Speed Control of PMSM Drive in Electric Vehicle Using Sliding Mode Controller

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ABSTRACT: This paper focuses on the speed regulation of permanent magnet synchronous motors (PMSM) in electric vehicle application using sliding mode control (SMC). Harris hawks optimizations (HHO) based sliding mode controller is adopted to increase the dynamic response of the PMSM motor, thereby enhancing vehicle performance. For the independent control of torque and flux, field oriented-control (FOC) is used to drive the PMSM. In this work, the speed reference provided for the controller is based on an electric car driving cycle that replicates real-world driving conditions. The optimal selection of sliding mode controller parameter enhances the dynamic characteristics of the speed regulation in electric vehicles, which is validated using the hardware in the loop (HIL-402) device. The HHO based sliding mode controller has superior performance in terms of robustness against load disturbances, fast convergence, and tracking accuracy.

KEYWORDS: Harris hawks optimization (HHO) permanent-magnet synchronous motor (PMSM) sliding mode control (SMC)

1.Introduction

The electric vehicle (EV) has received much attention as a potentially effective way to reduce the atmospheric pollution caused by greenhouse gas emissions. The permanent magnet synchronous motor (PMSM) is considered for electric vehicles due to its strong power density, high torque, low volume, and high efficiency. This study includes the PMSM drive, which is powered by a battery through an inverter and a bidirectional dc-dc converter, as illustrated. The bidirectional dc-dc converter aids the regenerative braking which helps to reduce the challenges concerning drive range in electric vehicles. Owing to the nonlinearity and complexity of PMSM systems, several research studies focused on the development of robust controllers to achieve a satisfactory speed response in PMSM, field-oriented control (FOC) is one of the potential solutions owing to the reduced ripple, fast dynamic characteristics, and high control precision. The block diagram of the FOC method used to regulate PMSM with a standard double-loop topology. Performance of the system is greatly impacted by the outer speed controller. The majority of EV industrial drive systems have been using PI controllers due to their simple configuration and low cost. Due to the nonlinear nature of PMSM systems, their speed controllers must offer quick response times, accurate tracking, low overshoot, and robust disturbance rejection capabilities. However, using proportional and integral (PI) controllers is not a good solution to meet these requirements.

Sliding mode control is the ideal candidate for PMSM speed regulation due to its tracking and disturbance rejection capabilities. In a fractional order sliding mode controller is suggested for the PMSM speed control to minimize the impacts of chattering. To enhance the tracking and dynamic response characteristics employed a continuous fast terminal sliding mode control (CFTSMC) for speed control of PMSM. An integral type terminal sliding mode control is presented in with a disturbance observer to enhance the anti-disturbance property in the speed control of the PMSM drive. A hybrid control approach is described in by integrating a disturbance observer based on an iterative learning strategy and a fast integral terminal sliding mode control method to improve the accuracy of the PMSM speed control. However, these controllers introduce computational complexity in the design procedure and execution challenges. One of the critical design phases for a sliding mode controller is parameter configuration as it has a significant impact on the controller's efficacy. Based on their capacity to address challenging optimization issues, met heuristic optimization algorithms are exceptionally well suited for parameter optimization.

