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Original Article

Model Predictive Control-Based Field-Oriented Control for Speed Regulation of Electric Vehicle PMSM Drives

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Abstract - *This paper examines the enhancement of Electric Vehicle (EV) Permanent Magnet Synchronous Motor (PMSM) drives through the integration of Field-Oriented Control (FOC) with Model Predictive Control (MPC). The study aims to achieve high precision and dynamic response for PMSM drives under diverse operating conditions. FOC provides good control capability over full torque and speed ranges. MPC is an optimal control technique in which the calculated control actions minimize a cost function for a constrained dynamic system. The theoretical framework combines FOC and MPC principles, utilizing MPC's predictive capabilities to optimize d-q current references in real-time. The methodology encompasses the design and implementation of an MPC technique integrated with FOC, with key objectives including minimising torque ripples, maintaining vehicle stability through robust control loops, and optimising PMSM drive performance across a wide speed range of EV. Different types of torque control methodologies, such as PI Controller and Voltage Vector Control for PMSM Control, can be applied to an electric vehicle. The results indicate significant improvements in torque ripple reduction, dynamic response, and disturbance rejection, demonstrating the robustness and adaptability of the proposed control system compared with the PI Controller. This approach effectively addresses key challenges and signifies advancements over traditional control methods, contributing to the field of electric vehicle control systems.*

Keywords - *Permanent Magnet Synchronous Motor (PMSM), Field-Oriented Control (FOC), Model Predictive Control (MPC), Torque Ripple Minimization, Electric Vehicle (EV), Direct Torque Control (DTC), Direct Flux Control (DFC).*

1. Introduction

Electric drive plays a crucial role in automation and industrial processes, managing electrical machines' speed, torque, and position [1]. PMSMs have become increasingly popular among them for their superior efficiency, high power density, and outstanding performance. PMSMs are especially favored in applications requiring precise control and high dynamic performance, such as electric vehicles and aerospace systems [2]. Choosing PMSMs over other types, like induction motors or brushed DC motors, has several advantages. PMSMs deliver superior efficiency and power factor, require less maintenance because they lack brushes, and offer a more compact design for equivalent power ratings. Furthermore, using permanent magnets minimizes energy losses from magnetizing currents, leading to greater energy savings [3]. Controlling PMSMs presents several challenges. One major issue is torque ripple, leading to vibrations and noise, especially in precision applications. Additionally, achieving precise control across different operating conditions is difficult, particularly when faced with varying loads and uncertain motor parameters. Traditional control methods often fail to manage these complexities effectively [4].

The development of control techniques for PMSMs has advanced considerably over time [5]. Early on, scalar control methods like the Voltage/Frequency (V/F) control and voltage vector control method, PI control and Direct Flux Control (DFC) methods were popular due to their simplicity and ease of implementation. However, V/f control falls short in applications demanding high precision and dynamic response, as it lacks effective torque control and has limited dynamic performance [6-8]. MPC has a fast dynamic response and can improve motor control performance and efficiency.

Field-Oriented Control (FOC) enables independent management of the motor's flux and torque, like the control of a separately excited DC motor, and delivers enhanced dynamic response and efficiency. FOC is commonly employed in high-performance applications like electric vehicles [9]. However, it involves complex transformations and requires precise motor parameter knowledge, making its implementation and tuning more challenging [10]. Integration with MPC based FOC method maintains a constant ratio between voltage and frequency to regulate motor speed and preserve air gap flux, making it suitable for low-performance applications where precision is not crucial.

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Direct Torque Control (DTC) is an advanced technique recognized for its rapid torque response and robustness. It manages motor torque and flux by directly selecting the appropriate inverter switching states, bypassing the need for a modulator or current controller. This method is ideal for applications that demand quick torque adjustments and resilience to parameter variations [11]. Compared to DFC, the DTC offers better torque control. However, DTC may produce a high torque ripple and necessitates complex algorithms to handle switching states effectively.

Many methods have been proposed, such as Space Vector Modulation (DTC-SVM) and optimization of PI with Genetic Algorithm (GA), resulting in the development of the transient response. However, there is only a slight torque and flux ripple reduction in steady state conditions. In recent years, there has been a development in integrating Artificial Intelligence (AI) techniques, such as fuzzy logic and neural networks, into DTC to enhance its performance. MPC, combined with DTC, has gained attention due to its high performance and ease of implementation.

Voltage Vector Control involves managing the voltage vectors applied to the motor to regulate torque and flux. This approach enhances dynamic performance and reduces torque ripple, but it demands sophisticated algorithms and precise parameter estimation, making implementation and tuning more challenging [12]. Despite advancements in these traditional techniques, several issues persist:

- Achieving precise control across a broad range of operating conditions
- Minimizing torque ripple to reduce vibrations and noise
- Effectively handling parameter variations and external disturbances
- Simplifying the implementation and tuning of control algorithms

The main objectives of the proposed method are,

- To maintain a constant ratio between voltage and frequency to regulate motor speed and preserve air gap flux.
- Improve dynamic response, reduce torque ripple, and enhance overall stability.

The paper is organized as follows: Section 1 introduction of the research topic. Section 2 details the PMSM modelling. Section 3 presents different control techniques. The implementation of the control system is described in Section 4. Comparative results and discussions are presented in Section 5, and the paper concludes in Section 6. This structured approach ensures a comprehensive understanding of the development and implementation of MPC-based FOC for PMSM drives in EVs, addressing key challenges and highlighting the advancements over traditional control methods.

2. PMSM Modelling

Mathematical modelling of PMSMs is essential for understanding their performance and control. This section outlines the mathematical framework for PMSM modelling, detailing the key assumptions and the derivation of fundamental equations.

The following assumptions are made for modelling the PMSM:

- Neglect of Magnetic Saturation: The effects of magnetic saturation on the motor's behavior are considered negligible.
- Sinusoidal Back-EMF: The back Electromotive Force (EMF) is assumed to be sinusoidal.
- Exclusion of Minor Effects: Effects such as cogging torque, hysteresis, and eddy currents are minimal and, therefore, disregarded.

