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Assessment of Cutting-Edge Control Techniques for Dynamic Performance in Electric Vehicle Applications with Surface-Mounted Permanent Magnet Synchronous Motors

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ABSTRACT
Because of their numerous advantages, including as maximized efficiency, torque-to-weight ratio, power density, and increased dynamic performance, Surface-Mounted Permanent Synchronous Motors (SPMSM) are widely utilized in electric vehicle applications. Dynamic performance, which includes speed tracking, acceleration, and deceleration, is a crucial factor for EV applications. This research article compares the dynamic performance of two control methods often employed in electric vehicles for self-parking sensors: sophisticated Finite Control Set-Model Predictive Control (FCS-MPC) and traditional Field Oriented Control (FOC). The dynamics at acceleration and deceleration during a change in speed and speed ripples are the main focus of the comparison analysis. FCS-MPC has faster dynamics than traditional FOC approaches, making it more appropriate for future EVs, according to simulation results on MATLAB. While FCS-MPC suffers with higher speed ripples than FOC due to variable switching frequency and absence of modulators.
Keywords *– FCS-MPC, FOC, Dynamic Performance, SPMSM, Electric Vehicle.*

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I. INTRODUCTION

The rapid electrification of transportation systems has become a global priority due to increasing environmental concerns, depletion of fossil fuels, and stringent emission regulations. Most of the world's carbon dioxide emissions (CO_2) come from vehicles powered by internal combustion engines (ICEs), and the transportation industry is a major source of these gases, contributing between 30 and 50 percent. Consequently, electric vehicles (EVs) have emerged as a sustainable alternative, offering zero-emission operation, high efficiency, and improved energy utilization [1], [2], [3].

Among various electric traction motors, Permanent Magnet Synchronous Motors (PMSMs) have become the most preferred choice for EV propulsion systems due to their superior efficiency, high power density, compact size, and excellent torque-speed characteristics [4]. Compared to induction motors (IM) and switched reluctance motors (SRM), PMSMs exhibit better dynamic performance and efficiency, making them highly suitable for automotive applications [3], [5]. Two main types of PMSMs are used in EVs: surface-mounted PMSMs (SPMSMs) and interior PMSMs (IPMSMs) [6]. In particular, Surface-Mounted PMSMs (SPMSMs) are widely used due to their simple structure, reduced losses, and ease of control [7].

Electric vehicles operate under highly variable driving circumstances, including frequent acceleration, deceleration, regenerative braking, and variable load demands. Therefore, dynamic performance, including parameters such as rise time, settling time, torque response, and speed tracking accuracy, is pivotal in deciding overall system performance. As highlighted in recent studies, the traction motor must respond rapidly to changing operating conditions while maintaining stability and efficiency.

Electric vehicle traction systems require high-performance motor drives capable of operating under dynamic conditions. Important features include quick acceleration and deceleration, strong torque even at low speeds, a large speed range with steady torque and power regions, little torque ripple, great efficiency, and dependability. EV motors must operate under continuous speed variations and transient conditions, making dynamic performance a critical parameter. Dynamic performance is evaluated using acceleration time, deceleration time, overshoot, speed ripple, torque ripple and speed tracking error [1].

Conventional control strategies such as Field-Oriented Control (FOC) and Direct Torque Control (DTC) have been extensively employed for

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PMSM drives [8]. FOC provides precision at steady-state but witnessed as slower dynamic response due to cascaded control loops and modulation stages. DTC offers faster torque response but introduces significant torque ripple and variable switching frequency. To overcome these limitations, Model Predictive Control (MPC) has gained significant attention due to its ability to predict system behaviour and optimize control actions in real time [8], [9].

In particular, Finite Control Set Model Predictive Control (FCS-MPC) has emerged as a promising control strategy for EV applications due to its fast dynamic response, elimination of PWM modulators, and capability to handle nonlinear constraints directly [8], [10]. The predictive nature of MPC allows it to achieve superior transient performance compared to traditional control techniques [11].

Furthermore, advancements in power electronics, digital signal processing, and intelligent control techniques have significantly improved the dynamic performance of EV traction systems [8]. These developments have enabled the implementation of advanced control strategies such as MPC, adaptive observers, and artificial intelligence-based estimation techniques.

This paper focuses on analysing and comparing the dynamic performance of SPMSM drives for electric vehicle applications, emphasizing the role of advanced control strategies in improving acceleration and deceleration time and speed ripple.

II. MATHEMATICAL MODELLING OF SPMSM

The dynamic model of a SPMSM is typically expressed in the rotating d–q reference frame, which simplifies three-phase quantities into two orthogonal components.
The stator voltage equations are given as:

$$\frac{di_d}{dt} = \frac{1}{L_d}(v_d - R_s i_d + \omega_e L_q i_q)$$

(1)

$$\frac{di_q}{dt} = \frac{1}{L_q}(v_q - R_s i_q - \omega_e L_d i_d - \omega_e \psi_f)$$

(2)

Where = d-axis and q-axis currents, = stator voltages, = stator resistance, = inductances, = permanent magnet flux, = electrical angular speed. For SPMSM, , eliminating reluctance torque and simplifying control design.
The electromagnetic torque is expressed as:

$$T_e = \frac{3}{2} p \psi_f i_q$$

(3)

Where p = pole pairs. This indicates that torque is directly proportional to q-axis current, enabling independent torque control.The mechanical torque balance equations for the motor:

$$J\frac{d\omega_e}{dt} = T - T_l - B\omega_e$$

(4)

III. CONTROL STRATEGIES FOR SPMSM

3.1 Field-Oriented Control (FOC)

The block diagram shown below in Fig. 1[1] represents the FOC of PMSM with field weakening controller which can be operated over a wide speed range.

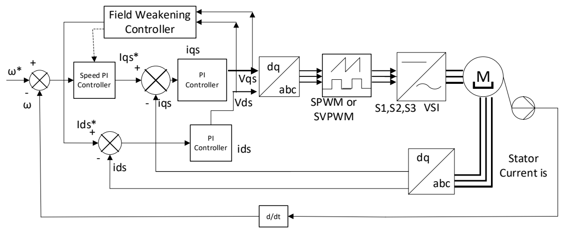

Fig. 1 Block diagram of FOC for PMSM drive

Two internal d and q axis current PI controllers and one external speed PI controller make up the full FOC controller, which is a closed control loop in cascade. By converting the stator current into a synchronously spinning reference frame d-q, the internal PI controllers determine the voltage reference and, deciding by the error between the current references and the measured currents. The current reference is determined by the external PI controller using the discrepancy between the rotor speed reference ϋ and the actual speed ϋ. A position sensor detects the exact location of the rotor at any given moment. By carefully crafting the system time constants, this cascaded closed loop control allows the inner current loops to react more quickly than the outer speed loops. The voltages and currents are limited to their rated values when the output of PI controllers is saturated. A reference voltage for modulators is achieved by transforming the voltage references that are created into three phases. The inverter regulates the PMSM's output voltage using the gating signal that is so acquired through modulators.

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To further enhance efficiency, the controller can incorporate Maximum Torque per Ampere (MTPA) control, which is similar to field weakening control and enhances the vehicle's speed range and maximum speed. Additionally, FOC has a short bandwidth, slow responsiveness, and a high switching frequency. FOC offer benefits of high steady-state accuracy and low harmonic distortion, same way it has disadvantages like slower dynamic response due to cascaded PI loops and dependence on accurate parameter tuning.

