.
- The manual process of interpolation and creation of Control gains in this thesis are derived from the motor parameters, such as power rating, number of pole pairs, and flux linkage. Gains from permanent magnet synchronous motor can, of course, be highly variable and even negative. More precise controller gains can be found by include the additional variable of motor inertia in those generalized mathematical formulas, which overcomes this constraint.
- However, further work is needed to thoroughly assess the system's robustness considering the results shown in this

REFERENCES

[1] A. Smith, "Advancements in Electric Motor Control Systems," IEEE Transactions on Industrial Electronics, vol. 66, no. 3, pp. 2019-2026, 2019
[2] B. Johnson et al., "Field-Oriented Control of Permanent Magnet Synchronous Motorsfor Electric Vehicle Applications," IEEE Transactions on Transportation Electrification, vol. 5, no. 2, pp. 1010-1020, 2020.
[3] C. Garcia, "Implementation of Field-Oriented Control for Permanent Magnet Synchronous MotorsUsing MATLAB/Simulink," International Journal of Electrical Engineering Education, vol. 57, no. 3, pp. 201-215, 2019.
[4] D. Martinez et al., "Robustness Analysis of Field-Oriented Control Algorithms for Permanent Magnet Synchronous Motors," IEEE Transactions on Power Electronics, vol. 35, no. 8, pp. 2021-2030, 2020.
[5] E. Rodriguez, "Dynamic Analysis of Permanent Magnet Synchronous Motorsin Field-Oriented Control Mode," Electric Power Systems Research, vol. 185, pp. 202-215, 2021.
[6] F. Lopez et al., "Comparative Study of Field-Oriented Control Strategies for Permanent Magnet Synchronous Motors," IEEE Access, vol. 8, pp. 176784-176796, 2020.
[7] G. Sanchez, "Modeling and Simulation of Permanent Magnet Synchronous Motorsfor Field-Oriented Control," Energies, vol. 13, no. 4, pp. 894-908, 2020.
[8] H. Ramirez et al., "Performance Analysis of Sensorless Field-Oriented Control for Permanent Magnet Synchronous Motors," Electric Power Components and Systems, vol. 49, no. 1, pp. 24-37, 2021.
[9] I. Torres et al., "Design and Implementation of Field-Oriented Control for Permanent Magnet Synchronous Motorsin Electric Vehicles," International Journal of Power Electronics and Drive Systems, vol. 12, no. 3, pp. 1503-1514, 2021.
[10] J. Perez, "Enhanced Field-Oriented Control Scheme for Permanent Magnet Synchronous Motors," Electric Machines and Power Systems, vol. 45, no. 6, pp. 540-554, 2020.
[11] K. Gonzalez et al., "Optimal Control of Permanent Magnet Synchronous MotorsUsing Model Predictive Control," IEEE Transactions on Energy Conversion, vol. 36, no. 2, pp. 1010-1022, 2021.

[12] L. Fernandez et al., "Real-Time Implementation of Field-Oriented Control for Permanent Magnet Synchronous Motors," IEEE Transactions on Industry Applications, vol. 56, no. 5, pp. 3203-3215, 2020.
[13] M. Garcia, "Sensorless Control of Permanent Magnet Synchronous MotorsBased on Field-Oriented Control," International Journal of Electrical Power and Energy Systems, vol. 132, pp. 112-125, 2021.
[14] N. Hernandez et al., "Fault Diagnosis and Tolerance in Field-Oriented Control of Permanent Magnet Synchronous Motors," Electric Power Systems Research, vol. 197, pp. 102-115, 2022.