In a two-pole PMSM, as depicted in Figure 1, the rotor's reference axis maintains a time-varying angular position, (t), relative to the stationary stator reference axis [13]. Furthermore, the rotating Magneto Motive Force (MMF) produced by the stator windings exhibits an angular displacement, α, with respect to the rotor's d-axis.

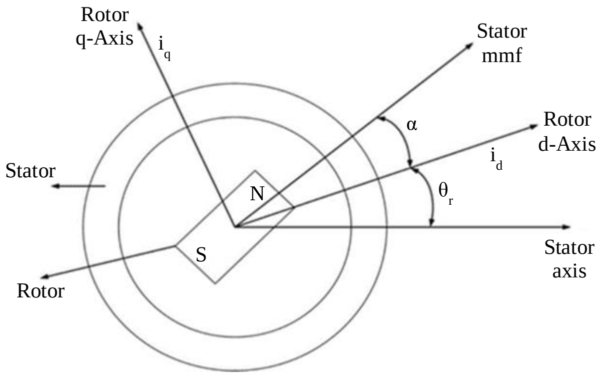


Fig. 1 Schematic of two Pole PMSM

Here surface mounted PMSM is used, where $L_{sq} = L_{sd} = L$ the equations describing the voltages in the model are presented as follows:

$$v_{sq} = R_s i_{sq} + \omega_r \varphi_{sd} + \rho \varphi_{sq} \tag{1}$$

$$v_{sd} = R_s i_{sd} - \omega_r \varphi_{sq} + \rho \varphi_{sd} \tag{2}$$

Where vsd, vsq, isd, and isq are the d-q axes of voltage and current, respectively. φsd, φsq is the stator winding d-q axes flux linkages. The expressions for the flux linkages are presented as follows:

$$\varphi_{sq} = L i_{sq} \tag{3}$$

$$\varphi_{sd} = L_d i_{sd} + \varphi_m \tag{4}$$

The amplitude of the fundamental PM flux linkage component is represented by φm. Substituting Equation (3) and (4) into Equation (1) and (2),

$$v_{sq} = R_s i_{sq} + \omega_r (L i_{sd} + \varphi_m) + \rho L i_{sq} \tag{5}$$

$$v_{sd} = R_s i_{sd} - \omega_r L i_{sq} + \varphi_m) + (L i_{sd} + \varphi_m) \tag{6}$$

Re-arranging the Equation (5) and (6):

$$\begin{bmatrix} v_{sq} \\ v_{sd} \end{bmatrix} = \begin{bmatrix} R_s + \rho \mathrm{L} & \omega_r L \\ -\omega_r L & R_s + \rho \mathrm{L} \end{bmatrix} \begin{bmatrix} i_{sq} \\ i_{sd} \end{bmatrix} + \begin{bmatrix} \omega_r \varphi_m \\ \rho \varphi_m \end{bmatrix} \tag{7}$$

The equation for the motor's generated torque is given by,

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\varphi_{sd} i_{sq} + \varphi_{sq} i_{sd}) \tag{8}$$

The mechanical equation of the torque,

$$T_e = T_l + B\omega_m + J\frac{d\omega_m}{dt} \tag{9}$$

The expression for the rotor's mechanical speed can be obtained by rearranging the Equation (9) as,

$$\omega_m = \int \left(\frac{T_e - T_l - B\omega_m}{J}\right) dt \tag{10}$$

$$\omega_m = \frac{2}{P}\omega_r \tag{11}$$

3. Control Techniques

Different control techniques were introduced to provide more advanced FOC and MPC solutions [14]. Integrating MPC with FOC offers a promising solution to the limitations of conventional control methods for PMSMs.

3.1. Design of FOC

FOC, also known as vector control, is an advanced and highly effective method for managing the torque and speed of PMSMs. This technique enhances dynamic performance by decoupling torque and flux control, allowing for independent management of these parameters, akin to the control of DC motors.

FOC converts the motor's three-phase stator currents into a two-phase orthogonal coordinate system, known as the d-q frame, which rotates synchronously with the rotor's magnetic field. This transformation streamlines the control strategy and enhances the motor drive's efficiency and responsiveness [16, 17]. The core mathematical processes in FOC involve the Clarke and Park transformations, as illustrated in Figure 2. The Clarke transformation maps the three-phase stator currents into a two-phase stationary reference frame (α-β). In contrast, the Park transformation converts these into the rotating d-q frame.

In the d-q frame, the d-axis current (i_d) aligns with the rotor flux and manages the flux linkage, while the q-axis current (i_q) is perpendicular to the rotor flux and regulates the torque. The core strategy of FOC involves controlling i_d to adjust the rotor flux and i_q to manage the motor's torque.

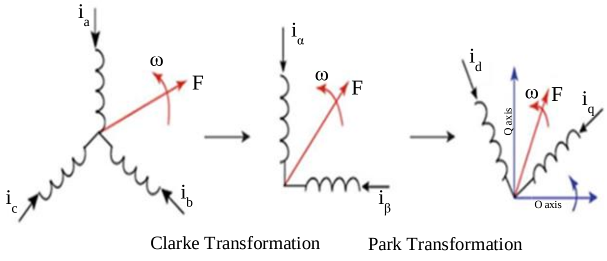


Fig. 2 Three-phase, two-phase and rotating reference frames

The control process starts with measuring the three-phase stator currents (i_{sa}, i_{sb}, i_{sc}). These currents are then converted into the α-β stationary frame using the Clarke transformation.

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{12}$$

Following this, the Park transformation transforms the α-β currents into the d-q rotating reference frame.