3.2 Model Predictive Control (MPC)

In the world of model predictive control, there are primarily two types of models: finite control set models and continuous control set models. In contrast to FCS MPC, which uses a limited number of switching states, CCS MPC requires a modulator to generate the inverter's switching state. Traditional FCS-MPC can only generate discrete switching states; this method, albeit requiring more computational work, can be used in circumstances that call for continuous reference voltage vectors. In light of the easiness for nonlinearities and constraints control, compared to CCS-MPC, FCS-MPC has more overall advantages [12]. The process of MPC basically divided into three parts:

1. Delay compensation is the first step in predicting the current states of the system using the measured current and voltage.
2. The predictive model then forecasts the potential next-moment system states for various voltage vectors.
3. The cost function is then used to pick the ideal voltage vector.

The process of basic MPC is shown in the fig. 2 [1].

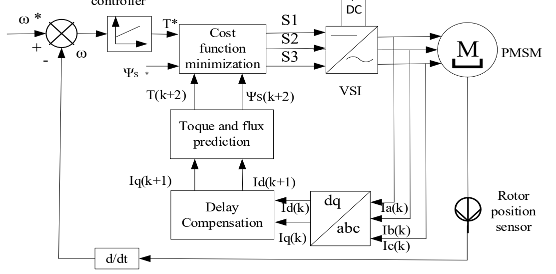

Fig. 2 Model Predictive Control scheme

FCS-MPC has advantages like fast dynamic response, absence of PWM modulator, ability to handle constraints, multi-variable optimization, direct control capability and fast dynamic response makes it more suitable for EV application. However, challenges include computational complexity, variable switching frequency and parameter sensitivity.

IV. SIMULATION AND RESULTS

The proposed control strategies for the SPMSM drive were validated using MATLAB/Simulink to analyze their dynamic performance under various operating conditions. The simulation investigates key performance indicators such as acceleration time, deceleration time, speed ripple and speed tracking accuracy under full load condition. The simulation model of the SPMSM is tested with control algorithm of FOC and FCS-MPC. The simulation results provide a comprehensive comparison of both control strategies, highlighting their effectiveness in improving the dynamic performance of SPMSM drives for electric vehicle applications. Table no. 1 shown in the figure below shows the SPMSM Parameters [14].

Table 1: SPMSM Parameters

Parameters	Values	Parameters	Values
Rated Power	750 W	**Resistance**	3.27 Ω
Rated Current	3.4 A	**Inductance**	10.2 mH
Rated Speed	3000 RPM	**Pole Pair**	4
Rated Torque	2.34 Nm		

4.1 MATLAB Simulation of FOC based SPMSM

Simulation of SPMSM on MATLAB is performed under different speed changes during acceleration and deceleration. The simulation diagram mainly includes speed controller, d and q axis current controller, Spece Vector Pulse Width Modulation (SVPWM), 2 level Voltage Source Inverter (VSI) and SPMSM. Fig. 3 below is the MATLAB schematics of FOC which gives results of dynamic performance of SPMSM.

Fig. 4 shows the step change in speed at different instant of time during acceleration and deceleration at full load of 2.34 Nm and rated current of 3.4 A. During acceleration speed changes from 1000 to 1500 rpm, 1500 to 2000 rpm, 2000 to 3000 rpm at instant 0.2 sec, 0.4 sec and 0.6 sec respectively. Same way during deceleration speed changes from 3000 to 2000 rpm, 2000 to 1500 rpm, 1500 to 1000 rpm at instant 0.8 sec, 1 sec and 1.2 sec respectively.

4.1.1 Acceleration during step change in speed

Fig. 5,6 and 7 represents close view of speed change at 1000 to 1500 rpm, 1500 to 2000 rpm and 2000 to 3000 rpm respectively which reveals that the actual speed of SPMSM tracks the reference speed. By observing the results the SPMSM takes around 40 ms to reach from 1000 to 1500 rpm, 40 ms to reach from1500 to 2000 rpm and 65 ms to reach from 2000 to 3000 rpm.