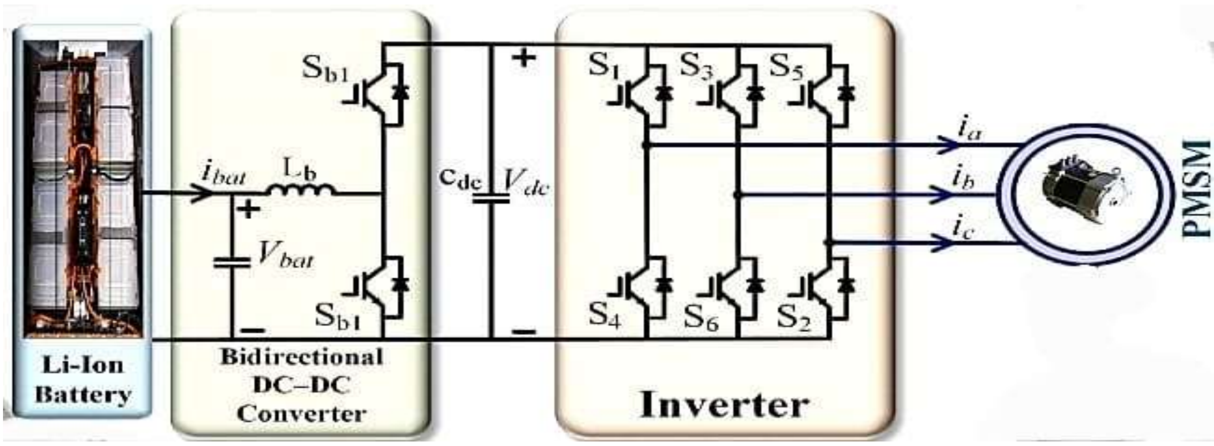

Figure1 Configuration of electric vehicle drive system

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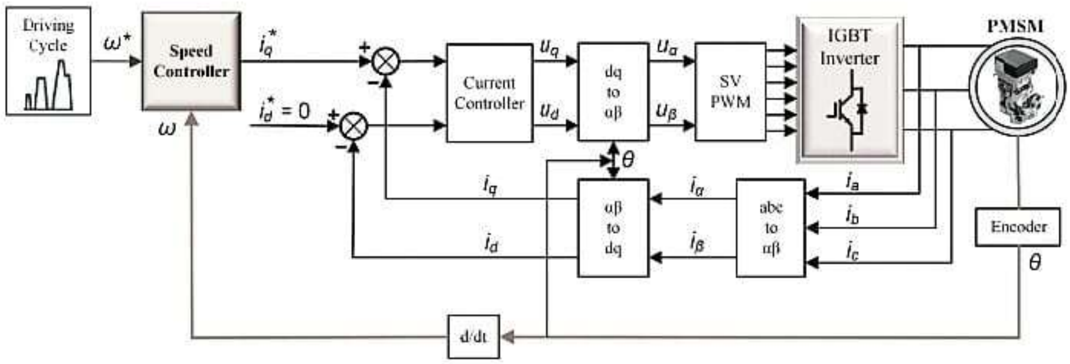

Figure 2 Structure of field oriented speed control for PMSM drive

particle swarm optimization (PSO), ant colony optimization (ACO), cuckoo search (CS) algorithm, artificial bee colony (ABC) algorithm, grey wolf optimizer (GWO), and whale optimization algorithm (WOA). Recently, Harris hawks optimization (HHO), which provides faster convergence for resolving real-world problems, is becoming more and more popular. The structure of this paper is as follows: The dynamic model of the PMSM drive is included in Section 2, and the design of sliding mode controller is given in Section 3. Section 4 is devoted to Harris hawks optimization approach. The experimental results of the system is discussed in Section 5, and the conclusions are presented in Section 6.

2. Dynamic model of PMSM

The modeling of the PMSM drive is done by neglecting the iron core saturation, hysteresis losses, eddy current losses and assuming that the three phase stator currents are symmetrical sinusoidal wave. The stator currents of the PMSM drive can be represented in terms of synchronous rotating d-q reference frame as

$$\begin{pmatrix} Vd \\ Vq \end{pmatrix} = \begin{pmatrix} R & 0 \\ 0 & R \end{pmatrix} \begin{pmatrix} id \\ iq \end{pmatrix} + \begin{pmatrix} Ld & Lq \\ -Ld & Lq \end{pmatrix} \begin{pmatrix} id \\ iq \end{pmatrix} + wr \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} id \\ iq \end{pmatrix} \text{ ----------- (1)}$$

where *id* and *iq* are stator currents, *ud* and *uq* are stator voltages, *Ld* and *Lq* are stator inductances in the d-q reference frame, *Rs* is the stator resistance, *ψm* is the rotor magnetic flux linkage and *ωe* is the rotor electrical speed. In this work, a surface-mounted PMSM drive is studied without considering the effect of saliency. Hence, *Ld* = *Lq* = *L*. The control of PMSM drive is based on the FOC by setting the d-axes reference current to zero (*i∗d* = 0), which effectively decouples the torque and flux components of the current.