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \tag{13}$$

Here, θ represents the rotor position, which is crucial for accurate transformations and control. For speed regulation, the motor speed (ω_m) is measured and compared with the reference speed (ω_{ref}). The speed error is then fed into a PI controller to generate the reference q-axis current (i_{sqref}):

$$i_{sq_{ref}} = K_{P_\omega}(\omega_{ref} - \omega_m) + K_{i_\omega}\int(\omega_{ref} - \omega_m)dt \tag{14}$$

The q-axis current error, defined as the difference between $i_{sq_{ref}}$ and the actual q-axis current (i_{sq}) is processed through another PI controller to produce the reference q-axis current ($i_{sq_{ref}}$):

$$i_{sq_{ref}} = K_{P_{sq}}\left(\mathrm{i}_{sq_{ref}} - i_{sq}\right) + K_{i_{\mathrm{sq}}}\int(\mathrm{i}_{sq_{ref}} - \mathrm{i}_{sq})dt \quad (15)$$

For d-axis control, the d-axis current error, which is typically the difference between the desired d-axis current ($i_{sd_{ref,}}$often set to zero for maximum efficiency) and the actual d-axis current (i_{sd}) is processed through a PI controller to generate the reference d-axis current ($i_{sd_{ref}}$):

$$i_{sd_{ref}} = K_{P_{sd}}\left(\mathrm{i}_{sd_{ref}} - i_{sd}\right) + K_{i_{\mathrm{sd}}}\int(\mathrm{i}_{sd_{ref}} - \mathrm{i}_{sd})dt \quad (16)$$

These reference currents are crucial for attaining the desired performance in the FOC scheme, ensuring that the motor operates efficiently and responds accurately to control inputs. Accurate control of these currents enables optimal torque production and flux regulation, which is essential for high-performance applications.

Precise rotor position information is vital for implementing FOC, typically acquired through rotor position sensors or estimated using sensor-less techniques. This accuracy ensures proper alignment of the rotating reference frame with the rotor's magnetic field, which is critical for correctly applying the Park transformation and the overall effectiveness of the control strategy.

3.2. MPC Algorithm

The MPC algorithm is a sophisticated control method aimed at enhancing the performance of PMSMs. It achieves this by forecasting the system's future behavior and minimizing a specified objective function. In this section, the MPC algorithm and its application are mentioned clearly, particularly how the reference currents produced by the FOC are utilized to create gating signals for the inverter.

MPC excels in managing multi-variable control systems and constraints, making it an ideal choice for PMSM drives. The core concept of MPC involves employing a predictive model to forecast the motor's future behavior over a finite horizon. By analyzing these predictions, MPC determines the optimal control actions needed by minimizing an objective function, which usually encompasses terms related to tracking errors and control effort [15,18].

The main objective function M in MPC is defined to evaluate the difference between the reference currents $i_{\mathrm{sd\_ref}}$ and $i_{\mathrm{sq\_ref}}$, and the predicted currents $i_{\mathrm{sd\_p}}$ and $i_{\mathrm{sq\_p}}$. The objective function can be expressed as:

$$M = \left(i_{sd\_ref} - i_{sd\_p}\right)^2 + \left(i_{sq\_ref} - i_{sq\_p}\right)^2 + \left(\omega_{ref} - \omega_r\right)^2 \quad (17)$$

The inverter's predictive model plays a crucial role in the MPC algorithm. It involves deriving the inverter's voltage vectors Vd and Vq from the switching functions [Sa, Sb, Sc] and the DC-link voltage V_{dc}. These switching functions correspond to the inverter output voltages V_a, V_b, and V_c for each possible inverter switching state, represented by gating signals S_1 through S_6. These voltage vectors are then transformed into the d-q frame. The calculation of the voltage vectors proceeds as follows:

$$V_a = \frac{V_{dc}}{3}(2S_a - S_b - S_c) \quad (18)$$

$$V_b = \frac{V_{dc}}{3}(2S_b - S_c - S_a) \quad (19)$$

$$V_c = \frac{V_{dc}}{3}(2S_c - S_a - S_b) \quad (20)$$

These voltages are then transformed to the d-q frame using the following equations:

$$v_{sd} = \frac{2}{3}\left(V_a\cos\theta + V_a\cos\left(\theta + \frac{4\pi}{3}\right) + V_a\cos\left(\theta + \frac{2\pi}{3}\right)\right) (21)$$

$$v_{sq} = \frac{2}{3}\left(V_a\sin\theta + V_a\sin\left(\theta + \frac{4\pi}{3}\right) + V_a\sin\left(\theta + \frac{2\pi}{3}\right)\right) (22)$$

The discrete-time form of the PMSM mathematical model, used for predicting future states are:

$$i_{sd\_p} = i_{sd} + \frac{T_s}{L}\left[v_{sd} - Ri_{sd} + L\omega_m i_{sq}\right] \quad (23)$$

$$i_{sq\_p} = i_{sq} + \frac{T_s}{L}\left[v_{sq} - Ri_{sq} + L\omega i_{sd} - \varphi\omega_m\right] \quad (24)$$

Where R, L, Ts, ωm, φ are stator resistance, stator inductance, sampling time, rotor measured speed, and permanent magnet flux linkage. The implementation of the MPC algorithm involves the following steps:

- Estimate Future Motor Currents: Predict the future states of the motor currents id and iq based on the current states and the voltages applied for each potential inverter switching state.
- Calculate Cost Function: Compute the cost function for each switching state, which typically includes terms related to tracking errors and control effort.
- Identify Optimal Switching State: Determine the switching state that minimizes the cost function.
- Apply Gating Signals: Implement the corresponding gating signals to the inverter to achieve the optimal control action.

The gating signals are determined by assessing the cost function for all possible inverter states. The state that results in the minimum cost is selected, and its corresponding gating signals are applied. Figure 3 illustrates the procedural steps in implementing the MPC algorithm through a flowchart. This approach ensures that the motor operates efficiently by closely tracking the reference currents and minimizing deviations from the desired performance.