4.1.2 Deceleration during step change in speed

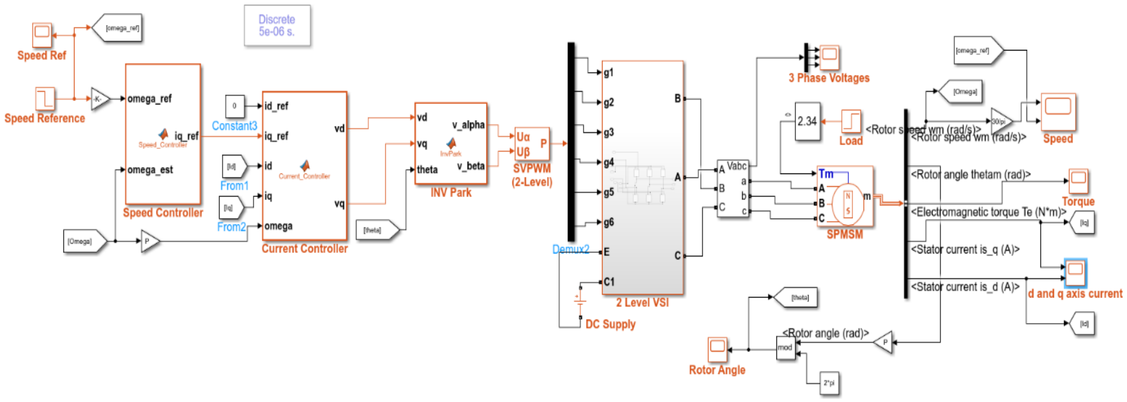

Figure 3: MATLAB Schematics of FOC

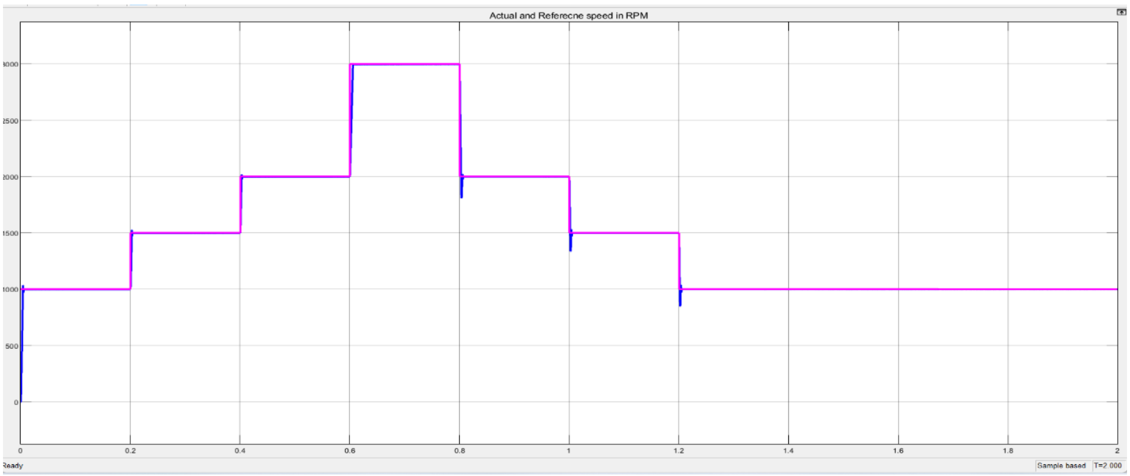

Figure 4: Step change in Speed at Different Instant of Time at Full Load of FOC

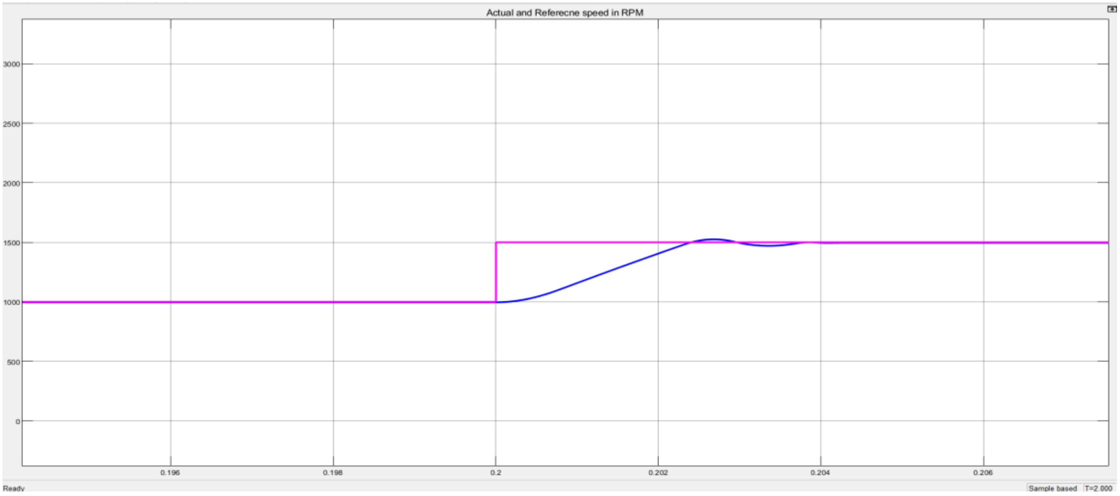

Figure 5: Acceleration Time to reach from 1000 to 1500 rpm at Full Load

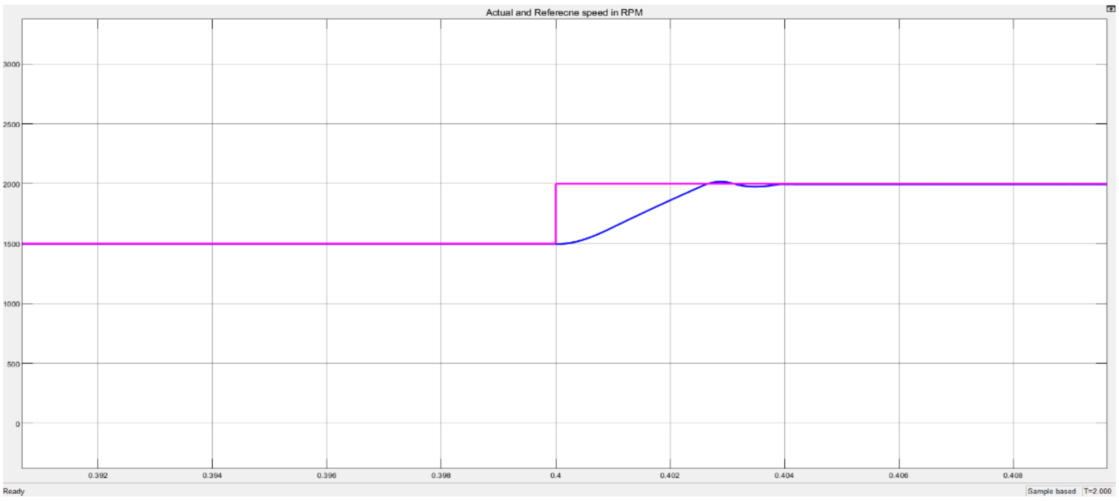

Figure 6: Acceleration Time to reach from 1500 to 2000 rpm at Full Load

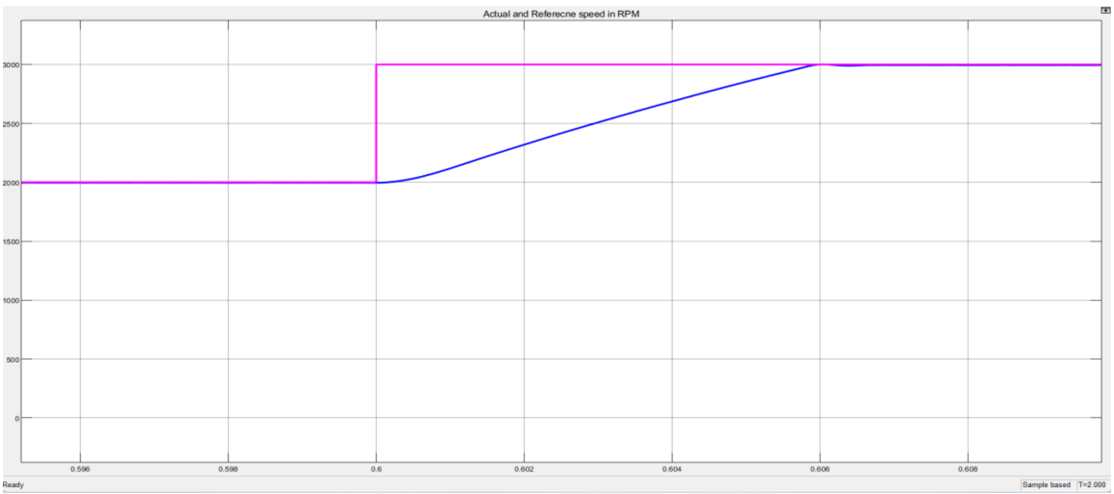

Figure 7: Acceleration Time to reach from 2000 to 3000 rpm at Full Load

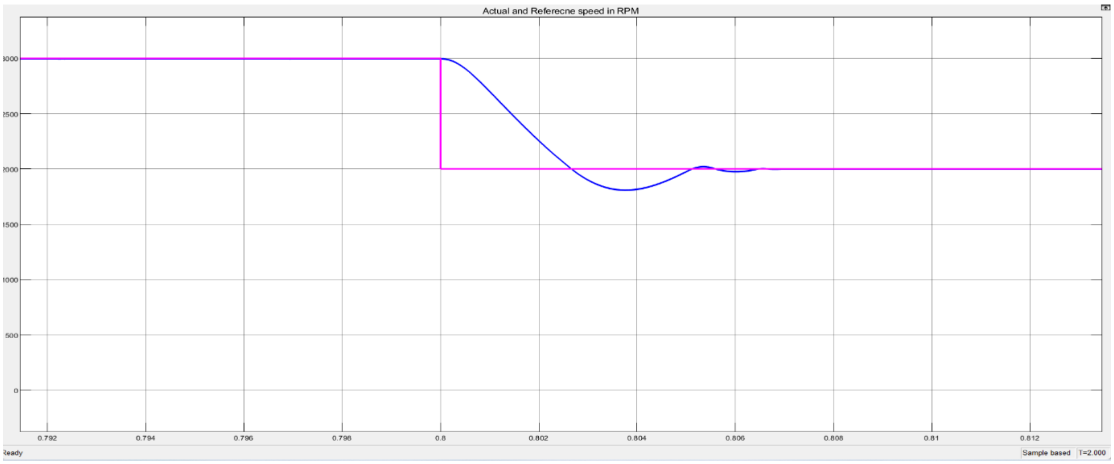

Figure 8: Deceleration Time to reach from 3000 to 2000 rpm at Full Load

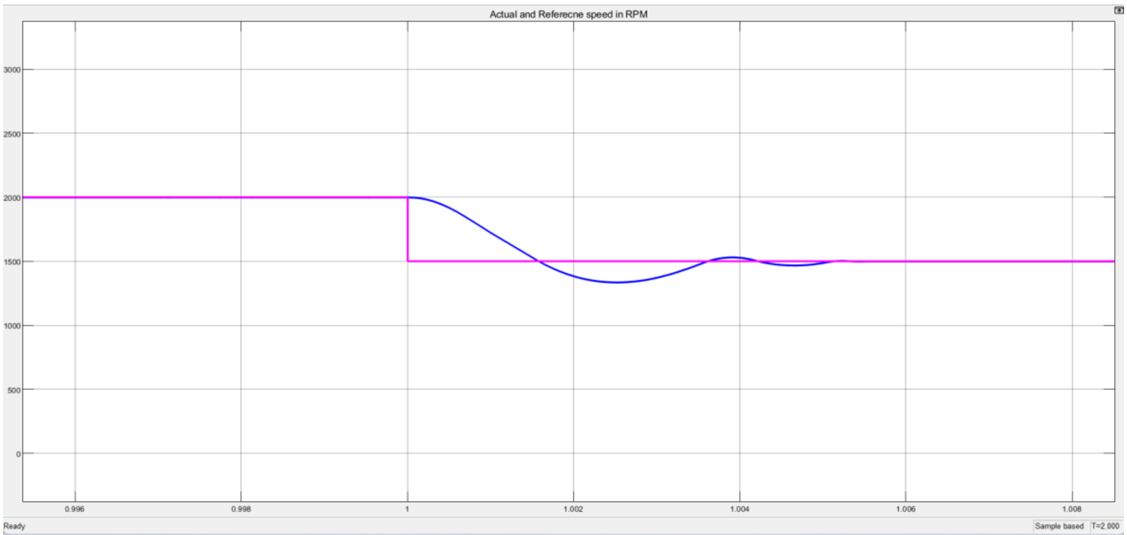

Figure 9: Deceleration Time to reach from 2000 to 1500 rpm at Full Load

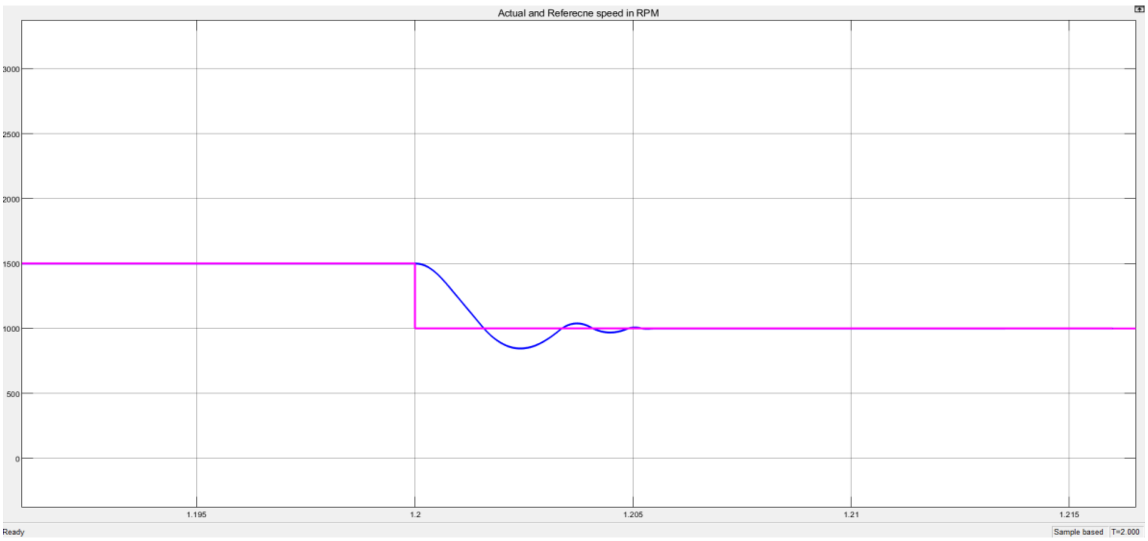

Figure 10: Deceleration Time to reach from 1500 to 1000 rpm at Full Load

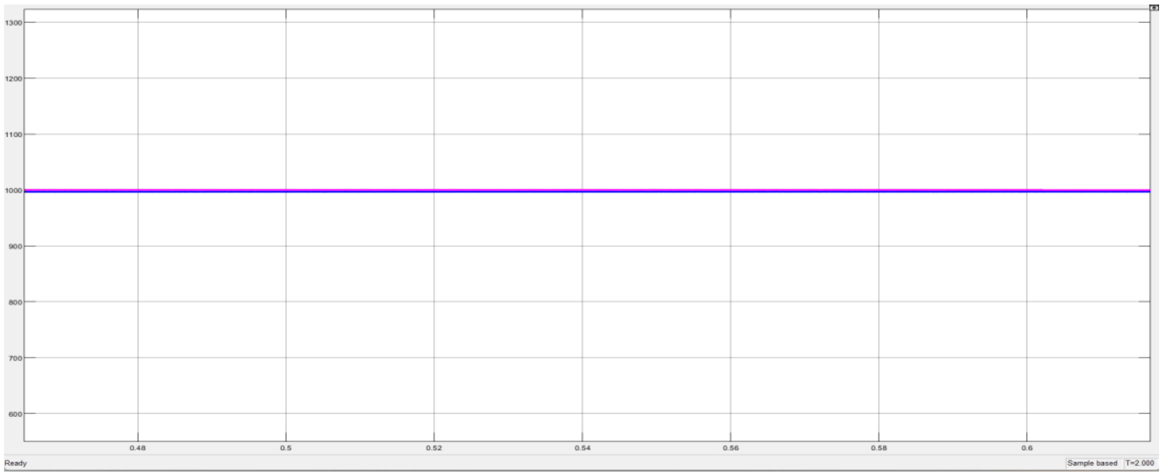

Figure 11: Speed ripple at 1000 rpm at Full Load

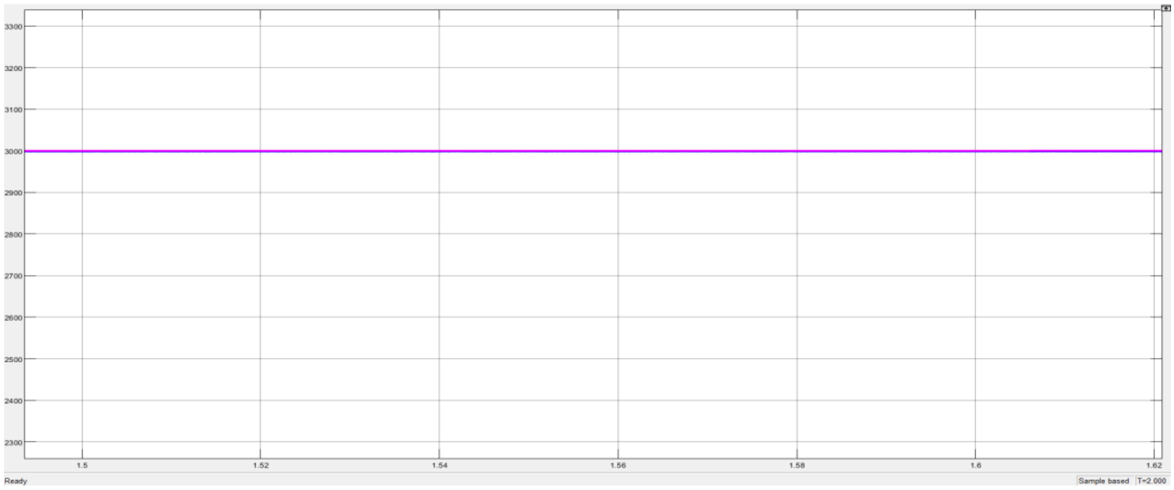