The structure of FOC of PMSM drive is shown in Fig. 2. The system consists of an outer speed controller and inner current controllers. The speed reference to the outer speed controller is given according to the dive cycle of the electric vehicle. The outer speed controller is implemented using sliding mode controller to generate the reference q-axes current based on the speed error. The inner current PI controllers regulates the d-axes and q-axes currents to generate the voltage references. These voltage references are modulated using space vector pulse width modulation (SVPWM) method, which generates the gate signals for switches in the inverter module. The encoder measures the rotor position from which the rotor speed is calculated using (2). The stator currents obtained from the current sensor is transferred to d-axes and q-axes currents using Clarke Transformation (*abc/αβ*) and Park Transformation (*αβ/dq*).

3. Design of sliding mode speed controller

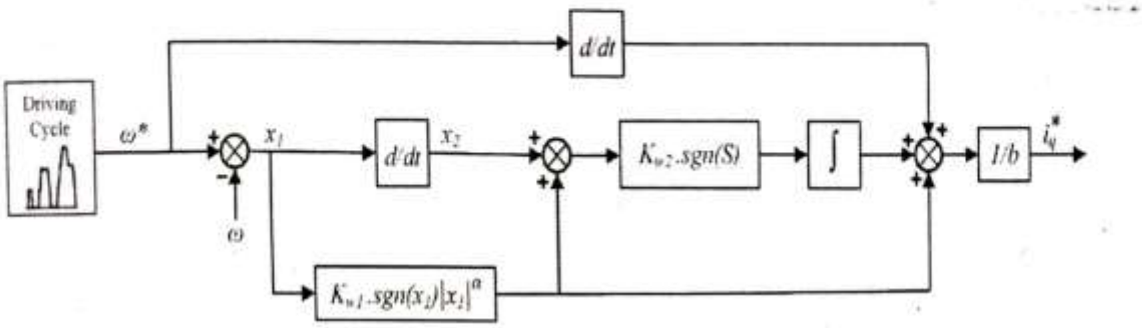

Figure 3. structure of sliding mode control

The design of a Sliding Mode Controller (SMC) for Permanent Magnet Synchronous Motors (PMSM) aims to achieve high-performance speed and torque control under parameter variations and external disturbances. PMSMs are widely used in industrial applications due to their high efficiency, compact size, and superior dynamic response. However, their control is challenging due to nonlinear dynamics and system uncertainties. Sliding Mode Control (SMC) is well-suited for such scenarios due to its robustness and simplicity. A sliding mode controller (SMC) is a control technique that uses a discontinuous control signal to alter the dynamics of a nonlinear system. It's a robust control strategy that's effective for systems that need high levels of precision and robustness, especially when there are disturbances and uncertainties. Electric vehicles are subjected to external disturbances, including wind speeds, road conditions, and frictional forces.

4. Bidirectional converter

A "Bidirectional Buck/Boost DC-DC Converter" comes under a "non-isolated converter" and this converter consists of two switches, 1 inductor, and 2 capacitors which are shown schematically in Figure 2.1. The converter has 2 operating modes i.e., Forward and Backward. In Forward mode, the electricity flows from the low voltage level such as the battery to the high voltage level side, and in this approach, the converter performs as a "Boost converter" . At the time of regenerative braking, the electricity flows back to the low voltage level side to rejuvenate the battery & the converter performs as a "Buck converter".