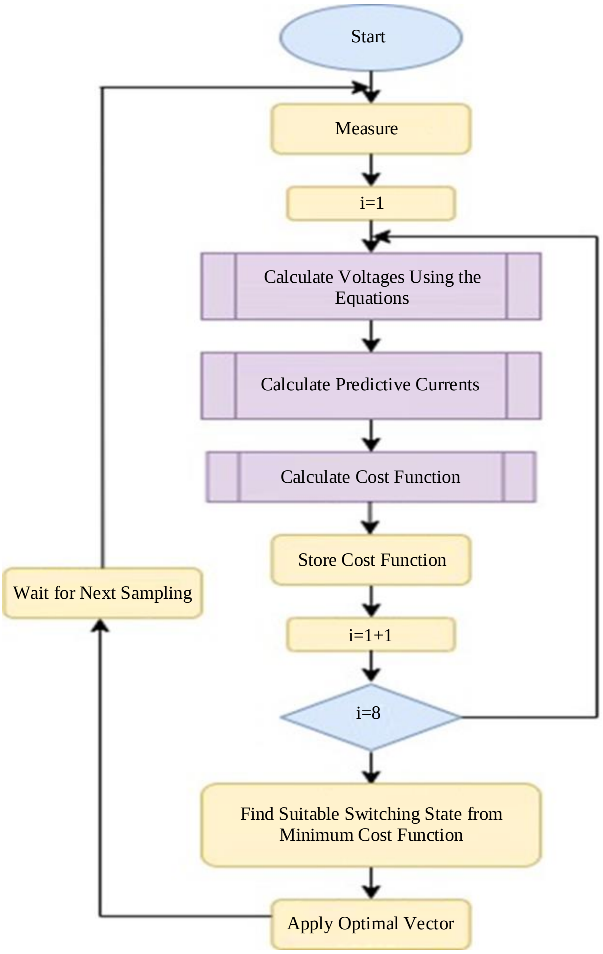


Fig. 3 MPC flow chart

4. Implementation of Control Techniques

The system block diagram for the proposed MPC-based Field-Oriented Control (FOC) of a PMSM drive, depicted in Figure 4, represents a detailed framework designed for optimal performance. At the heart of the system is the PMSM, which is managed by an MPC algorithm to improve dynamic response and reduce steady-state error. The control structure features current and speed controllers that utilize predictive models to account for the motor's dynamics and constraints. These controllers produce reference signals for the inverter, ensuring accurate modulation of the motor's voltage and current. Additionally, feedback mechanisms are integrated to continuously monitor and adjust system parameters, maintaining robust performance across varying operational conditions.

Integrating these elements in the block diagram underscores the smooth interaction between the predictive control algorithm and the motor drive components. This arrangement illustrates the effectiveness of the proposed technique in achieving high-performance motor control.

5. Results and Discussions

To evaluate the effectiveness of the proposed FOC with MPC for speed control of a 3.4 kW PMSM drive, simulation studies were conducted using MATLAB/Simulink. The performance of the proposed control scheme was analyzed across four distinct scenarios:

- Starting characteristics: Assessing the behavior of the system from a standstill.
- Dynamic response to a sudden load change from no load to full load: Evaluating the system's reaction to a sudden shift from no load to full load

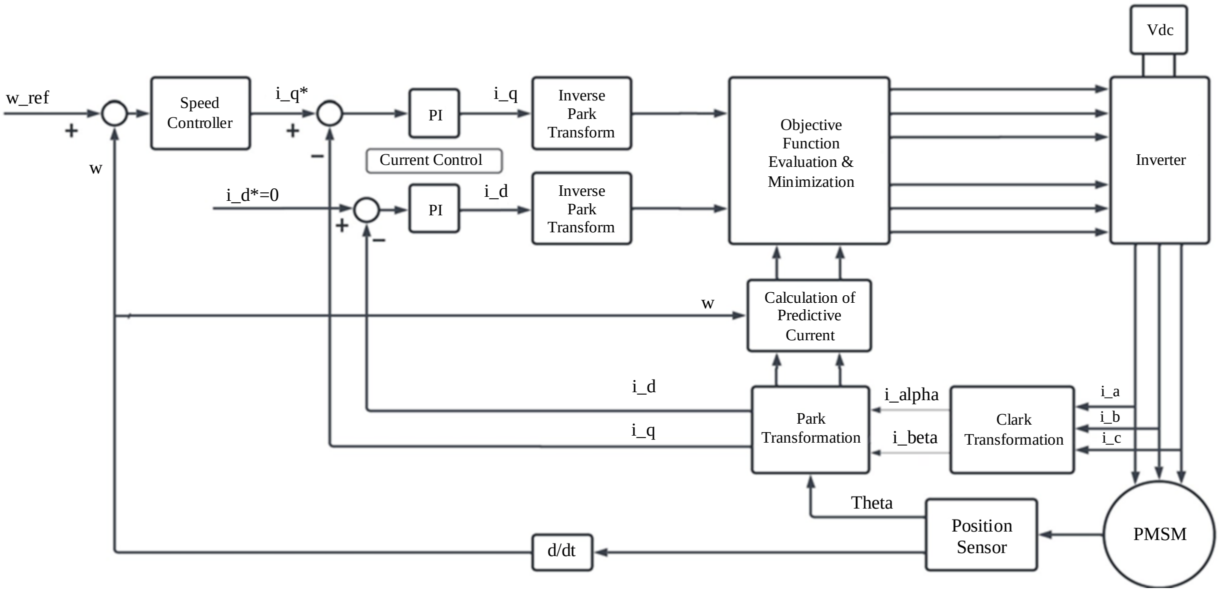


Fig. 4 Block diagram of proposed system

- Dynamic Response at Low Speeds**:** Examining the system's response to a sudden load change from no to full load at low speeds.
- Steady-state characteristics: Analyzing the system's performance with a sampling time of 10 µs. The results from these scenarios were compared with those obtained using a traditional Proportional-Integral (PI) controller to gauge the improvements and effectiveness of the proposed MPC-based FOC control scheme.