Figure 12: Speed ripple at 3000 rpm at Full Load

Fig. 8, 9 and 10 represents close view of speed change at 3000 to 2000 rpm, 2000 to 1500 rpm and 1500 to 1000 rpm respectively which reveals that the actual speed of SPMSM tracks the reference speed. By observing the results we can say that the SPMSM takes around 65 ms to reach from 3000 to 2000 rpm, 50 ms to reach from 2000 to 1500 rpm and 51 ms to reach from 1500 to 1000 rpm.

4.1.3 Speed Ripple

Fig. 11 represents speed ripple at 1000 rpm and fig. 12 represents speed ripple at 3000 rpm. It can be observed that the speed ripple at both the speed is very less around 4 rpm when we take difference between maximum and minimum value at both value of speeds.

4.2 MATLAB Simulation of FCS-MPC based SPMSM

Now here the current PI controller of q and d axis is replaced by FCS-MPC and also SVPWM block is completely removed as shown in the fig. 13 below gives improved dynamic performance of SPMSM and no need of park and inverse park transformation

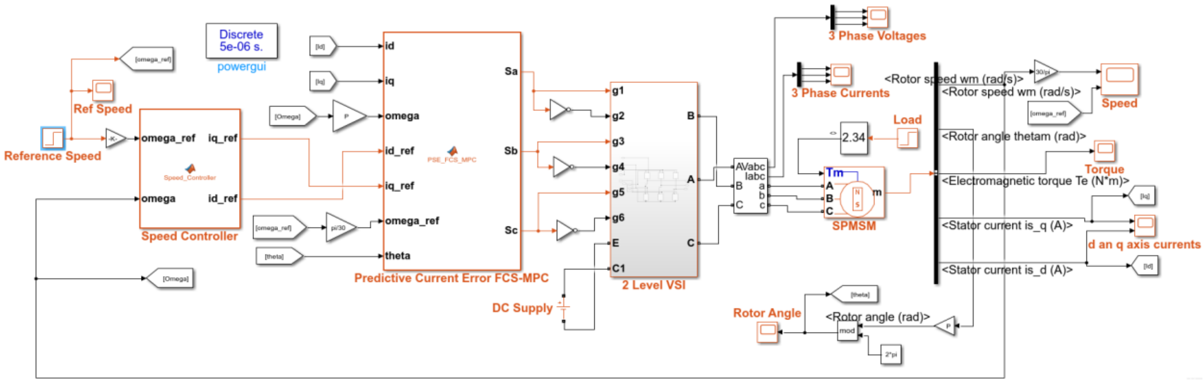