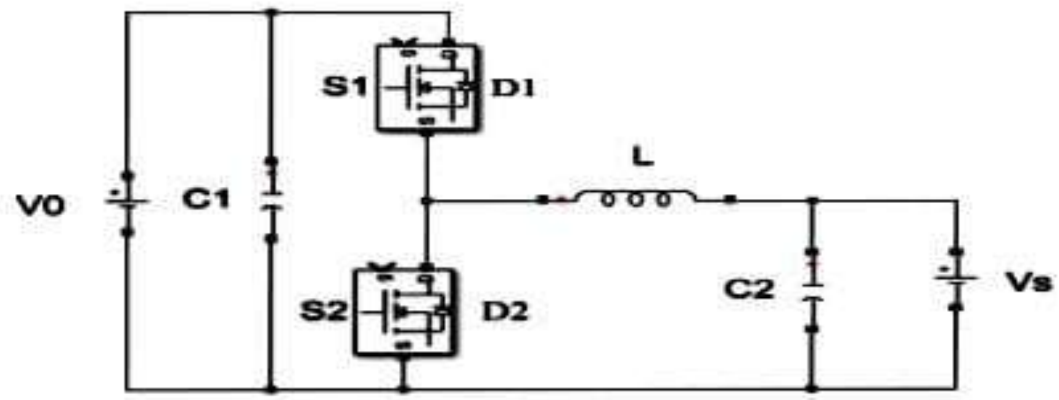

Figure 4. Bidirectional dc-dc converter

Mode of operation
Boost mode:

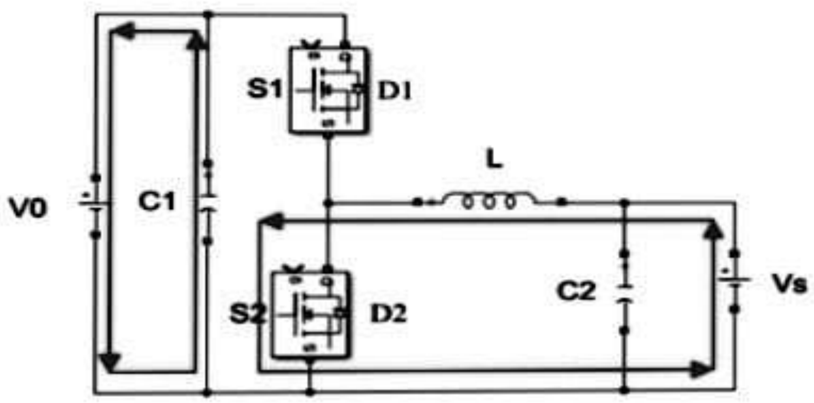

Figure 5 . When s2 is ON

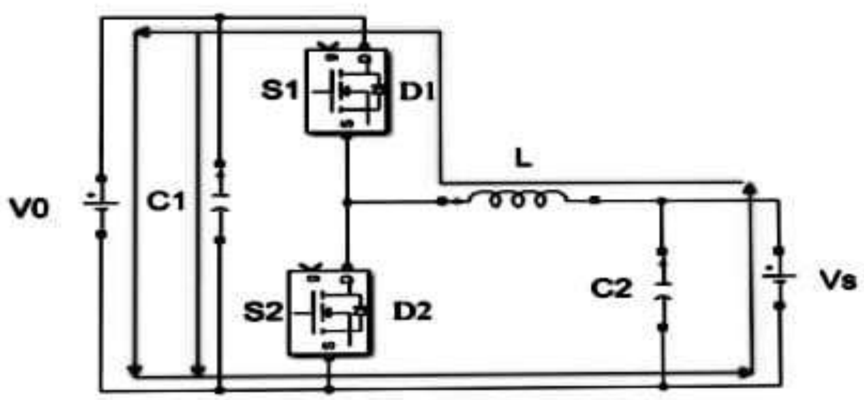

Figure 6. When D1 is forward biased

Figure2 shows how current is flowing when S2 is ON & S1 is OFF. Inductor charges & the current will increase linearly. Figure 3 is when diode D1 is ON, S1 & S2 are OFF and diode D2 is reverse biased. The energy accumulated in the inductor will start discharging through diode D1. In this mode, the energy from the source and inductor will be fed to the load, thus there will be a step up in voltage level.

