engineering proceedings

Proceeding Paper

Permanent Magnet Synchronous Machine Control Performance and Analysis for Environment-Friendly Electric Vehicle Applications †

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† Presented at the 8th International Electrical Engineering Conference, Karachi, Pakistan, 25–26 August 2023.

Abstract: Due to its superior performance, rapid development, and environmental friendliness, the permanent magnet synchronous machine (PMSM), in all of its various design forms, is becoming a crucial component in electric vehicle (EV) applications. This research article shows the numerical implementation and design of a potential vector control for PMSM, intended for electric vehicle application and implemented analytically to achieve maximum efficiency at the lowest possible costs. Additionally, this paper contains crucial machine features, operation assumptions, and simulation validations that are used to actualize machine design. It is shown, via intensive analytical expression and discussion, that step-up changes account for 90% of the rated value, whereas step-down changes account for 10% of the rated value. By implementing advanced measures, the present research endeavors to augment the control effectiveness, operational efficiency, and dependability of PMSMs in EVs.

Keywords: electrical vehicles (EVs); PMSM; PWM; MATLAB; modeling; simulation

Citation: Sardar, M.U.; Yaqoob, M.; Akbar, S.; Shah, S.I.A.; Shahid, M.U.; Mutloob, T. Permanent Magnet Synchronous Machine Control Performance and Analysis for Environment-Friendly Electric Vehicle Applications. *Eng. Proc.* **2023**, *46*, 7. https://doi.org/10.3390/engproc2023046007

Academic Editors: Abdul Ghani Abro and Saad Ahmed Qazi

Published: 20 September 2023

1. Introduction

Many people believe that electric vehicles will be the norm in the future since they are extremely efficient, emit no localized pollution, are silent, and allow the grid operator to regulate electricity. However, there are still significant problems with electric cars that need to be fixed. A limited driving range, a lengthy charging period, and a hefty price are the three primary difficulties. These three primary issues are all connected to the vehicle's battery system. The battery pack should have adequate power to manage accelerations and decelerations, as well as enough energy to allow for a specific driving range. To accurately anticipate the energy consumption of electric automobiles, a precise model of the vehicle is essential [1,2]. An electric vehicle's model is quite intricate since it has so many distinct parts, such as a battery, electric motor, gearbox, and power electronics. The choice of each power system component (electric machines, power electronics, batteries, etc.) will thus receive less attention because this is a very challenging undertaking in and of itself. As a result, this chapter's primary focus will be on the approach to the modeling and design process [3–5]. However, the approach described here is equally appropriate for different architectural styles and component selections.

2. Research Areas in EVs

Due to the rising concerns regarding energy efficiency, energy prices, and environmental protection, electric vehicle (EV) technology has grown significantly in recent years. Applications for rare-earth magnets in SM motor made of neodymium–iron–boron ($Nd_2Fe_{14}B$) and samarium–cobalt (Sm_2Co_{17}) therefore generate a high degree of design, controllability, efficiency, and torque, as well as dependability and robustness as demonstrated in Table 1 [6].

Table 1. PM synchronous and induction motor comparison [7].

Quality	Synchronous Motor	Induction Motor
Speed	Constant and unaffected by load	The speed diminishes as the load rises
Torque-voltage characteristic	Direct relationship between torque and input voltage	Direct relationship between torque and input voltage squared
Cost	More expensive than IM	Cost-effective motor

From milli-Watt-secs to hundreds of kWs, PM motors are employed in a variety of power applications. There are also initiatives to use PMs in large motors with a minimum 1 MW rating. Due to this, PM motors are used in a wide variety of applications, from stepping motors for timepieces to enormous PM synchronous motors for ship propulsion (e.g., icebreakers, naval frigates, cruise ships, and medium-sized cargo boats) [8,9]. A schematic diagram of an electric car with a PMSM drive is illustrated in Figure 1.

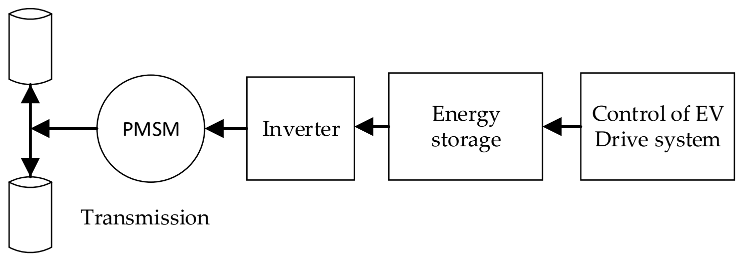

Figure 1. Schematic diagram of EV system.