Figure 13: MATLAB Schematics of FCS-MPC

Fig. 14 shows the step change in speed at different instant of time during acceleration and deceleration at full load of 2.34 Nm and rated current of 3.4 A same as in FOC. During acceleration speed changes from 1000 to 1500 rpm, 1500 to 2000 rpm, 2000 to 3000 rpm at instant 0.4 sec, 0.8 sec and 1.2 sec respectively. Same way during deceleration speed changes from 3000 to 2000 rpm, 2000 to 1500 rpm, 1500 to 1000 rpm at instant 1.6 sec, 2 sec and 2.4 sec respectively.

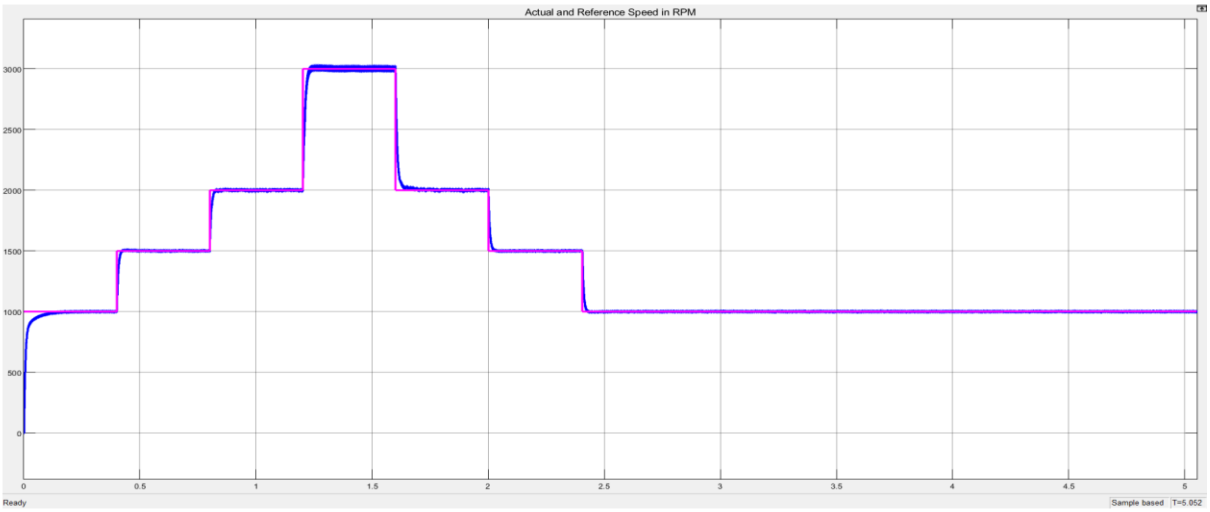

Figure 14: Step change in Speed at Different Instant of Time at Full Load of FCS-MPC

4.2.1 Acceleration during step change in speed

Fig. 15, 16 and 17 represents close view of speed change at 1000 to 1500 rpm, 1500 to 2000 rpm and 2000 to 3000 rpm respectively which reveals that the actual speed of SPMSM tracks the reference speed. By observing the results the SPMSM takes around 24 ms to reach from 1000 to 1500 rpm, 24 ms to reach from1500 to 2000 rpm and 35 ms to reach from 2000 to 3000 rpm.