Buck mode

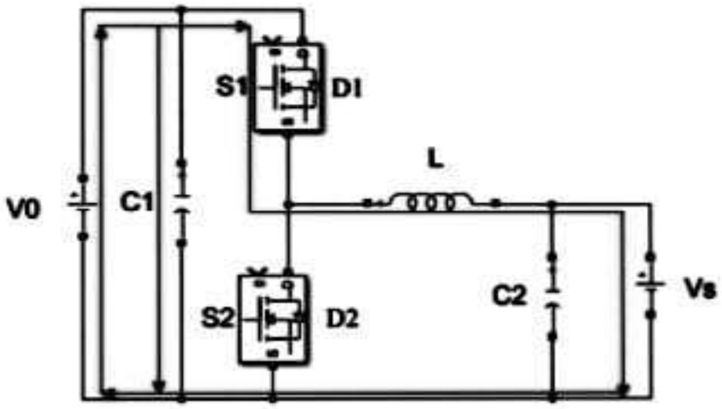

Figure 7. When s1 is ON

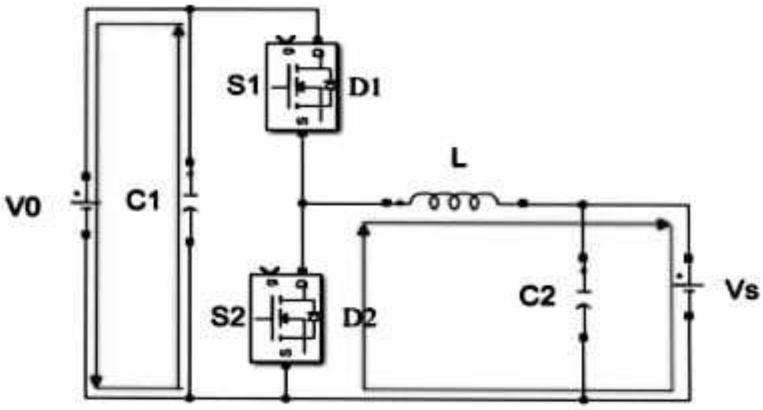

Figure 8. When D2 is forward biased

Figure 4 shows how current is flowing when S1 is ON, S2 is OFF & both the diodes D1 & D2 are reverse biased. The energy stored in the inductor will discharge in a negative slope. Figure 5 shows when diode D2 is ON, D1 is reverse biased & S1 and S2 are OFF. During regenerative braking, this mode of operation is employed to charge the battery.

Converter design

The output voltage for the Bidirectional Buck/Boost converter is obtained by

$$Vo = \frac{Vs}{(1-D)} \quad \text{------------------------ (2)}$$

Inductor ripple current & Voltage ripple can be calculated by using

$$\Delta IL = \frac{VsD}{Lf} \quad \text{---------------------- (3)}$$

$$\Delta Vc = \frac{VsD}{8Lf^2\,C} \quad \text{---------------------(4)}$$

Inductor and Capacitor values can be calculated using

$$L = \frac{VsDR}{2fVo} \quad \text{----------------------(5)}$$

$$C = \frac{DVs}{16f^2Vo} \quad \text{-----------------------(6)}$$

Where V_o - output voltage
Vs - Input voltage
D - Duty ratio
f - Switching frequency
L – Inductor
R - Equivalent resistance
C – Capacitor

This design framework ensures a robust and efficient bidirectional converter tailored for PMSM drives in energy-sensitive applications like EVs.