3. Mathematical Modelling of PMSM

3.1. PM Synchronous Motor Described Mathematically

Space vector theory may be utilized to comprehend the vector control design paradigm. Complex space vectors are used to express the three-phase motor quantities. Two orthogonal axes are all that are required to describe the complex space vectors. The motor may be viewed as a two-phase mechanism [10].

3.2. PM Synchronous Motor Vector Control

Field-oriented theory is utilized to regulate the space vectors of magnetic flux, current, and voltage in the elegant control approach known as vector control for a PM synchronous motor. The coordinate system may be set up to separate the vectors into components that produce magnetic fields and torque [11–14]. This vector control method was created specially to give PM synchronous motors a similarly dynamic performance. In the given equation, the analytical formulations of EVs are as follows:

$$i_s = k\left(I_{sa} + aI_{sb} + a^2 I_{sc}\right) \tag{1}$$

$$u_{SA} = R_S i_{sa} + \frac{d}{dt}\Psi_{SA},\ u_{SB} = R_S i_{SB} + \frac{d}{dt}\Psi_{SB},\ u_{SC} = R_S i_{SC} + \frac{d}{dt}\Psi_{SC},\ \frac{d\omega}{dt} = \frac{p}{J}\left[\frac{3}{2}p\left(\Psi_{S\alpha} i_{S\beta} - \Psi_{S\beta} i_{S\alpha}\right) - T_L\right] \quad (2)$$

3.3. An Illustration of Vector Control

To implement vector control, these steps should be followed and Figure 2 should be implemented:

- Measurements of the motor's phase voltages and currents;
- Clarke transformation to convert them into the two-phase system;
- The inverse Park transformation is used to convert the stator-voltage space vector from the d–q coordinate system to the two-phase system, and output is produced.

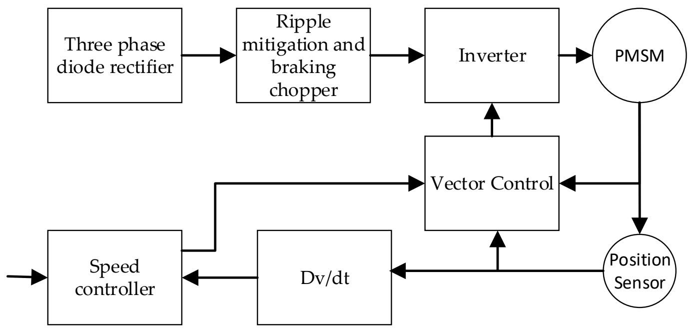

Figure 2. Proposed Synchronous Motor Vector Control in MATLAB.

4. Vector Controller Design Implementation

The design started with an adaptive control strategy. This vector controller technique dynamically modifies control parameters based on the motor's operating conditions, boosting efficiency, and performance under varying load conditions, as depicted in the results. Then, implementing fault-tolerant control techniques allows the vector controller to detect and mitigate motor or drive system defects, ensuring continued operation and minimizing downtime, as explained in Table 2 below.

Table 2. Controller design implementation.

Sr. No.	Design Procedure	Implementation Plan	Sr. No.	Design Procedure	Implementation Plan
1.	Sampling Time	• Sampling time (s) allocation • Simulation time step.	3	Maximum switching frequency	• Selection • This is not used when using the average value inverter.
2.	Current controller hysteresis band	• This value is the total bandwidth distributed symmetrically around.	4	The controller measurement vector	• The torque reference which is speed error • Second is the speed reference.

5. Simulation of PMSM Control

The simulation of a PMSM was performed in MATLAB/Simulink by using a block of PSMS available in block library of SimPowerSystems in the category of Machines.

5.1. Case I (W_{ref} = 300 rpm)

In Figure 3 below, the simulation results, using a 300 rpm reference speed, are displayed. When the rated torque is changed stepwise, the resulting speed waveform retains its reference value. The initial setting for the load torque imparted to the machine's shaft is 3 Nm, which is the nominal value. At t = 0.5 s, it increases to 10 Nm, and at 1.5 s, it decreases to 0 Nm. Step-up changes account for 90% of the rated value, whereas step-down changes account for 10% of the rated value.