This comparative study emphasizes key performance metrics, such as transient response, including settling time, rise time, and overshoot, to underscore the benefits of the FOC with the MPC method. The analysis highlights the proposed controller's superior ability to manage various load conditions, ensuring smooth and efficient motor operation. By evaluating these metrics, the study provides detailed insights into the robustness and effectiveness of the FOC MPC approach across different operating scenarios, demonstrating its potential advantages over traditional PI control methods. Table 1 lists the parameters of PMSM.

Table 1. PMSM parameters

Parameter	Value
Voltage, V	380 V
Rated Output Power	3.4 KW
Rated Speed, N	3000 rpm
Stator Resistance, R_S	1.93 Ω
Q-axis inductance, L_q	0.0114 H
D-axis inductance, L_d	0.0114 H
PM Flux linkage, φ_m	0.265 Wb
No. of poles, P	8
Motor Inertia, J	0.11 kgm^2

5.1. Starting Characteristics

Analysis of Figures 5, 6(a), and 6(b) offers a detailed comparison of the performance differences between the MPC-based FOC and the traditional PI controller in regulating the speed of the PMSM drive under starting conditions. Figure 5 directly compares the speed responses for both control strategies. This figure demonstrates the enhanced performance of the MPC-based FOC, characterized by a faster rise time, reduced overshoot, and quicker settling time compared to the PI controller.

Figures 6(a) and 6(b) show a more detailed examination of the individual controller responses. Figure 6(a) illustrates the speed response of the PI controller, which reveals significant overshoot and oscillations during the startup phase. These characteristics highlight the controller's difficulties in managing the rapid changes in torque and speed demands associated with motor startup.

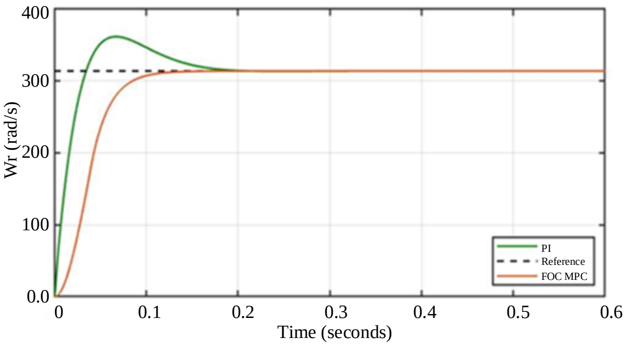
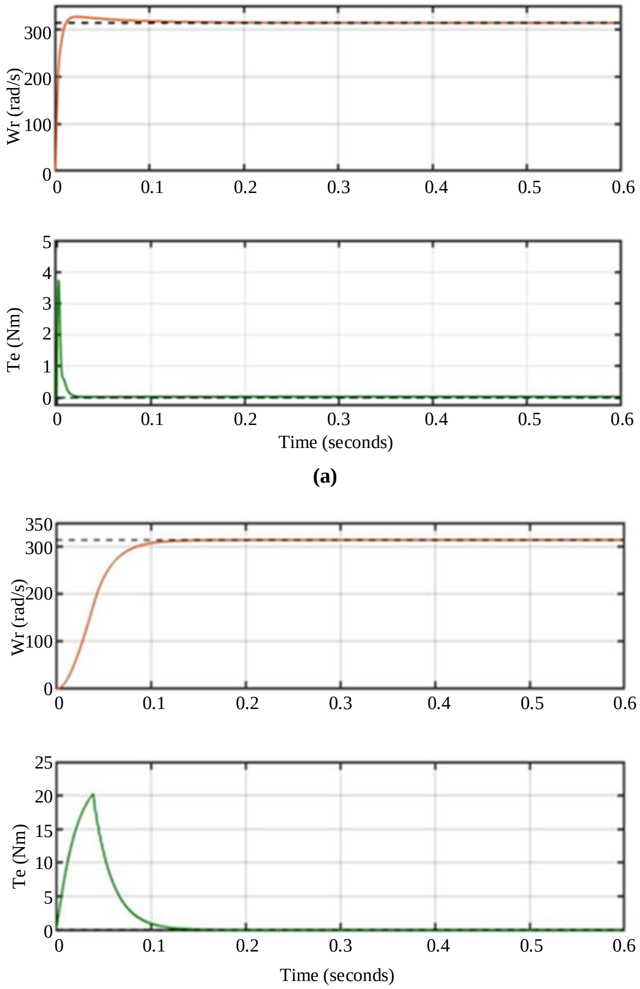


Fig. 5 Speed response of the PMSM at starting conditions with no load and rated speed

In contrast, Figure 6(b) demonstrates the exceptional performance of the MPC-based FOC. It shows a smooth and rapid acceleration to the rated speed without overshooting. This superior transient response is attributed to the MPC controller's ability to predict and adjust for system dynamics, resulting in a more precise and robust control strategy.



(a)