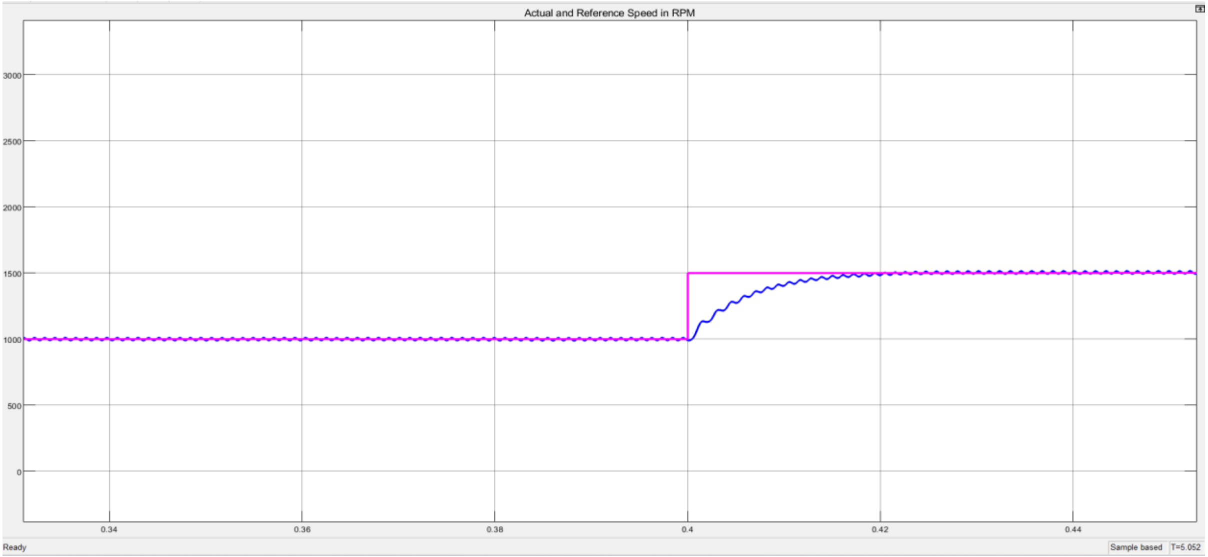

Figure 15: Acceleration Time to reach from 1000 to 1500 rpm at Full Load

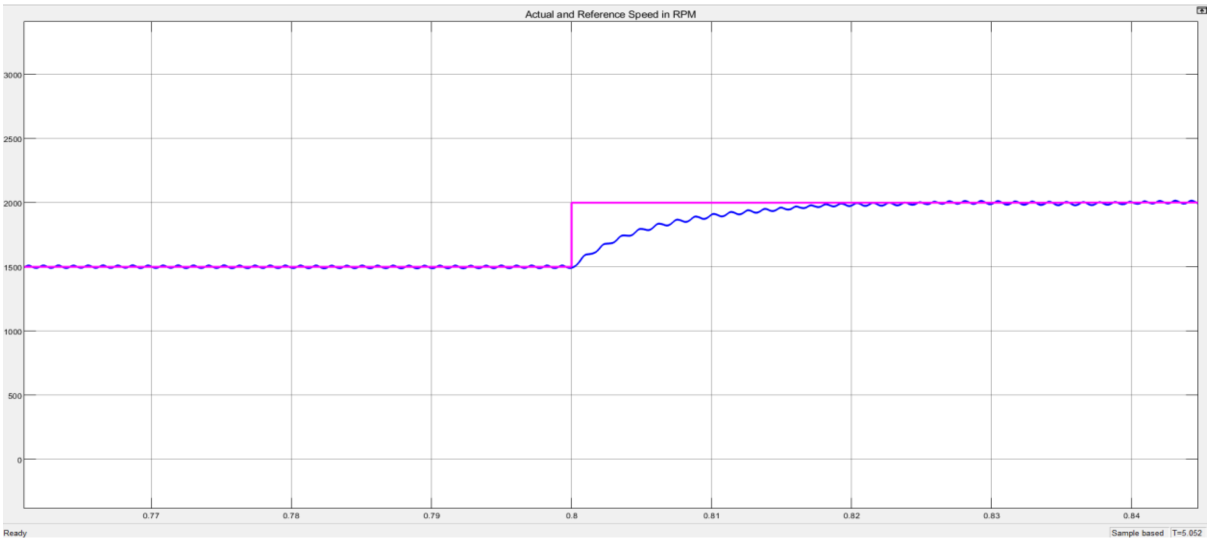

Figure 16: Acceleration Time to reach from 1500 to 2000 rpm at Full Load

4.2.2 Deceleration during step change in speed

Fig. 18, 19 and 20 represents close view of speed change at 3000 to 2000 rpm, 2000 to 1500 rpm and 1500 to 1000 rpm respectively which reveals that the actual speed of SPMSM tracks the reference speed. By observing the results we can say that the SPMSM takes around 62 ms to reach from 3000 to 2000 rpm, 30 ms to reach from 2000 to 1500 rpm and 34 ms to reach from 1500 to 1000 rpm.

4.2.3 Speed Ripple

Fig. 11 represents speed ripple at 1000 rpm and fig. 12 represents speed ripple at 3000 rpm. A noticeable amplitude of the speed ripple is observed at both the speed is large as compared to FOC. Speed ripple at 3000 rpm is around 50 rpm and at 1000 rpm is around 20 rpm as shown in fig. 21 and 22 respectively when we take difference between maximum and minimum value at both value of speeds.