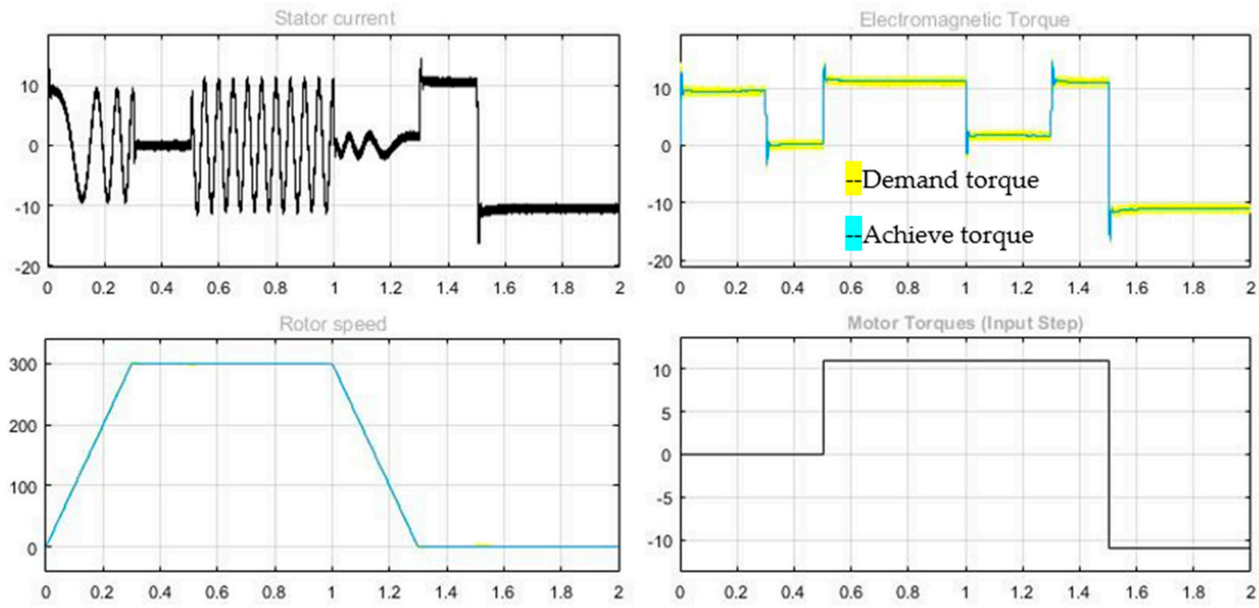

Figure 3. Output waveform in 2.0 sec simulation.

5.2. Case II (Wref = 1000 rpm)

The reference speed used in this case is 800 rpm. All of the results are shown in Figure 4 below.