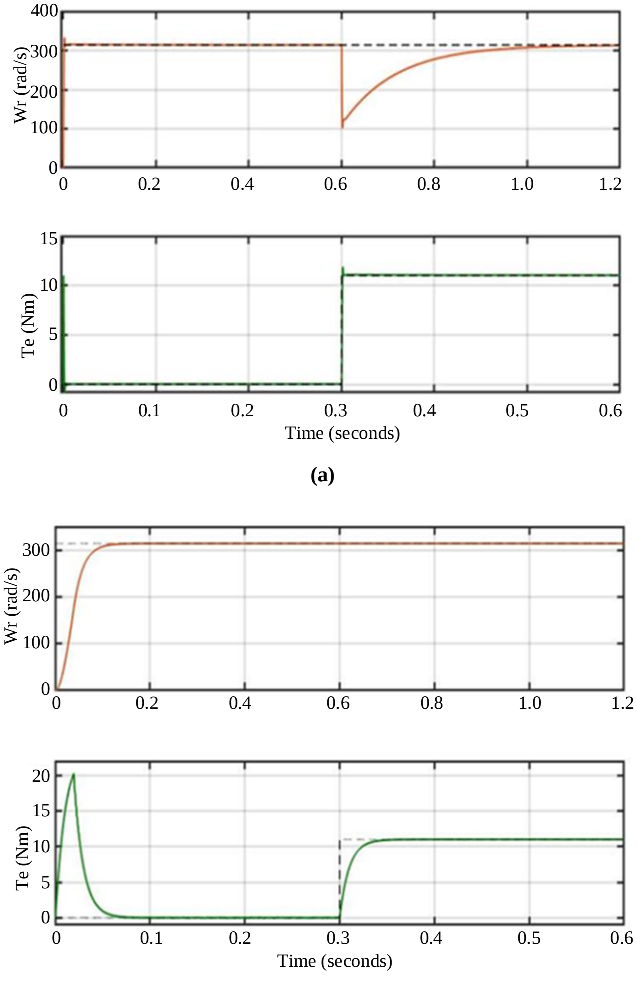
(b)

Fig. 6 Starting characteristics of PMSM drive at rated speed with (a) PI, and (b) MPC based FOC.

5.2. Dynamic Response of Torque Transition from No Load to Full Load

The dynamic response of the PMSM drive to a sudden torque change from no load to full load is assessed in Figure 7(a). This figure illustrates the speed and torque response of the PMSM drive under traditional Proportional-Integral (PI) control.

Initially, the motor speed quickly reaches the reference value of 314 rad/s, indicating effective steady-state performance. However, at 0.6 seconds, when a sudden torque of 11 Nm is applied, there is a notable dip in speed, highlighting the PI controller's slower response to abrupt load changes. Additionally, the torque response exhibits an initial overshoot and a prolonged settling period, underscoring the PI controller's limitations in stabilizing the system under such disturbances. Figure 7(b) showcases the response using MPC based FOC.



(a)

(b)

Fig. 7 Dynamic response of (a) PI, and (b) MPC based FOC for a sudden change in load from no-load to full load.

Similarly to PI control, the motor speed initially reaches the reference value. However, when the sudden torque change occurs at 0.6 seconds, the speed remains stable with no visible dip, demonstrating the MPC-based FOC's superior disturbance rejection capability.

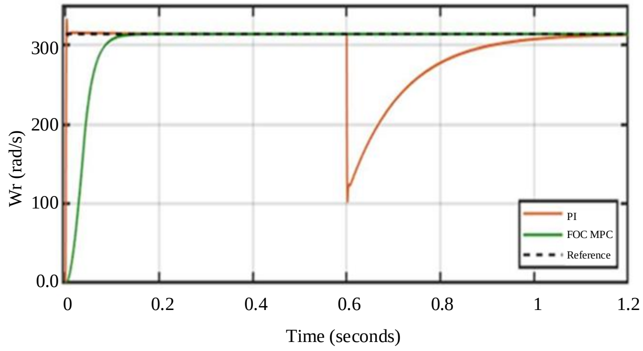
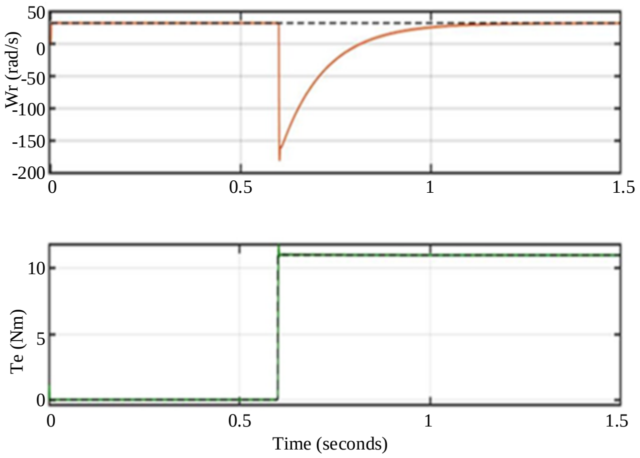


Fig. 8 Transient characteristics of drive for a sudden change in load from no-load to full load

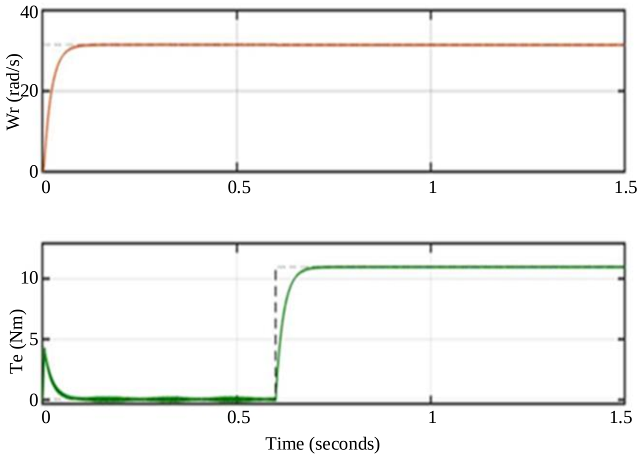
Figure 8 provides a clear comparison of the speed responses for both controllers. It shows that the MPC-based FOC maintains a steady speed profile with minimal deviation, whereas the PI-controlled drive exhibits a significant speed dip followed by a recovery phase. This comparison underscores the robustness and efficiency of MPC-based FOC in managing dynamic load changes, demonstrating its superiority as a control strategy for PMSM drives.

5.3. Dynamic Response of Motor at Slow Speed

Figures 9(a) and 9(b) present the speed torque characteristics for PI-controlled and MPC-based FOC-controlled PMSM drive at low speeds (10% of rated speed). It can also be observed from Figure 9(b) that the initial torque overshoot in the MPC based FOC controller at low-speed operations is 25% of the rated speed operation of the drive.