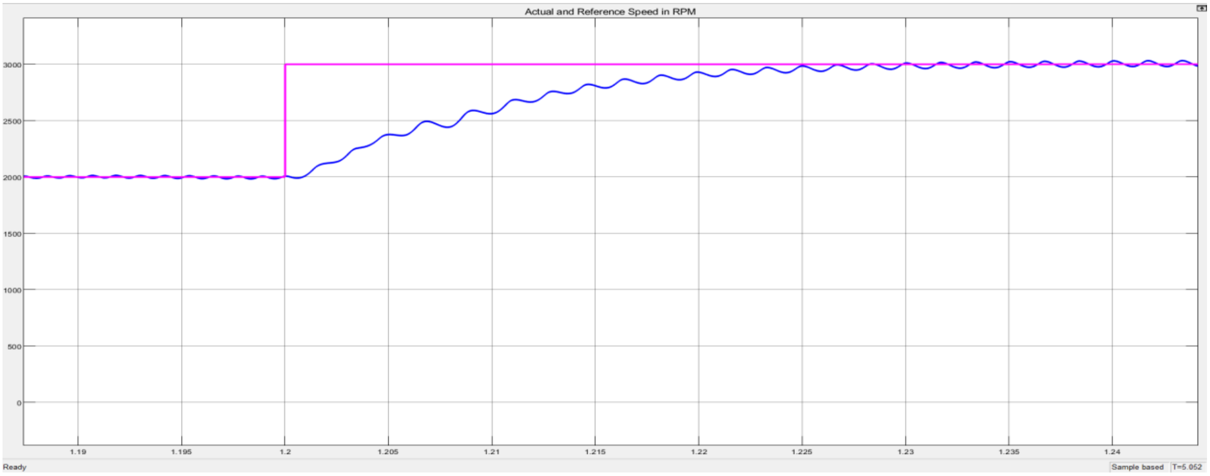

Figure 17: Acceleration Time to reach from 2000 to 3000 rpm at Full Load

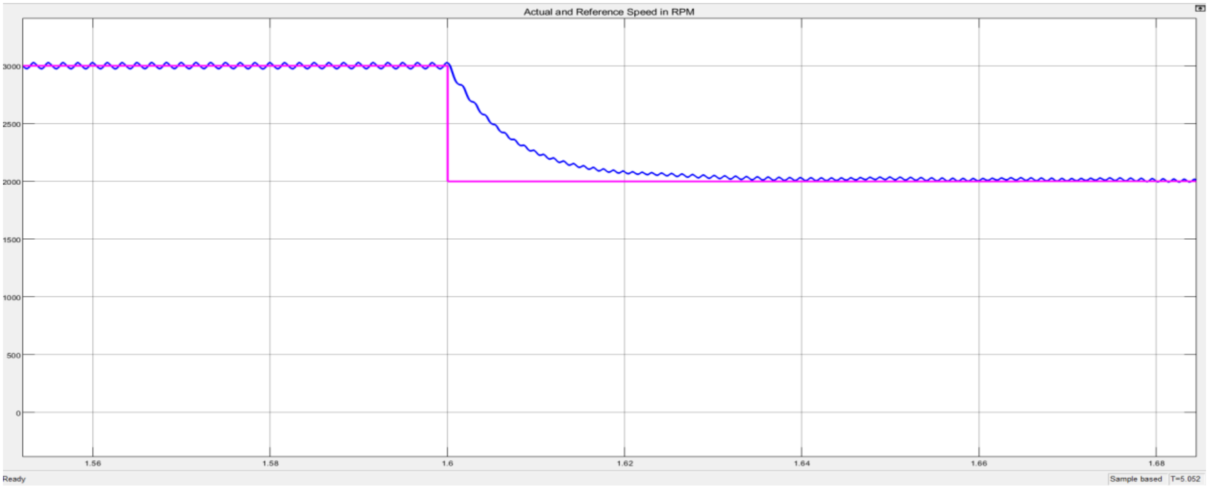

Figure 18: Deceleration Time to reach from 3000 to 2000 rpm at Full Load

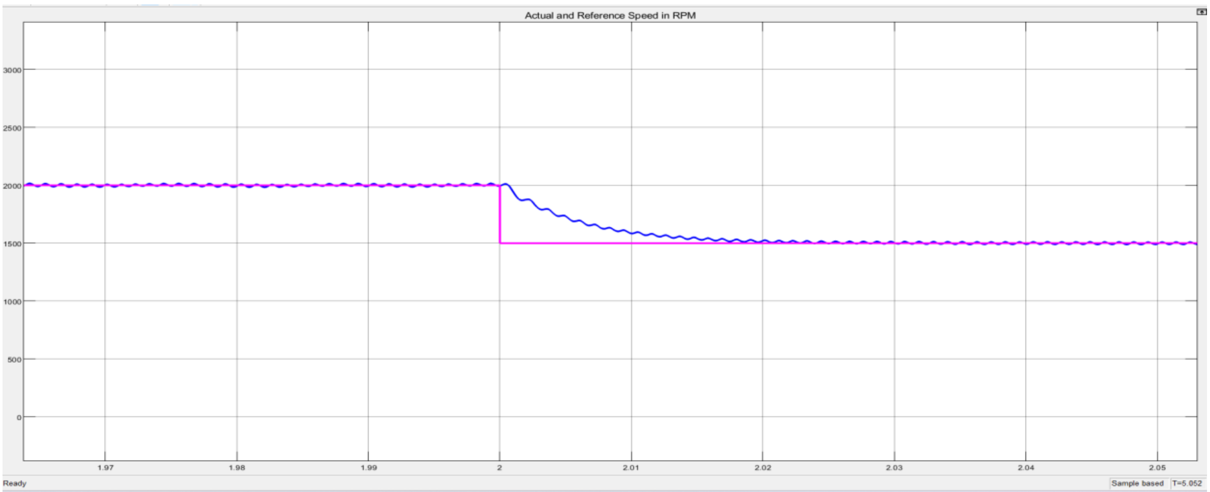

Figure 19: Deceleration Time to reach from 2000 to 1500 rpm at Full Load

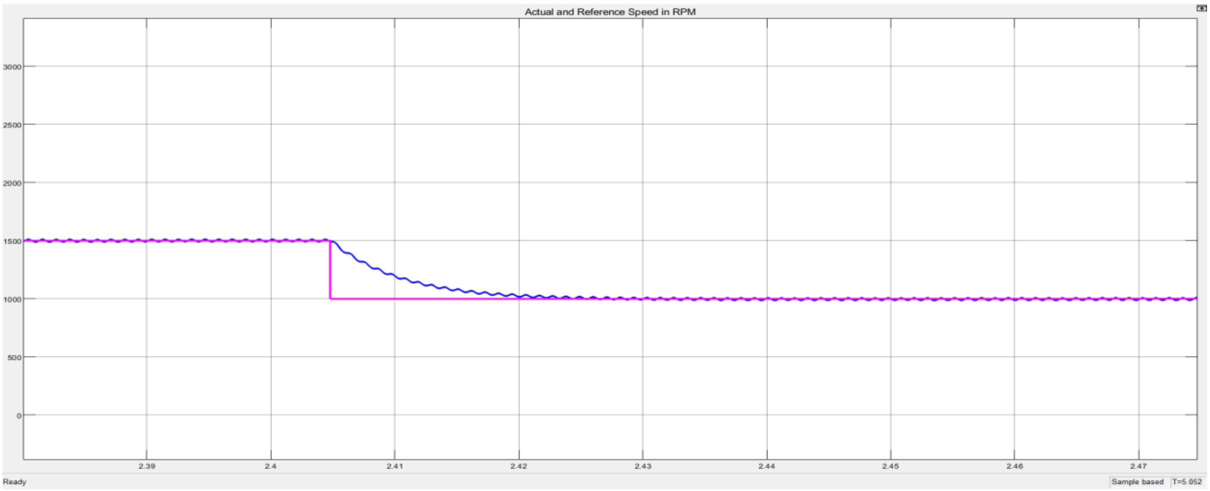

Figure 20: Deceleration Time to reach from 1500 to 1000 rpm at Full Load

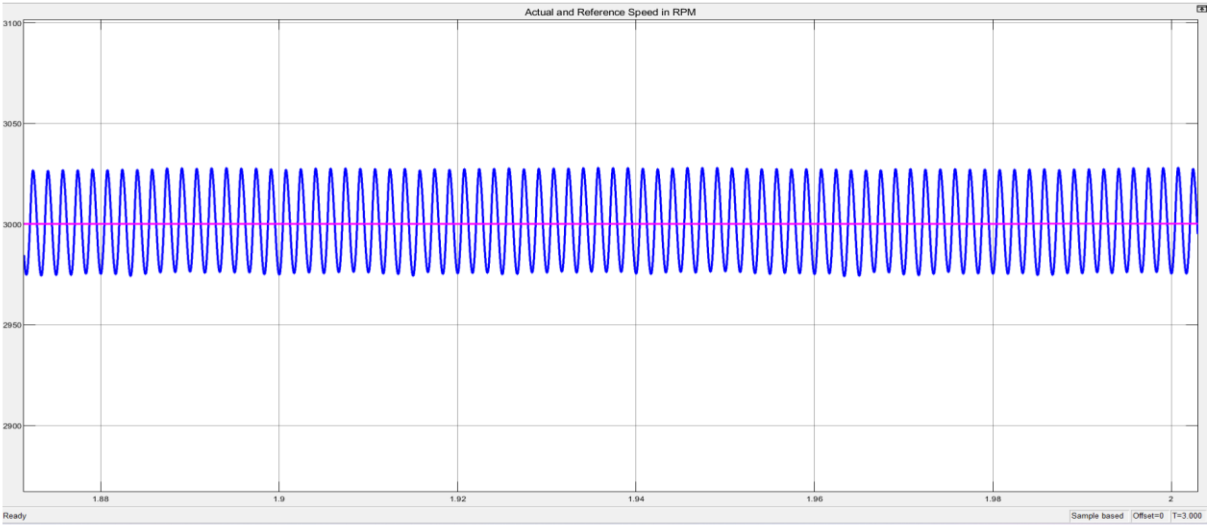

Figure 21: Speed ripple at 3000 rpm at Full Load

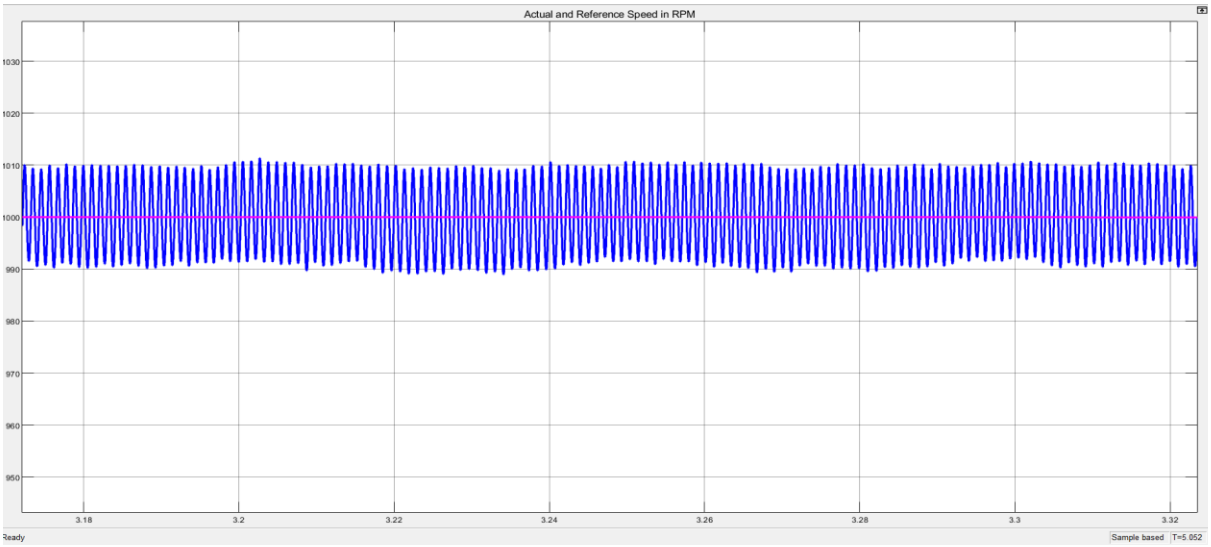

Figure 22: Speed ripple at 1000 rpm at Full Load

V. DISCUSSION

The performance of the SPMSM drive under FOC and FCS-MPC was evaluated through MATLAB/Simulink simulations under dynamic operating conditions speed variations and speed ripples.

The speed response of the SPMSM was analysed for step changes in reference speed. It is observed that the FCS-MPC method achieves significantly reduced acceleration time and reduced deceleration time compared to FOC. The predictive nature of FCS-MPC enables direct selection of optimal switching states, thereby eliminating delays associated with modulation and cascaded control loops. In contrast, FOC exhibits a relatively slower response due to the presence of PI controllers and PWM modulation, which introduce inherent delays. Additionally, a small overshoot is observed in FOC during transient conditions, whereas FCS-MPC maintains better control with minimal overshoot.

The speed tracking capability of both control strategies was evaluated under varying reference speeds. FCS-MPC demonstrates superior tracking performance with faster convergence to the reference speed. FOC also achieves accurate steady-state tracking but shows slower transient response and slight deviation during rapid speed changes. This behavior is attributed to the tuning limitations of PI controllers and the dependency on system parameters. Table no. 2 below represents comparison of acceleration and deceleration time between a FOC and FCS-MPC under step change in speed at full load condition.

The byproduct of the simulation show that the FCS-MPC exhibits comparatively higher speed ripple than the conventional FOC method, particularly at higher operating speeds. It is observed around 50 rpm at higher speed of 3000 rpm and 20 rpm at medium speed of 1000 rpm in FCS-MPC and 4 rpm at both 3000 and 1000 rpm in FOC. This behaviour is primarily attributed to the discrete nature of FCS-MPC, where a finite number of inverter switching states are directly applied without the use of a modulation stage. As a result, the switching frequency becomes variable, leading to fluctuations in the applied voltage vectors and consequently higher ripple in torque and speed.