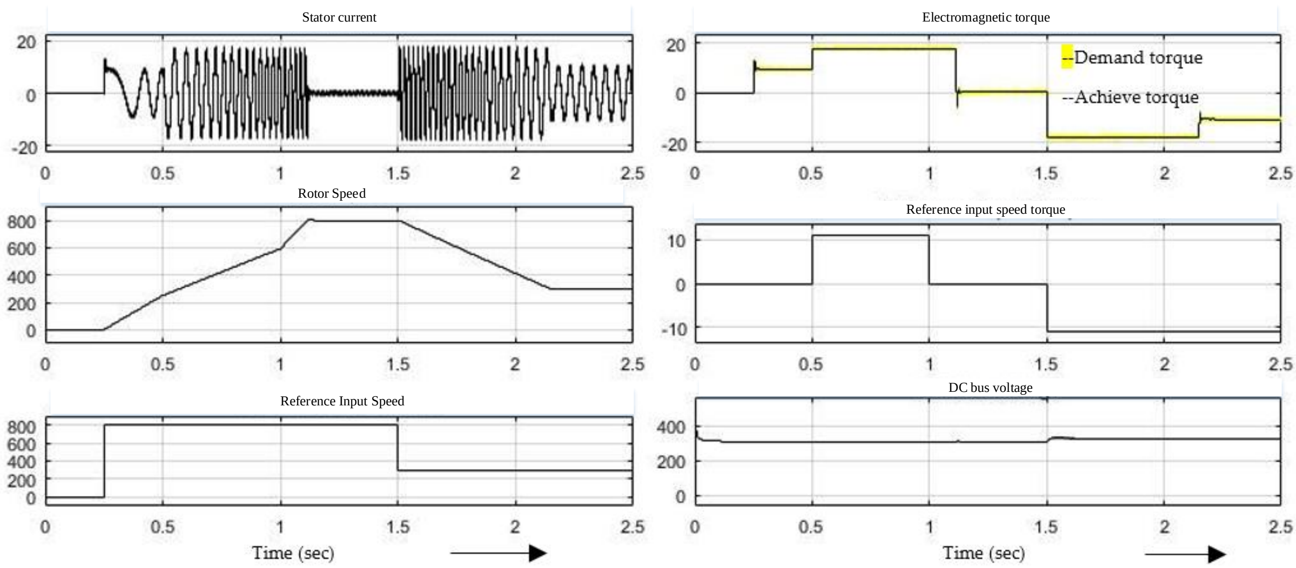

Figure 4. Output waveform.

6. MATLAB Simulation for Desired Speed and Torque Response

The MATLAB simulation below displays a permanent magnet synchronous machine (PMSM) and an inverter scaled for use in a typical car. Although in this instance the inverter is directly connected to the vehicle's battery, a DC–DC converter step is typically present in the middle. As illustrated in Figure 5, when building the PMSM controller, the model may be used to determine the architecture and gains that will deliver the required torque performance.

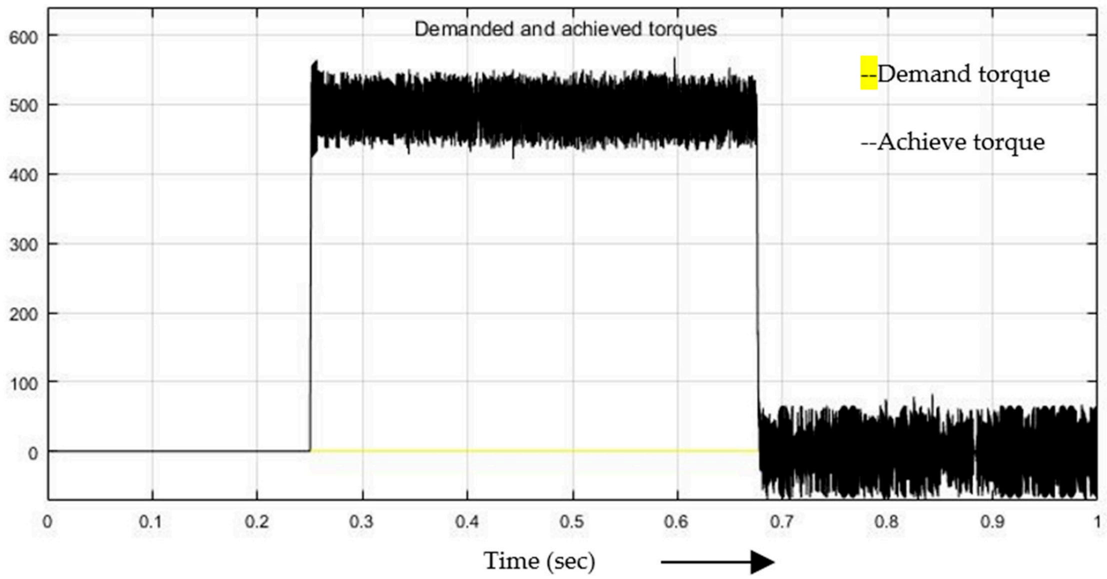

Figure 5. MATLAB simulation showing achievement of required torque.

The rotor of the PM is fitted with several permanent magnet materials, including Sm_2Co_3, Sm_2Co_{17}, and Nd-Fe-B. The effectiveness of the PMSM is also altered by altering the magnets [15].

7. Results and Discussion

The paper focuses on the control performance and analysis of Permanent Magnet Synchronous Machines (PMSMs) used in electric vehicles (EVs). This research achieves the numerical design and implementation to make a possible vector control strategy for PMSMs in EVs as efficient and cost-effective as possible. The simulation validation, machine features, and operation assumptions are all considered, and it is pointed out that 90% of the rated value comes from step-up changes, and 10% comes from step-down changes. The research suggests novel methods of utilizing PMSMs in electric vehicles (EVs) which work better, run more effectively, and are more reliable. An EV's motor drive, comprising a permanent magnet synchronous motor, is modeled using a design procedure because the characteristics of each component of the power system converters are utilized. The use of independent controllers for each input with the least amount of power loss and the creation of a suitable process for controller design are specifically the primary improvements incorporated.

Author Contributions: All authors contributed equally to the completion of this paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: There are no conflict of interest stated by the authors.

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