(a)



(b)
Fig. 9 Dynamic response of (a) PI, and (b) MPC based FOC controlled PMSM drive torque transition from no load to full load at low-speed.

At t=0.6s, a torque transition from no load to full load causes a noticeable speed deviation in the PI-controlled drive, as illustrated in Figure 10. In contrast, the MPC-based FOC controller demonstrates superior performance by effectively maintaining speed stability under this condition.

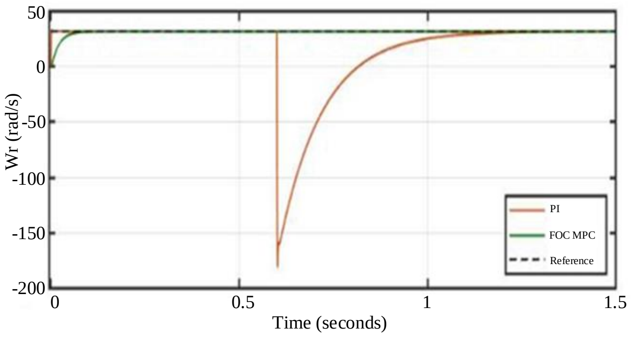


Fig. 10 Speed comparison of low-speed operation

5.4. Steady State Characteristics

The analysis of PMSM drive responses under full load (11 Nm) and rated speed (314 rad/s) is illustrated through comparative graphs of traditional PI and MPC-based FOC controllers. Figure 11 displays the speed response for both controllers. It shows that the PI controller reaches the rated speed by t=0.15s significantly earlier than the MPC-based FOC, which achieves the same speed by t=0.5s.

The PI controller exhibits minimal overshoot and quickly stabilizes at the rated speed, demonstrating effective speed control under these conditions. However, the MPC-based FOC achieves an even smoother speed transition, with virtually no overshoot and rapid convergence to the rated speed. This underscores the MPC-based FOC's superior efficiency in managing sudden load changes while maintaining exceptional stability and precision.

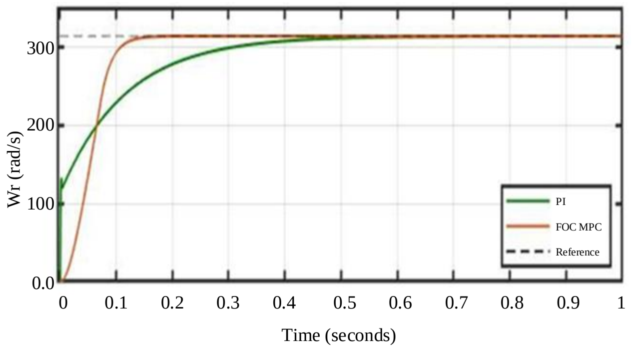


Fig. 11 Speed response comparison at rated speed

Figure 12 compares the torque responses for the two control strategies. While the PI controller's torque response demonstrates minimal overshoot and rapid stabilization at the desired torque of 11 Nm, it lacks the refined control seen with the MPC-based FOC. The MPC-based FOC shows an initial torque overshoot, reaching up to 23 Nm, but this is quickly corrected, and the system stabilizes at the reference torque. This brief overshoot is a trade-off for the MPC algorithm's proactive adjustments, ultimately leading to more precise and stable torque control.

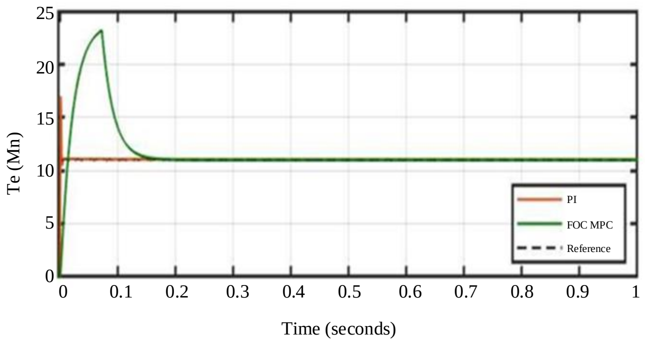


Fig. 12 Torque response comparison at full-load

Further examination of the steady-state characteristics from Figure 13 reveals additional advantages of the MPC-based FOC.

In steady-state operation, the MPC-based FOC maintains the desired speed and torque with minimal fluctuations, ensuring consistent and reliable performance. In contrast, although effective, the PI controller exhibits slightly more variability in maintaining target values, indicating a less robust steady-state control than the MPC-based approach. The advanced predictive capabilities of the MPC algorithm enable it to anticipate and counteract deviations more effectively, resulting in a more stable and precise control over time.

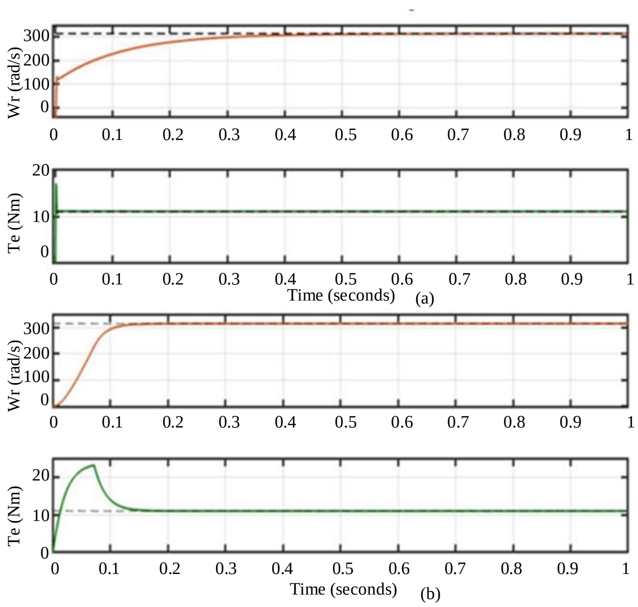


Fig. 13 Response of the PMSM drive for rated speed and full-load condition (a) PI, and (b) MPC based FOC.