5. Simulation circuit
simulation for FOC

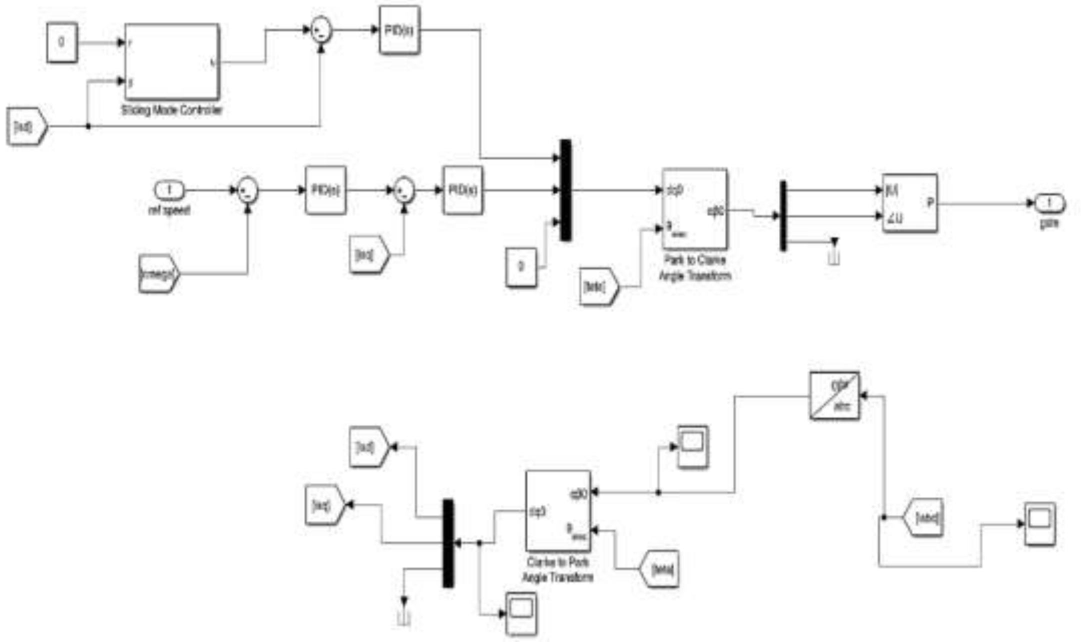

Figure9. FOC for PMSM
FOC (Field-Oriented Control) for PMSM (Permanent Magnet Synchronous Motor) is a popular control method used to achieve precise control of torque, speed, and position in PMSMs. FOC ensures efficient motor operation by maintaining the magnetic flux and torque components independently.

Speed control of PMSM drive

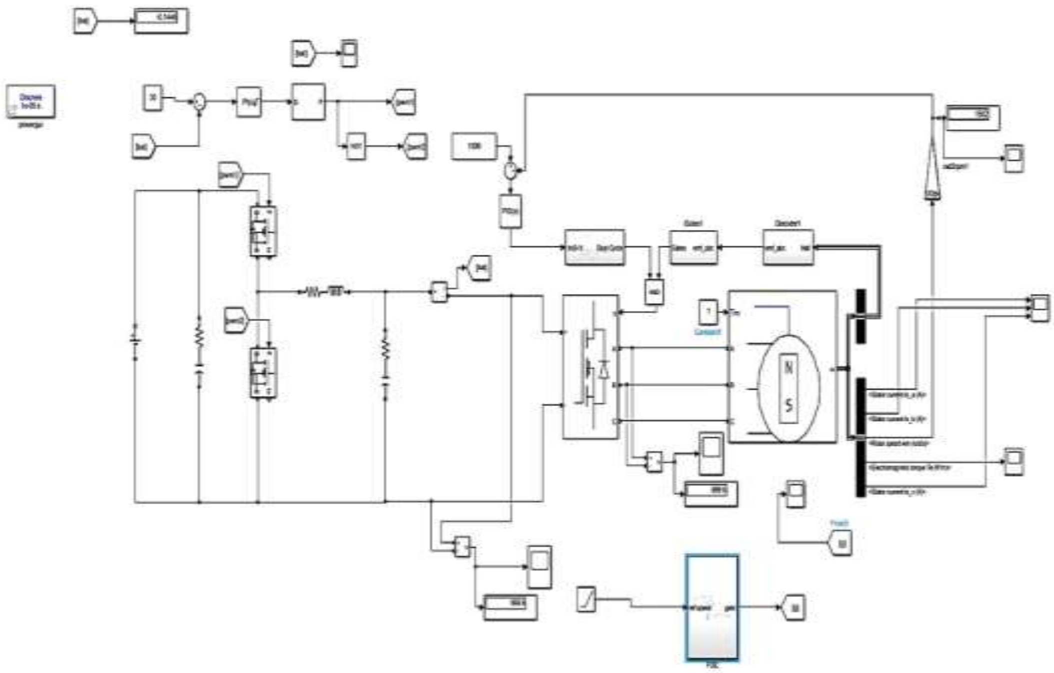

Figure10.Speed control of PMSM drive
A speed control simulation for a Permanent Magnet Synchronous Motor (PMSM) drive can be implemented in a variety of environments, such as MATLAB/Simulink, or other simulation tools. Below is a step-by-step guide to creating a basic simulation setup.