In contrast, the FOC technique employs modulator, which ensures a constant switching frequency and generates a smoother voltage waveform. This continuous modulation significantly reduces harmonic distortion in the stator currents, resulting in lower torque ripple and improved steady-state performance. Furthermore, at higher speeds, the sensitivity of FCS-MPC to parameter mismatch and prediction errors increases, which can further amplify ripple components in the system. On the other hand, FOC maintains relatively stable performance due to its well-established control structure and filtering effect of PWM.

From the simulation results, it is evident that despite higher ripple FCS-MPC outperforms FOC in terms of dynamic performance, particularly in transient conditions. The key advantages of FCS-MPC include faster rise and settling time and direct control without modulation delay However, FCS-MPC also presents certain challenges, such as higher computational complexity, variable switching frequency and slightly increased speed ripple .On the other hand, FOC remains a reliable and simpler control method with smooth steady-state performance but lacks the fast dynamic response required for modern EV applications.

VI. CONCLUSION

This paper presented a comprehensive analysis of the dynamic performance of SPMSM drives for electric vehicle applications using FOC and FCS-MPC. The study focused on evaluating key performance indicators such as acceleration time, deceleration time, speed tracking accuracy, and speed ripple under various operating conditions.

When compared to traditional FOC, the simulation results show that FCS-MPC greatly improves the SPMSM drive's dynamic performance. The predictive control approach enables faster transient response, reduced settling time, and superior disturbance rejection capability. Additionally, FCS-MPC achieves more accurate speed tracking during rapid changes in reference speed, making it highly suitable for electric vehicle applications characterized by frequent transients.

Although FCS-MPC exhibits slightly higher torque ripple and increased computational complexity due to real-time optimization and variable switching frequency, these limitations are outweighed by its superior dynamic characteristics. In contrast, FOC provides smoother steady-state performance and simpler implementation but suffers from slower response due to cascaded control loops and modulation delays.

Overall, the findings confirm that FCS-MPC is a highly promising control strategy for next-generation electric vehicle drive systems requiring fast dynamic response, robustness, and high efficiency. Future research can focus on reducing computational burden, optimizing cost functions, and integrating artificial intelligence-based techniques to further enhance performance and enable real-time implementation in industrial EV applications.

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