6. Conclusion

The findings of this research underscore the significant advantages of integrating MPC with FOC for PMSM drives. Extensive simulations demonstrate that the MPC-based FOC strategy notably improves dynamic response, reduces torque ripple and enhances overall stability, particularly during torque transitions and varying load conditions. Comparative analysis with traditional Proportional-Integral (PI) control reveals that the MPC-based approach excels in terms of faster rise times, reduced overshoot and superior steady-state performance. The improved control accuracy and robustness of the MPC-based FOC method make it a promising solution for high-performance applications that require rapid and precise motor control.

By leveraging the predictive capabilities of MPC, the system can anticipate future states and optimize control actions in real-time, thereby increasing the efficiency, overall stability and reliability of the PMSM drive. This study confirms the effectiveness of the proposed control strategy and highlights its potential to address the limitations of conventional methods.

There is a future scope for further reduced torque and flux ripple by suggesting a Model Predictive Torque Control Technique by Pulse Width Modulation (MPTC-PWM) and Discrete Space Vector Modulation (DSVM) to achieve flux-linkage and electromagnetic torque ripple reduction in finite-set predictive control (FS-MPTC).

References

[1] Iqbal Husain et al., “Electric Drive Technology Trends, Challenges, and Opportunities for Future Electric Vehicles,” *Proceedings of the IEEE,* vol. 109, no. 6, pp. 1039-1059, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[2] Adel Merabet, “Advanced Control for Electric Drives: Current Challenges and Future Perspectives,” *Electronics*, vol. 9, no. 11, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[3] Suryakant et al., “Minimization of Torque Ripples in PMSM Drive Using PI- Resonant Controller-Based Model Predictive Control,” *Electrical Engineering*, vol. 105, pp. 207-219, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[4] Tomasz Rudnicki et al., “Performance Analysis of a PMSM Drive with Torque and Speed Control,” *2015 22nd International Conference Mixed Design of Integrated Circuits & Systems (MIXDES),* Torun, Poland, pp. 562-566, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[5] Qiong Wang, Shuanghong Wang, and Chuanhai Chen, “Review of Sensorless Control Techniques for PMSM Drives,” *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 14, no. 10, pp. 1543-1552, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[6] Byung-Geuk Cho et al., “Simple Position Sensorless V/f Scalar Control Method for Permanent-Magnet Synchronous Motor Drives,” *Journal of Power Electronics*, vol. 21, pp. 1020-1029, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[7] Michal Vidlak, Pavol Makys, and Lukas Gorel, “A Novel Constant Power Factor Loop for Stable V/f Control of PMSM in Comparison against Sensorless FOC with Luenberger-Type Back-EMF Observer Verified by Experiments,” *Applied Sciences*, vol. 12, no. 18, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[8] Vishesh Biyani et al., “Vector Control Implementation in PMSM Motor Drive for Electric-Vehicle Application,” *2022 4th International Conference on Energy, Power and Environment (ICEPE)*, Shillong, India, pp. 1-8, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] Vivek Kumar Yadav, Kuldeep Sahay, and Adeeb Uddin Ahmad, “Performance Improvement of Hybrid Electric Vehicle Using Supercapacitors Energy Storage System,” *Journal of Electrical Systems*, vol. 18, no. 2, pp. 233-245, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[10] Pradeep Kumar, Sandeep Dhundhara, and Ruchi Makin, “Performance Analysis of PMSM Drive Based on FOC Technique with and without MRAS Method,” *2016 International Conference on Recent Advances and Innovations in Engineering (ICRAIE)*, Jaipur, India, pp. 1-6, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[11] Ravi Eswar Kodumur Meesala et al., “Modified Direct Torque Control of PMSM Drive for Electric Vehicle Application,” *2021 IEEE Madras Section Conference (MASCON)*, Chennai, India, pp. 1-5, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[12] Sanjeet Kumar Dwivedi, Michael Laursen, and Steffan Hansen, “Voltage Vector Based Control for PMSM in Industry Applications,” *2010 IEEE International Symposium on Industrial Electronics*, Bari, Italy, pp. 3845-3850, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[13] Yasser Abdel-Rady Ibrahim Mohamed, “Design and Implementation of a Robust Current- Control Scheme for a PMSM Vector Drive with a Simple Adaptive Disturbance Observer,” *IEEE Transactions on Industrial Electronics*, vol. 54, no. 4, pp. 1981-1988, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[14] G. Divya, and Venkata Padmavathi S., “Intelligent Power Management of Electric vehicle with onboard PV by ANN-Based Model Predictive Control,” *Journal of Electrical Systems*, vol. 20, no. 2, pp. 2395-2417, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[15] Yongchang Zhang et al., “Performance Improvement of Model-Predictive Current Control of Permanent Magnet Synchronous Motor Drives,” *IEEE Transactions on Industry Applications*, vol. 53, no. 4, pp. 3683-3695, 2017. [CrossRef] [Google Scholar] [Publisher Link].

[16] Wonhee Kim, Chuan Yang, and Chung Choo Chung, “Design and Implementation of Simple Field-Oriented Control for Permanent Magnet Stepper Motors without DQ Transformation,” *IEEE Transactions on Magnetics*, vol. 47, no. 10, pp. 4231-4234, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[17] Rakesh Shriwastava et al., “Performance Analysis of FOC Space Vector Modulation DCMLI Driven PMSM Drive,” *Bulletin of Electrical Engineering and Informatics*, vol. 12, no. 5, pp. 2682-2692, 2023. [CrossRef] [Google Scholar] [Publisher Link].

[18] Hongfeng Li, Zhengyu Liu, and Jianyu Shao, “A Model Predictive Current Control Based on Adaline Neural Network for PMSM,” *Journal of Electrical Engineering & Technology*, vol. 18, pp. 953-960, 2022. [CrossRef] [Google Scholar] [Publisher Link]