6.simulation result

Stator current

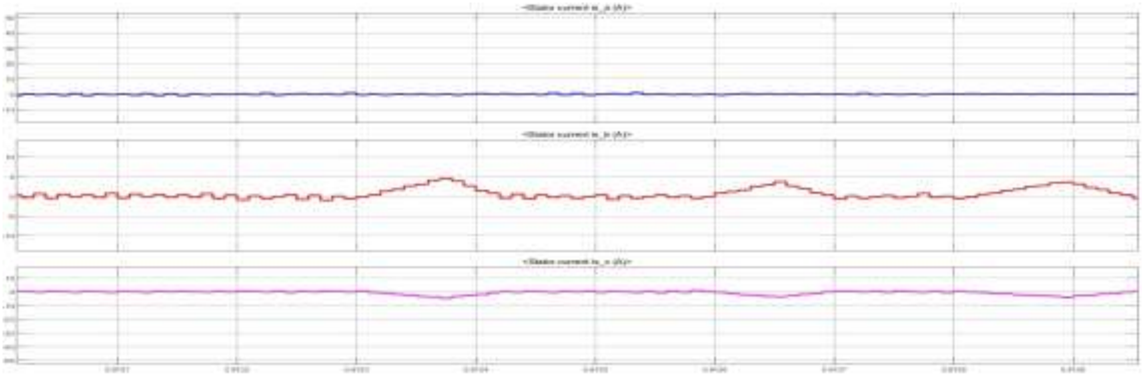

Figure 11. Stator current

The stator current waveform in a PMSM simulation depends on the motor's operating conditions and control strategy. Below are some key characteristics and expectations for the stator current waveforms.

Electromagnetic torque

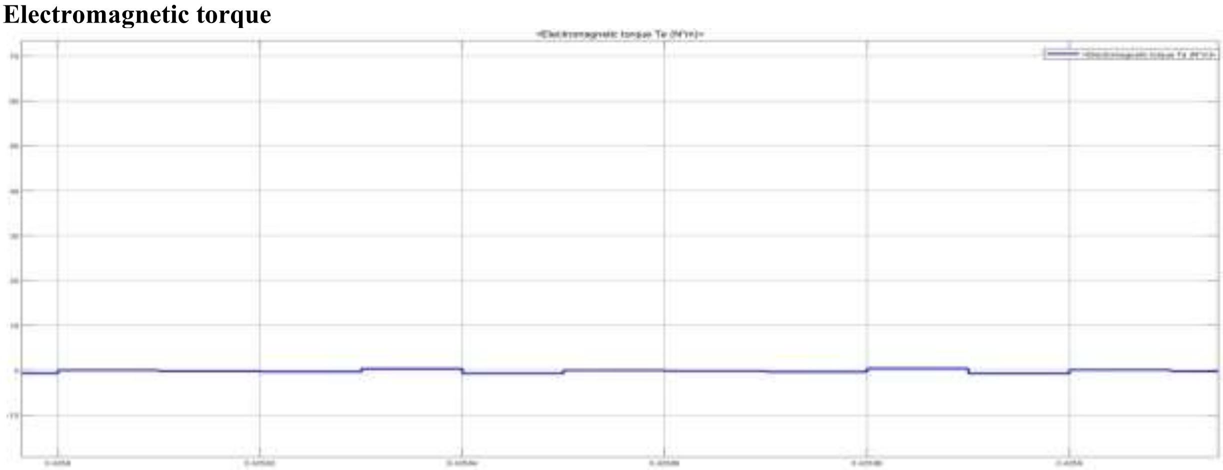

Figure12. Electromagnetic torque

The simulation waveform of electromagnetic torque (Te) in a PMSM drive can exhibit specific patterns depending on the motor operation, control strategies, and load dynamics. Below are the typical cases and what you might observe in the waveform.

Rotor speed

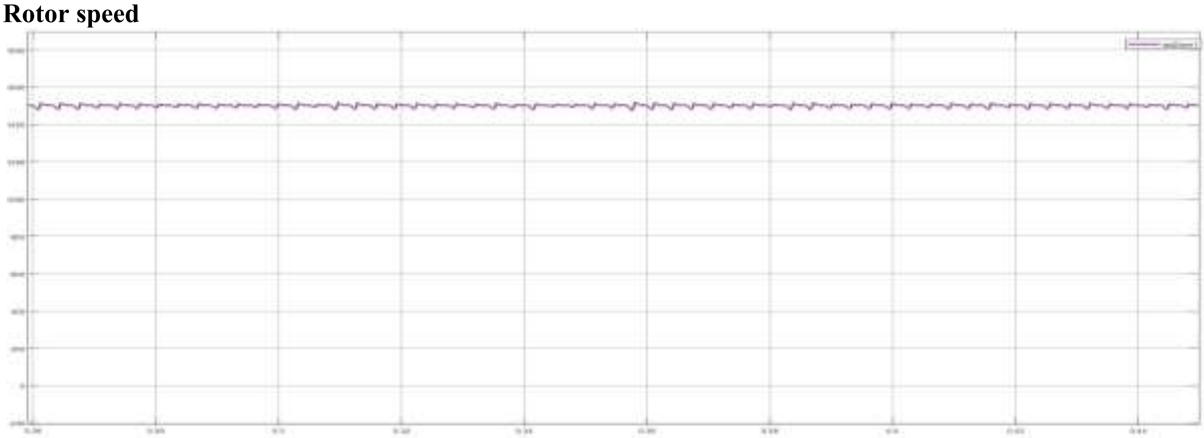

Figure 13. Rotor speed

The rotor torque waveform for a Permanent Magnet Synchronous Motor (PMSM) drive is an important result in simulations to evaluate system performance. Here's how you can generate and analyze the rotor torque waveform during a simulation.

FOC waveform

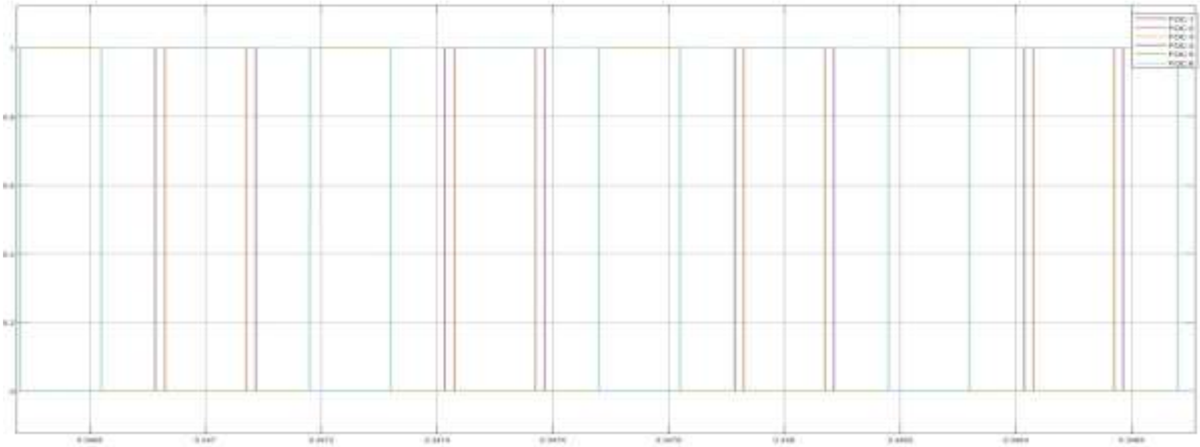

Figure 14. FOC waveform

Field-Oriented Control (FOC) for PMSM produces specific waveforms that reflect the motor's performance. The simulation typically involves current, voltage, torque, and speed waveforms. Here's what you can expect and how to interpret them.

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